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VII DATA USE ANALYSIS AND PROCESSING (DUAP)

FINAL PROJECT REPORT

(PHASE II)

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16. Abstract

This report covers several key subjects related to the generation of IntelliDrive^{SM} probe vehicle data and use of this data in application of interest to state departments of transportation and local public transportation agencies. The evaluations conducted as part of this project are primarily based on the probe vehicle data collection system that was deployed by the U.S. Department of Transportation (USDOT) around Novi, Michigan, in 2008 for its Vehicle-Infrastructure Integration (VII) Proof-of-Concept (POC) test program. This system was designed around the use of the 5.9-GHz Dedicated Short Range Communication (DSRC) wireless protocol to enable vehicles to communicate with Roadside Equipment (RSE). The generation of snapshots further followed the protocols defined within the SAE J2735 DSRC Message Set standard.

Following a general introduction in Chapter 1, Chapter 2 briefly reviews the protocols that were used to generate and retrieve probe vehicle snapshots, while Chapter 3 presents a general evaluation of the POC test data that were accumulated during the 2008 test program. This is followed by a presentation in Chapter 4 of the evaluation framework of the current project. This presentation includes an overview of the envisioned DUAP system and descriptions of project stakeholders, potential data sources, supporting technologies, applications of interests, and potential operational constraints. Chapter 5 then presents a general description of the Paramics IntelliDrive^{SM} virtual simulator that is used to conduct some of the subsequent evaluations. While the initial POC test program aimed to evaluate data collection capabilities across a range of application, this program was significantly shortened due to various technical issues. This resulted in incomplete data collection and partial application designs that were insufficient to complete the initial project deliverables associated without rely on simulation. Chapter 6 then examines the effects of snapshot generation protocols and privacy policies on data latency, data quality, and the ability to track vehicles over short distances. Chapter 7 follows with a mapping of application data needs and general descriptions of processes required to convert raw probe data into useful information, while Chapter 8 evaluates how basic traffic flow performance measures (flow rates, flow density, travel times, speed profiles, queue parameters) can be estimated from probe data in systems featuring full and partial proportions of probe vehicles. Chapter 9 further develops a concept of operations for an enhanced traffic monitoring system incorporating probe vehicle and other data sources, while Chapter 10 investigates various issues that must be considered when developing application deployment plans. Chapters 11, 12 and 13 finally present a summary of primary findings, lessons learned and recommendations for future work.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1. Introduction

Over the past several years, federal, state, and local transportation agencies have been working together with private commercial stakeholders to evaluate opportunities offered by emerging wireless communication capabilities to enhance highway safety, improve the efficiency of network operations, reduce the environmental impacts of transportation activities, and provide convenience services to travelers. These activities have centered on the potential for establishing reliable connectivity between vehicles, roadway infrastructure, and wireless consumer devices carried by travelers such as cellular phones. The vision is that vehicles will eventually be able to exchange relevant information with other vehicles, roadside infrastructure devices, and portable devices carried by travelers.

To explore the potentially transformative capabilities offered by wireless technologies, the U.S. Department of Transportation initiated in 2006 a research program on vehicle connectivity. This program, which was initially known as the Vehicle-Infrastructure Integration (VII) initiative, is now known as the IntelliDrive^{SM} initiative. Its major aims were to support the development and testing of communication technologies and new applications, assess infrastructure needs, and benefits and costs of potential applications, and developing viable infrastructure and application deployment strategies.

The Data Uses and Analysis Processing (DUAP) program was initiated in 2006 by the Michigan Department of Transportation (MDOT) to complement research initiatives from the federal government and the car manufacturing industry. The purpose of this project was to evaluate how emerging applications and data collection capabilities could support the safety, mobility and system management needs of state departments of transportation, with a primary focus on MDOT needs.

To help put the evaluations described in this report within context, the remainder of this chapter presents background information on the federal IntelliDrive^{SM} research initiative, how the DUAP project relates to the federal initiative, and a history of the project. An outline of the report organization is also presented at the end of the chapter.

1.1. USDOT IntelliDrive^{SM} Program Initiative

The federal research program on vehicle connectivity was established in 2006 as the Vehicle-Infrastructure Integration (VII) initiative. Research efforts within the initial program almost exclusively focused on the use of the Dedicated Short-Range Communication (DSRC) wireless standard (ASTM, 2003). This standard, which was adopted in 2003, reserves seven licensed communication channels at the 5.9 GHz band primarily for safety applications. Since access to the channels is controlled, the expectation was that DSRC technology would enable vehicles to establish reliable, low-latency wireless communication with other DSRC-equipped vehicles or devices within a range of 3280 ft (1000 m) at speeds of up to 120 mph (193 km/h).

A major outcome of the initial VII program was the deployment in 2008 of a Proof-of-Concept (POC) test bed in Michigan featuring 57 DSRC roadside communication units (RSEs). This test bed was used to determine if the initial communication concepts were sound, could provide an effective mechanism for wirelessly sending and receiving information to and from vehicles, and could support intended applications. While technical issues resulted in limited application testing, the POC tests successfully demonstrated the viability of using DSRC for establishing communication with vehicles.

While the initial connectivity concepts almost exclusively relied on the use of roadside DSRC devices to communicate with vehicles, changes in the communication technology landscape since the inception of the research program led to the recognition that significant benefits could be obtained from a more comprehensive use of technology. Instead of focusing solely on DSRC technology, research efforts started to look at the potential for using smart cellular phones, Bluetooth-enabled devices, WiMax devices, and satellite communications. This led to the rebranding of the research program from VII to IntelliDrive^{SM} in 2009 and in the promotion of research on both DSRC and non-DSRC based applications.

1.2. Scope of DUAP Program

As indicated, the DUAP program was initiated in 2006 by the Michigan Department of Transportation (MDOT) to complement research initiatives from the federal government and the car manufacturing industry. The purpose of this program was to investigate how emerging data collection capabilities, particularly the ability for vehicles to provide system status and traffic snapshots data, could help MDOT improve roadway safety, manage traffic, and implement efficient asset management programs.

Figure 1-1 shows how the DUAP program relates to the IntelliDrive^{SM} operational framework. Elements of interest to the DUAP program are indicated by the blue and green bubbles. The focus is on processes supporting data collection, aggregation, storage, and uses in applications of interest to MDOT. The program thus generally covers processes aiming to collect information from vehicles traveling within a road network. There is generally no consideration of processes aiming to send information back to drivers or onboard vehicle systems, with the exceptions of processes supporting Advanced Traveler Information Systems (ATIS) operated by MDOT. This includes processes supporting the use of changeable message signs and the displaying of traffic conditions information on the MI Drive website. All processes supporting applications that are to be developed by car-manufacturers, after-market device suppliers or private service firms are also typically outside the score of the DUAP program.

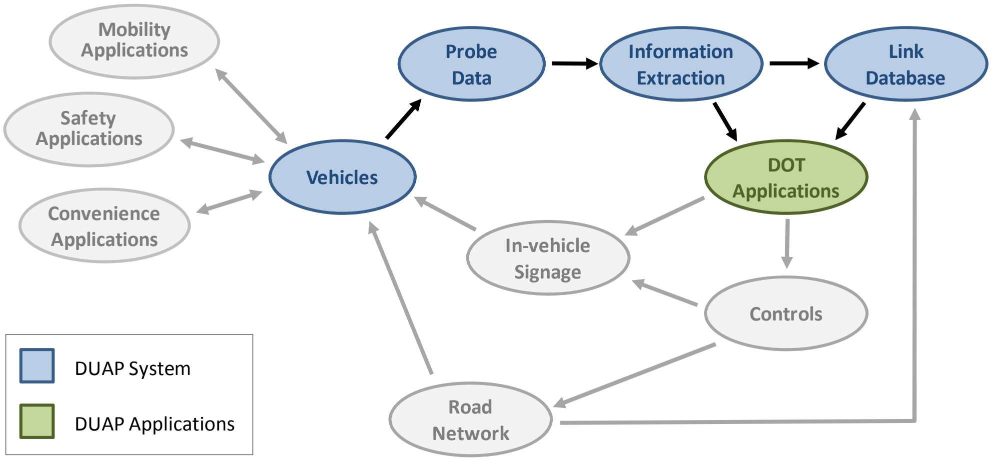


Figure 1-1 – DUAP IntelliDrive^{SM} Operational Scheme

Figure 1-2 further illustrates how a DUAP system is envisioned to interact with existing MDOT operations. The expectation is that a DUAP system will draw data from envisioned IntelliDrive^{SM} systems, existing MDOT data sources, relevant external sources, and various MDOT projects that may be executed. These data sources would not only be used to enrich information used in existing MDOT applications but also to facilitate the development of new applications within MDOT, as well as applications outside MDOT relying on data managed by the agency.

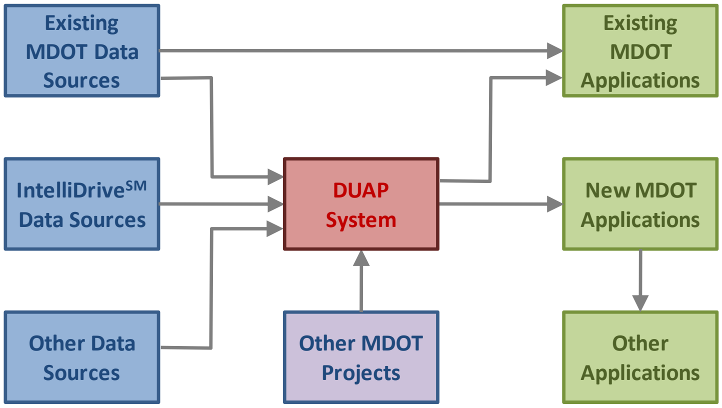


Figure 1-2 – DUAP Evaluation Framework

1.3. DUAP Project History

The key initial targets within the DUAP program were to:

- Identify uses for the IntelliDrive^{SM} data
- Develop algorithms to use and process the data
- Develop prototype applications and data management software
- Evaluate how well the data and algorithms could function in a department of transportation operational setting

Specific questions that sought to be answered, particularly when considering the potential to eventually collect data from most, if not all, vehicles in real time included:

- How can probe vehicle data be used to provide significant improvements in road condition assessment, road safety, traffic management, and asset management?
- How can probe data be used to transform MDOT's business practices and better achieve MDOT's organizational goals?
- What are potential issues regarding the ability to efficiently use the collected data?
- What processes are required to convert data into meaningful measures?
- What other ways can MDOT benefit from probe data?

A first set of tasks under the DUAP umbrella were awarded to Mixon/Hill in 2006. These efforts led to the publication in 2007 of documents describing a concept of operations for the DUAP system, the proposed system architecture, and general system requirements (Mixon/Hill, 2007a, 2007b, 2007c).

UMTRI's involvement in the DUAP program was intended to fulfill MDOT's need for independent evaluation and documentation of IntelliDrive^{SM} applications and databases that were being developed by other consultants involved in the DUAP program. There was also an interest in evaluating how results from the USDOT VII POC test program could affect data collection capabilities and uses.

An initial set of test applications that were to be the focus of the analyses to be conducted by UMTRI were selected based on input from MDOT and information contained in the DUAP documents produced by Mixon/Hill. Based on these reviews, the evaluations were to focus on prototype applications supporting the following evaluation capabilities:

- Real-time and historical traffic information
- Performance measure calculations
- Congestion mitigation
- Weather traffic impacts
- Asset management
- Predictive traffic impacts

However, re-scoping of the UMTRI portion of the DUAP project became necessary following substantial changes in the program. These changes were triggered by the USDOT modifying and shortening its VII POC test program. This change resulted in limited data collection and partial application designs that were insufficient to complete the deliverables identified in the initial DUAP project. Instead of solely relying on field data to conduct application and impact evaluations, activities were modified to leverage the potential that existed within UMTRI to simulate the generation and retrieval of probe vehicle data using a virtual model of the USDOT's Michigan POC test bed within the Paramics microscopic traffic simulation model. Additional outreach activities not described within this report, such as the production of the periodic "VII Newsletter", were also added to the DUAP program.

1.4. Organization of Report

The remainder of this report describes the outcome of the various research activities that were conducted at UMTRI as part of the DUAP program. Presentation of the various evaluations is organized as follows:

- **Chapter 2:** Provides a summary of the probe vehicle data collection system that were deployed within the USDOT Michigan POC test bed and which are the primary focus of a majority of the evaluations reported in this document.
- **Chapter 3:** Provides a summary of the primary findings of the USDOT POC test program relevant to the DUAP program.
- **Chapter 4:** Presents the framework within which the DUAP evaluations were conducted. This includes reviews of existing sensing technologies, relevant potential data sources, and applications of interests to the DUAP program.
- **Chapter 5:** Describes the Paramics IntelliDrive^{SM} Probe Vehicle Data Generator that was used to enable the evaluation of probe data uses over conditions not currently covered by existing test bed data.
- **Chapter 6:** Examines the effects of snapshot generation protocols and privacy policies on data latency, data quality, and the ability to track vehicles over effective distances.
- **Chapter 7:** Maps application data needs and describes general data processes that may be required to convert raw probe vehicle data into information usable by individual applications.
- **Chapter 8:** Evaluates whether or how flow rates, density, speed profiles, average travel times, delays, number of stops, queue parameters, turn percentages, vehicle classification, and vehicle occupancy could be estimated from collected probe vehicle data.

- **Chapter 9:** Develops a concept of operations for an enhanced traffic monitoring system integrating probe vehicle data collection to other data sources.
- **Chapter 10:** Investigates various issues that should be considered when selecting which applications to deploy and when developing application deployment plans.
- **Chapter 11:** Provides a summary of the primary findings of the projects and some recommendations for future work.
- **Chapter 12:** Provides general lessons learned regarding the collection and use of IntelliDrive^{SM} data.
- **Section 13:** Provides recommendations for future work to promote the development and deployment of IntelliDrive^{SM} applications of interest to public transportation agencies.

2. IntelliDrive^{SM} Probe Vehicle Data System Overview

This chapter provides an overview of the IntelliDrive^{SM} probe vehicle data generation and collection system considered in the DUAP program. This system closely reflects the USDOT VII POC system that was deployed in Novi, Michigan, in 2008. Elements presented include:

- General system architecture
- Onboard vehicle equipment units (OBEs)
- Roadside communication units (RSEs)
- Backhaul network
- Probe data generation
- Probe data upload at RSEs
- Probe message content

2.1. System Architecture

Figure 2-1 illustrates the overall architecture of the USDOT POC system. Within this architecture, the mobile terminals represent vehicles equipped with onboard DSRC wireless communication capability. The roadside equipments (RSEs) represent DSRC communication units installed at fixed locations within the test network, typically near a roadway, such as on a lamppost, gantry, or other suitable roadside structure. Within this system, vehicles were able to exchange data and messages with RSEs and other vehicles equipped with DSRC communicators. Each RSE was further connected to a regional Service Delivery Node (SDN) via a backhaul link. Through this connection, information received at an SDN could be sent to other SDNs, thus allowing data to be propagated across the entire network. A link to a central server was also provided to allow collected data to be stored at a single location.

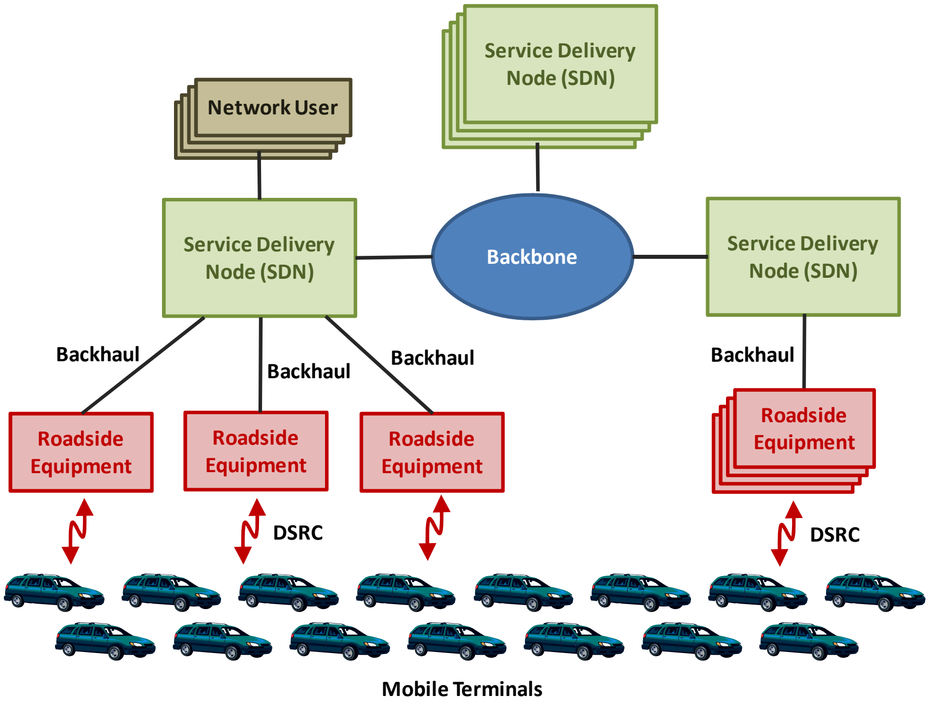


Figure 2-1 – Overall Structure of POC Test Architecture
(Adapted from VIIC Consortium, 2009)

2.2. Onboard Equipment Units (OBEs)

The equipment installed onboard each test vehicle consisted of a self-contained computer system designed to support a wide variety of applications and services. This equipment was the central piece of hardware responsible for vehicle interactions within the VII network.

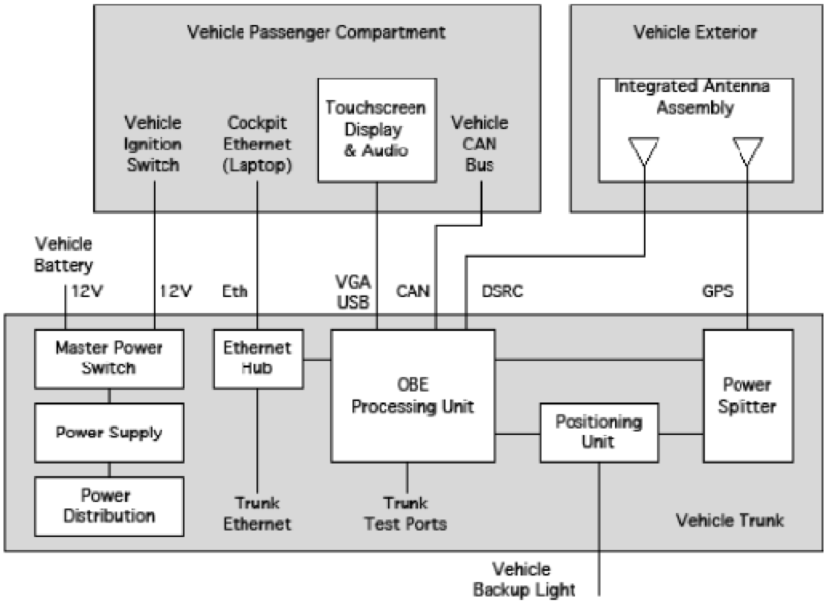


Figure 2-2 – Onboard Equipment Subsystem Block Diagram
(Source: VIIC Consortium, 2009)

Figure 2-2 illustrates the basic architecture of the OBEs that were used in the POC tests. Each OBE was based on an Intel processor running on a Linux operating system. Each unit was designed to support communications with other IntelliDrive^{SM} components, exchanges data with various vehicle systems through an interface with the vehicle's Controller Area Network (CAN) and accommodates driver interaction through a Human-Machine Interface (HMI). Subsystems also included a touch-screen display device, an external Global Positioning System (GPS) receiver, an external DSRC antenna, and a programmable power management system. The computing platform hardware further provided daughter card slots and assorted local interfaces to provide additional features, control, and test flexibility during POC test activities.

Figure 2-3 provides a functional view of the various services that were implemented within an OBE to support probe vehicle data generation and collection, as well as potential onboard application operations. At the center of the system is the probe data application, which was responsible to generating, storing and managing the transmission of snapshots to RSEs. Various basic services were then were implemented around this central component to support OBE operations:

- **Positioning Services:** Provision of vehicle position and time information to applications, including notification messages about geographic events
- **Security Services:** Provision of specialized security functions (signing, verification, encryption, and decryption) for use by applications
- **Logging Service:** Capability to log information about various system events

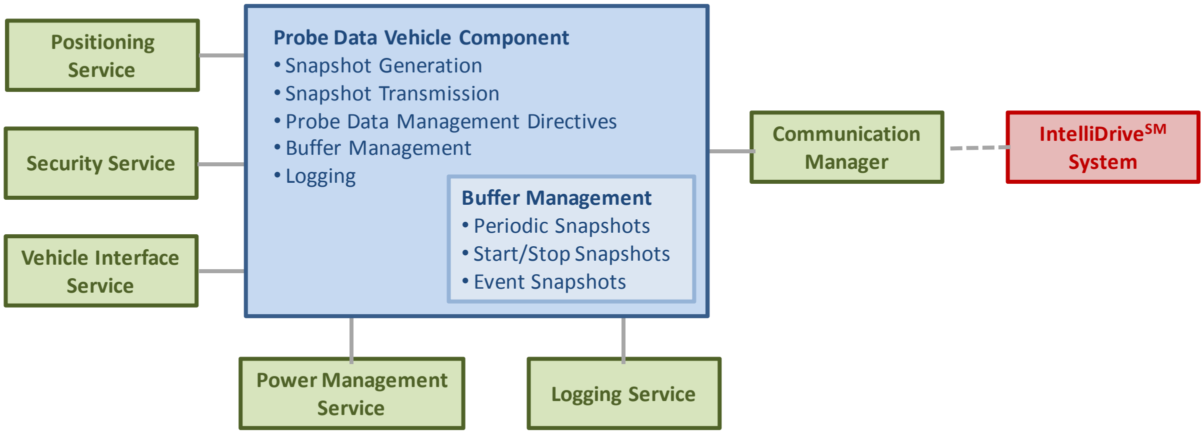


Figure 2-3 – Functional Elements of Vehicle Probe Data Generation and Collection
(Reproduced from VIIC Consortium, 2009)

- **Vehicle Interface:** Provision of a common referencing scheme and means for accessing vehicle data; this interface also allowed the OBEs to be used in a variety of vehicle types without the need to customize the interface of each application to each vehicle type
- **Power Management:** Provision of power to various OBE systems
- **Communications Manager:** Interface between applications, security services, and DSRC radio subsystems

2.3. Roadside Communication Units (RSEs)

The RSEs were intended to serve as communication network endpoints. Their role was to provide connectivity between OBEs, SDNs, and other remote services. In the initial VII concept, all data exchanges between vehicles and infrastructure elements were envisioned to pass through an RSE using DSRC wireless communication protocols. The more recent IntelliDrive^{SM} concept modifies this operating environment by also considering data collection through alternate wireless paths, such by using cellular phones.

The RSEs used in the POC tests were self-contained units that could be mounted on a signal controller, lamppost, gantry, or other suitable roadside structure. One of these is shown in Figure 2-4. Each RSE included support for a DSRC radio and a GPS receiver. RSEs also included data routing functions and a set of proxy applications that extended the services residing at the SDN out to each RSE associated with that SDN. The proxy applications essentially passed messages to and from their counterpart SDN services, in addition to interfacing with the DSRC radio subsystem. The radio subsystem included a DSRC radio and a radio handler that could accept or send messages to and from the various proxies, as well as construct or update a playlist of all broadcast messages to be transmitted. Depending on the situation, an RSE could also be connected to a local transaction processor or a local safety system, such as a local tolling system or traffic signal controller.

Figure 2-4 – Installed RSE Unit in USDOT POC Test Bed in Michigan

2.4. Backhaul Network

The backhaul network provided physical data transport from an RSE to the SDN. This network was actually comprised of several logical interfaces. A Simple Network Management Protocol (SNMP) interface was used to audit and manage the operation of the various RSE elements. An XML-based Remote Process Control interface was further used to deliver to an RSE content that needed to be broadcast by it, while a general-purpose TCP/UDP/IP interface was used to transfer data packets between the RSE and the SDN services.

2.5. Probe Vehicle Data Generation

Processes governing the generation of probe vehicle data are defined in the SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary standard [SAE International, 2008]. This section briefly describes the:

- Types of snapshots generated
- Snapshot generation protocols
- Processes used to store data within a vehicle before it can be uploaded to an RSE

2.5.1. Types of Snapshots Generated

Three basic types of snapshots are defined within the SAE J2735 standard:

- **Periodic snapshots**, meant to record the status of various vehicle systems at specific intervals
- **Stop/start event snapshots**, meant to record when a vehicle stops and starts moving after having made a stop
- **Special event snapshots,** meant to record when specific changes in specific vehicle status occur, such as when brakes are applied, wipers or headlights turned on, etc.

2.5.2. Snapshot Generation Protocols

Each type of snapshot is generated according to a programmable policy defining data collection rate and content. The following summarizes the default protocols used for the POC tests:

- Under normal operation, periodic snapshots were to be generated at intervals based on the vehicle's speed. The default setting was to generate a snapshot every 20 s for vehicles traveling at speeds greater than or equal to 60 mph, every four s for speeds lower than 20 mph, and at intervals linearly interpolated between 4 and 20 s for speeds between 20 and 60 mph. To save memory, no periodic snapshots were collected when a vehicle was stopped.

- A stop event was recorded after a vehicle had been immobilized for a certain interval. To avoid recording multiple stops in stop-and-go situations, a stop was only recorded if no other stop event has been recorded in the past few seconds. The default setting was to record a stop after a vehicle had been immobilized for five s when at least 15 s had elapsed since the last recorded stop.
- A start event was recorded when the speed of a vehicle currently considered to be stopped increased above 10 mph.
- Special events snapshots were generated when specific changes in vehicle status would be observed, such as when brakes were applied, headlights turned on or off, etc.

The above protocols could be changed by system operators to allow data collection to be tailored to specific situations. For instance, periodic snapshots could be generated according to fixed intervals or according to distance traveled. The triggers leading to the generation of stop/start and special event snapshots could also be altered. These changes could be applied either globally, to affect all the vehicles within the network, or locally, to affect only vehicles in proximity of a specific or a group of RSEs.

2.5.3. Data Storage within Vehicles

Once generated, the snapshots were passed to the Buffer Management service, which managed data storage via a configurable data replacement policy. This policy defined how long a snapshot should remain unsent in the buffer before it is deleted, how long the gap between groups of snapshots taken under a given Probe Sequence Number (PSN) should be, and other criteria.

Within the buffer, the default approach was to insert periodic snapshots in the order in which they were generated, with the newest placed on top of the list to position it first in line for retrieval. Stop/start event snapshots were inserted in a similar fashion, but always on top of any existing periodic snapshots to allow their retrieval before periodic snapshots.

Snapshots were added to the buffer as long as space was available. When the buffer became full, the second-oldest periodic snapshot was removed to make room for new snapshots. The oldest periodic snapshot was kept to retain information about the length of time and traveled distance since the last RSE communication. This snapshot was only removed if no other periodic snapshot remained. If the buffer became entirely filled with stop/start event snapshots, the oldest stop/start snapshot was then removed to make room for new stop/start snapshots, but not for new periodic snapshots.

2.6. Data Upload to RSEs

Figure 2-5 illustrates the process for uploading snapshots from probe vehicles. After a vehicle would have established a secure and stable connection with an RSE, it would start transmitting to the RSE the snapshots contained in its buffer. Snapshots were typically sent in groups of up to four per message, with only snapshots containing the same PSN included in each message, in the following order:

- Event triggered snapshots were transmitted first, based on the fact that they may be used to characterize specific adverse conditions that may be of interest to traffic operations and are therefore more critical than other types of snapshots.

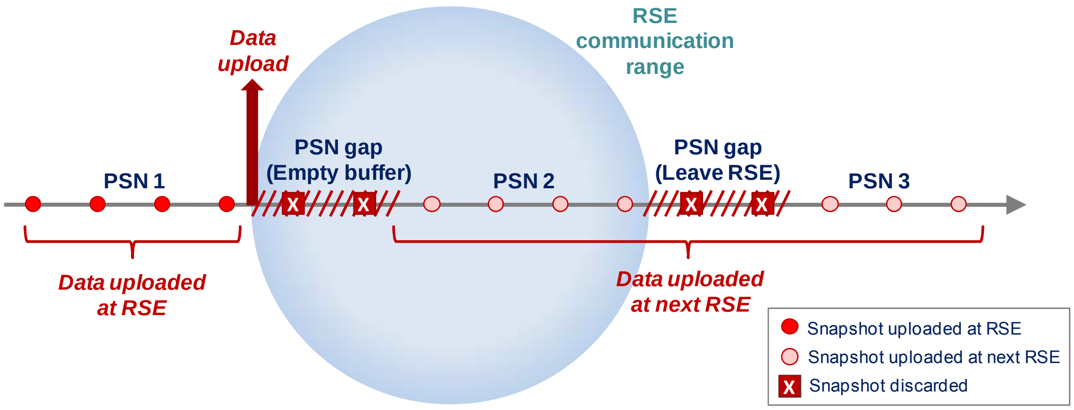


Figure 2-5 – Data Handling around RSEs

- Stop and start event snapshots were second in line, based on their ability to provide finer information on incidents and various dynamic parameters concerning traffic flow.
- Periodic snapshots were the last in line.

After a vehicle would have finished transmitting its data contained in its onboard buffer, it would then delete all the snapshots contained within it and initiate a PSN change. As explained in the following subsection, this would result in a gap in the snapshot collection process. Following the gap, snapshots collection would resume with the new PSN.

Vehicles were further prevented from communicating more than once with a given RSE. New snapshots generated by a vehicle while still within range of an RSE after an initial data transmissions had been completed were then kept in the vehicle's memory buffer until another RSE was reached.

The termination of a connection with an RSE would also trigger a PSN change. This occurred either after a vehicle had moved out of the range of an RSE or after a connection was unexpectedly terminated due to technical issues.

If a vehicle would unexpectedly lose its connection with an RSE, all snapshots contained within the buffer would be deleted, whether they had been transmitted or not. A PSN change would then occurs. If the vehicle would reestablish connection with the same RSE, it would then be considered as a different vehicle by the RSE.

Snapshots received by RSEs were forwarded to a Service Delivery Node (SDN), which then forwarded the data to publish/subscribe services that were tasked with accumulating the data. After the snapshots had been forwarded to all requesting subscribers, any data that may have been accumulated in the SDN were deleted. This process was implanted to aid in scalability, particularly within the context that the tested system may eventually need to process enormous volumes of data, as well as to avoid issues associated with public maintenance of the data.

2.7. Privacy Protection Rules

To allow sequences of snapshots to be linked to specific vehicles where needed, vehicles were instructed to tag an identification number to all captured periodic and stop/start event snapshots. This number, which is known as the Probe Segment Number (PSN) was determined independently by each vehicle. However, to prevent PSNs from being used to track vehicles over long distances, the following constraints based on recommended standards were implemented:

- The PSN used by a vehicle had be changed after 3280 ft (1000 m) or 120 s, whichever occurred last to prevented a vehicle from tagging the same PSN to all the snapshots generated during a given trips. The 3280 ft and 120 s thresholds theoretically allowed tracking vehicles over distances similar to what an observer standing on the side of the road could already do.
- After all snapshots contained in a vehicle's onboard memory buffer would have been transmitted to an RSE, other snapshots subsequently generated with the same PSN could not be uploaded to the same or other RSEs. This rule was imposed to remove the ability of tracking vehicle movements from one RSE to the next.
- The termination of a RSE connection automatically triggered a change of PSN. This rule essentially enforced the previous one by preventing any PSN to be used at more than one RSE. It also allowed reducing potential data losses that would arise if vehicles were allowed to keep using the same PSN following the termination of an RSE connection.
- The PSN was automatically changed after the memory buffer of a vehicle would become empty. This typically occurred after a vehicle had terminated sending all snapshots stored within its buffer to an RSE. This rule was again designed to reduce potential snapshot losses that would arise if vehicles were allowed to keep using the same PSN following termination of an RSE connection.
- Following a PSN change, all snapshots generated during a randomly determined interval of 3 to 13 s, or 164 to 820 ft (50 to 250 m), whichever occurs first, were discarded. This rule was imposed to make it difficult to try to track vehicle movements by attempting to use data recorded within each snapshot to logically link sequences of snapshots with different PSNs.

Vehicle anonymity was further enforced by requiring snapshots to hold no information that could be used to link the snapshots to a particular vehicle. Probe messages were also anonymously signed to assure that the sender is legitimate, and locally encrypted to avoid issues with radio eavesdropping.

2.8. Probe Vehicle Message Content

When a vehicle came within range of an RSE, onboard communication functions packaged the snapshots stored within the vehicle's memory buffer into a series of messages that were then sequentially transmitted to the RSE. The vision was that each probe vehicle messages would contain a maximum of four snapshots. For instance, a vehicle having 26 snapshots to upload would send these in a series of 7 messages, with each of the first six messages containing four snapshots and the last message containing the remaining two snapshots. This communication approach was adopted based on bandwidth analysis and communication efficiency considerations linked to the need to send potentially large amount of data from fast-moving vehicles to fixed roadside communication units.

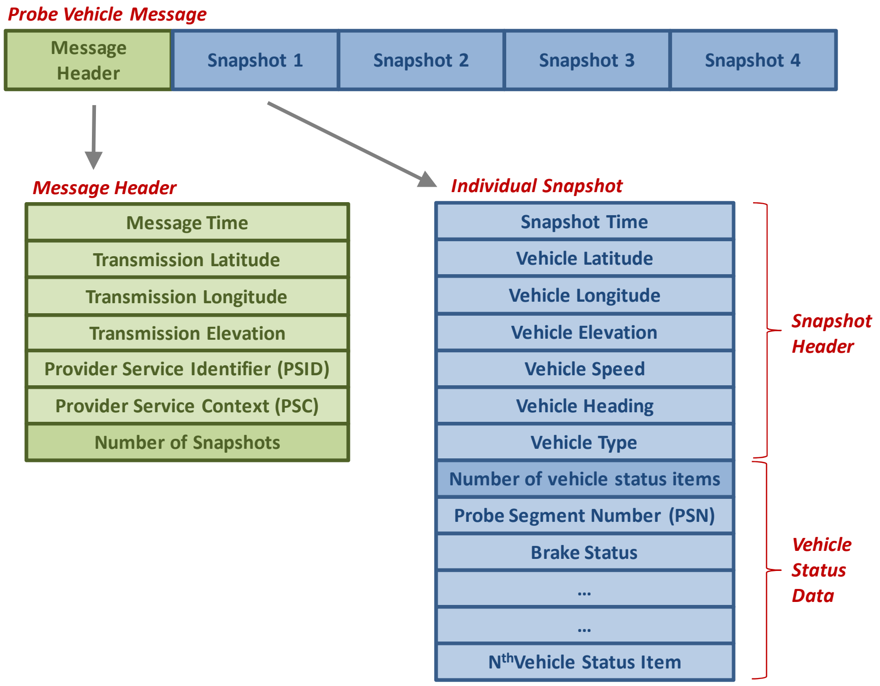


Figure 2-6 – Typical Structure of a Probe Vehicle Message

Figure 2-6 illustrates a simplified probe message structure as defined in the SAE J2735 dataset standard [SAE International, 2006, 2008]. This structure divides a message into two primary sections:

- A probe message header that is to contain information about the time the message was generated, the location of the transmission, some application information data, and a count of the number of snapshots included in the message.
- A series of individual snapshots transmitted with the message.

The following sections provide detailed description of the data items that can be expected to be included in the message header and individual snapshots. These descriptions are made using examples of probe vehicle messages that were collected during the summer and fall of 2008 as part of the USDOT POC test program in Novi, Michigan. Since the exact content of probe vehicle messages is still subject to development, it should be kept in mind while going through the following sections that final IntelliDrive^{SM} deployments may exhibit slight variations in message content.

2.8.1. Probe Message Header Data Items

Probe message header data are meant to identify the context in which each message is generated. Table 2-1 describes various data fields expected to be included in each message header. This includes the time the message was generated, information about the location of the transmission and codes defining the application generating the message and its purpose. This information will allow an application to determine whether it has already received a specific message. For each parameter, the table also shows the standardized measurement unit, the precision used for the measurement (if applicable), and a list of specific values that could be assigned to the parameter.

Examples of message header data are shown in Table 2-2. The table shows the header of 24 probe vehicle messages that were generated during the USDOT POC test program in Michigan in 2008. The data shown is not the raw probe vehicle data, but a formatted data converting the transmitted raw probe data into more meaningful measures. This formatting was done at UMTRI by post-processing the raw probe data from the POC test program through a Microsoft Excel Visual Basic macro.

The first header item in the POC probe vehicle messages is a serial number that uniquely identifies each message. For the POC test, the first five characters of the serial number uniquely identified an OBE. This allowed determining which of the test vehicles generated each message. For instance, it can be observed in Table 2-2 that the probe vehicle messages were generated by the vehicles holding the OBEs labeled “OB422,” “OB325,” and “OC548.” This provision was implemented for testing purposes only, as current standards stipulate that no information allowing a message to be traced to a specific vehicle should be transmitted with probe data.

Table 2-1 –POC Probe Message Header Data Fields

Parameter		**Description**	**Units**	**Precision**	**Value recorded in snapshot**
Message ID		Unique probe message ID	n/a	n/a	Message ID
SDN	Year	Year data was recorded	Calendar year	n/a	Year in yyyy format
	Month	Month data was recorded	Month name	n/a	Month of year (1 – 12)
	Day	Day data was recorded	Days of week	n/a	Day of month (0 – 31)
	Hour	Hour data was recorded	Hour of day	1 hour	Hour of day (0 – 24)
	Min	Minute data was recorded	Minutes within hour	1 min	Minutes from start of hour (0 – 59)
	Sec	Second data was recorded	Seconds within minute	0.001 s	Milliseconds from start of minute (0 – 59999)
	Msg	Message count	Messages	n/a	Number of messages sent from a specific vehicle during a given transmission
RSE	Year	Year data was recorded	Calendar year	n/a	Year in yyyy format
	Month	Month data was recorded	Month name	n/a	Month of year (1 – 12)
	Day	Day data was recorded	Days of week	n/a	Day of month (0 – 31)
	Hour	Hour data was recorded	Hour of day	1 hour	Hour of day (0 – 24)
	Min	Minute data was recorded	Minutes within hour	1 min	Minutes from start of hour (0 – 59)
	Sec	Second data was recorded	Seconds within minute	0.001 s	Milliseconds from start of minute (0 – 59999)
	Long	Geographical longitude	Degrees	0.000125°	-7,200,000,000 to 7,200,000,000, representing a range of -90° to +90°
	Lat	Geographical latitude	Degrees	0.000125°	-14,400,000,000 to 14,400,000,000, representing a range of -180° to +180°
	Elev	Elevation of vehicle	Meters	0.1 m	Measured elevation minus 1000 m
	Heading	Heading of vehicle	Degrees	0.00459°	Heading measurement (0-360^0) multiplied by 182.0417
	Speed	Speed of vehicle	Meters per second	0.01 m/s	Speed measurement multiplied by 100. Should be 0 for any fixed RSE
Snapshot Count		Number of snapshots in message	Snapshots	n/a	Number of snapshots, between 1 and 4

Table 2-2 – Sample of Formatted Probe Messages from POC Test: Header Data

MESSAGE HEADER																										SNAPSHOT DATA					
Message Serial Number	SDN Time Stamp							RSE Time Stamp						RSE Identification						Data Confidence					Snapshot	Position Data					
	Year	Mo	Day	Hour	Min	Sec	Msg	Year	Mo	Day	Hour	Min	Sec	RSE ID	Long	Lat	Elev	Heading	Speed	Time	Pos	Elev	Heading	Speed	Count	Year	Mo	Day	Hr	Min	Sec
															(degs)	(degs)	(m)	(degs)	(m/s)												
0C548030 00000000 234440	2008	8	27	00	02	41	0	2008	8	27	0	2	34	34	-83.4329780	42.4242305	102466	358.989185	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	0	2	32
0C548030 00000000 515439	2008	8	27	00	05	20	0	2008	8	27	0	5	15	34	-83.4332535	42.4306831	102494	358.280556	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	0	5	14
0C548030 00000000 519913	2008	8	27	00	05	20	1	2008	8	27	0	5	19	34	-83.4332535	42.4306831	102494	358.280556	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	0	4	53
0C548030 00000000 550316	2008	8	27	00	05	56	0	2008	8	27	0	5	50	34	-83.4332689	42.4309919	102500	358.346475	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	0	5	49
0C548030 00000002 506175	2008	8	27	00	25	09	0	2008	8	27	0	25	6	34	-83.4348300	42.4420228	102459	210.523198	0	n/a	n/a	n/a	n/a	n/a	3	2008	8	27	0	24	59
																										2008	8	27	0	23	57
																										2008	8	27	0	23	
0B325030 00000133 854890	2008	8	27	13	38	58	0	2008	8	27	13	38	54	34	-83.4317060	42.4390690	102396	269.026279	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	13	38	
0B325030 00000133 955080	2008	8	27	13	39	58	0	2008	8	27	13	39	55	34	-83.4356573	42.4389904	102459	272.349693	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	13	39	
0C453030 00000134 126291	2008	8	27	13	41	29	0	2008	8	27	13	41	26	34	-83.3268965	42.3839000	101899	265.955554	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	13	41	
0B422030 00000134 228177	2008	8	27	13	42	32	0	2008	8	27	13	42	28	34	-83.3200465	42.3735283	101947	0.0000000	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	13	42	
0B422030 00000134 302792	2008	8	27	13	43	08	0	2008	8	27	13	43	2	34	-83.3200465	42.3735283	101947	0.0000000	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	13	42	
0B422030 00000140 458885	2008	8	27	14	05	06	0	2008	8	27	14	4	58	34	-83.4349565	42.4418483	102472	211.121962	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	14	1	
																										2008	8	27	14	0	
																										2008	8	27	14	0	
																										2008	8	27	14	0	
0B422030 00000140 505828	2008	8	27	14	05	06	1	2008	8	27	14	5	5	34	-83.4356150	42.4410533	102462	210.622076	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	14	0	
																										2008	8	27	13	59	47
																										2008	8	27	13	59	32
																										2008	8	27	13	59	17
0B422030 00000140 506028	2008	8	27	14	05	06	2	2008	8	27	14	5	6	34	-83.4356150	42.4410533	102462	210.622076	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	13	59	2
																										2008	8	27	13	58	47
																										2008	8	27	13	58	32
																										2008	8	27	13	58	17
0B422030 00000140 506229	2008	8	27	14	05	06	3	2008	8	27	14	5	6	34	-83.4357133	42.4409200	102459	209.023542	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	13	58	2
																										2008	8	27	13	57	47
																										2008	8	27	13	57	32
																										2008	8	27	13	57	16
0B422030 00000140 506638	2008	8	27	14	05	07	0	2008	8	27	14	5	6	34	-83.4357133	42.4409200	102459	209.023542	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	13	57	
																										2008	8	27	13	56	
																										2008	8	27	13	56	
																										2008	8	27	13	56	
0B325030 00000140 504181	2008	8	27	14	05	11	0	2008	8	27	14	5	4	34	-83.4349704	42.4418374	102435	211.292253	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	13	56	
																										2008	8	27	13	56	
																										2008	8	27	13	56	
																										2008	8	27	13	55	44
0B325030 00000140 511124	2008	8	27	14	05	11	1	2008	8	27	14	5	11	34	-83.4356254	42.4410449	102437	210.243042	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	13	55	33
																										2008	8	27	13	55	14
																										2008	8	27	13	54	59
																										2008	8	27	13	54	48
0B325030 00000140 511847	2008	8	27	14	05	12	0	2008	8	27	14	5	11	34	-83.4356254	42.4410449	102437	210.243042	0	n/a	n/a	n/a	n/a	n/a	3	2008	8	27	13	53	29
																										2008	8	27	13	53	14
																										2008	8	27	13	52	59
0B325030 00000140 512119	2008	8	27	14	05	12	1	2008	8	27	14	5	12	34	-83.4357174	42.4409228	102434	208.320406	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	14	5	2
																										2008	8	27	14	5	
																										2008	8	27	14	5	
																										2008	8	27	14	5	
0B325030 00000140 512420	2008	8	27	14	05	12	2	2008	8	27	14	5	12	34	-83.4357174	42.4409228	102434	208.320406	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	14	4	
0B325030 00000140 511529	2008	8	27	14	05	12	3	2008	8	27	14	5	11	34	-83.4356254	42.4410449	102437	210.243042	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	13	54	
																										2008	8	27	13	54	
																										2008	8	27	13	54	
																										2008	8	27	13	53	44
0B325030 00000140 512516	2008	8	27	14	05	13	0	2008	8	27	14	5	12	34	-83.4357174	42.4409228	102434	208.320406	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	14	4	34
																										2008	8	27	14	4	30
																										2008	8	27	14	4	26
																										2008	8	27	14	4	22
0B325030 00000140 512722	2008	8	27	14	05	13	1	2008	8	27	14	5	12	34	-83.4357174	42.4409228	102434	208.320406	0	n/a	n/a	n/a	n/a	n/a	4	2008	8	27	14	4	8
																										2008	8	27	14	4	2
																										2008	8	27	14	3	57
																										2008	8	27	14	3	
0B325030 00000140 512924	2008	8	27	14	05	13	2	2008	8	27	14	5	12	34	-83.435801	42.4408026	102435	206.628486	0	n/a	n/a	n/a	n/a	n/a	1	2008	8	27	14	2	

In the SAE J2735 standard, the type of message being sent is defined through the following parameters:

- Provider Service Identifier (PSID)
- Provider Service Context (PSC)

These two elements are evolutions of the Application Class Identifier (ACID) and Application Context Mark (ACM) concepts shown in earlier DSRC application documents. They are meant to provide an application classification scheme to facilitate the processing of messages. The PSID is a 4-byte numeral value indicating the general topic of an application and the implicit format of associated messages. The PSC is a supplemental 32-byte value associated with a PSID that contains additional information about the service generating the message.

According to the IEEE 1609.4 standard, applications generating probe vehicle messages shall transmit messages using a PSID of 5 and a PSC of 3. This combination of values will for instance indicate that probe data transmission is a one-way communication stream, from a vehicle to an RSE, with no acknowledgement sent back to the vehicle by the RSE. It is further expected that individual applications will be designed with an awareness of the target topics and message formats they can process. While PSIDs may not be associated with any specific application implementation, actual programs implementations will be designed to handle messages with specific types of PSIDs and to process specific PSCs.

Following the message serial number are two time stamps recording when a probe message was received by an RSE and when it was subsequently received at a SDN. Comparing these times to the moment a snapshot was created (time stamp in snapshot header) allows estimating the age of each snapshot when it reaches an RSE or SDN. In the POC tests, probe messages only contained the RSE time stamp. The SDN time stamp was not recorded within a message but stored in the name of the file used to save each message. Post-processing of the filenames containing the recorded probe messages allowed reconstituting the SDN time stamp and incorporating it into the data of Table 2-2.

The next set of parameters identifies the RSE that has received the data. For each RSE, a unique ID number is recorded, together with a latitude, longitude and elevation measurement. It is assumed that these measurements give the location of the RSE. However, as can be observed in Table 2-2, these measurements slightly vary from one message to the next even though all the messages were received by the same RSE. These variations could be results of the accuracy of the GPS instrumentation used to obtain the measurement. The elevation measurements are clearly in error, as areas of the POC test sit at elevations of approximately 900 ft (around 275 m). For instance, it can be checked in Table 2-5, which is presented later and shows examples of individual snapshots taken by individual POC test vehicles, that elevation measurements associated with individual snapshots are in the correct range. The meaning of the heading measurement for RSEs is further unclear. A zero speed measurement is finally expected, as the receiving RSE are fixed objects.

The second to last set of data records the reliability of the measurements contained within the header. These fields are described in Table 2-3. These data fields are set to record the 95% confidence interval associated with the time, position, elevation, heading, speed, and throttle measurements. These are meant to provide the recipient of the data with information on the limitation of the sensing equipment, and not to support any type of automated error correction or to guarantee a maximum possible error. This information was unfortunately not recorded by any of the POC test vehicles.

Table 2-3 – POC Probe Message Confidence Interval Parameters

Parameter	Description	Units	Confidence range	
Time	95% Confidence of time data	Seconds	0 = Not equipped	8 = 0.2 s
			1= 100 s	9 = 0.1 s
			2 = 50 s	10 = 0.05 s
			3 = 20 s	11 = 0.02 s
			4 = 10 s	12 = 0.01 s
			5 = 2 s	13 = 0.005 s
			6 = 1 s	14 = 0.002 s
			7 = 0.5 s	15 = 0.001 s
Pos	95% Confidence of latitude and longitude data	Meters or Degrees	0 = Not equipped	8 = 2 m (0.00002°)
			1 = 500 m (0.005°)	9 = 1 m(0.00001°)
			2 = 200 m (0.002°)	10 = 0.5 m (0.000005°)
			3 = 100 m (0.001°)	11 = 0.2 m (0.000002°)
			4 = 50 m (0.0005°)	12 = 0.1 m (0.000001°)
			5 = 20 m (0.0002°)	13 = 0.05 m (0.0000005°)
			6 = 10 m (0.0001°)	14 = 0.02 m (0.0000002°)
			7 = 5 m (0.00005°)	15 = 0.01 m (0.0000001°)
Elev	95% Confidence of elevation data	Meters	0 = Not equipped	8 = 2 m
			1 = 500 m	9 = 1 m
			2 = 200 m	10 = 0.5 m
			3 = 100 m	11 = 0.2 m
			4 = 50 m	12 = 0.1 m
			5 = 20 m	13 = 0.05 m
			6 = 10 m	14 = 0.02 m
			7 = 5 m	15 = 0.01 m
Heading	95% Confidence of heading data	Degrees	0 = Not equipped	4 = 1°
			1 = 45°	5 = 0.1°
			2 = 10°	6 = 0.05°
			3 = 5°	7 = 0.01°
Speed	95% Confidence of speed data	Meters per second	0 = Not equipped	4 = 1 m/s
			1 = 100 m/s	5 = 0.1 m/s
			2 = 10 m/s	6 = 0.05 m/s
			3 = 5 m/s	7 = 0.01 m/s
Throttle	95% Confidence of throttle data	Percent of throttle range	0 = Not equipped	
			1 = 10%	
			2 = 1%	
			3 = 0.5%	

The last piece of information is the number of snapshots included in the message. As per data communication specifications, probe messages could include a maximum of four snapshots. It can be verified in Table 2-2 that the number of snapshots per message varies between one and four. Approximately 57% of the probe messages collected during the POC tests included only one snapshot; 16% included two snapshots; 7% included three snapshots; and 20% included four messages.

2.8.2. Snapshot Header Data Items

The snapshot header data identify the time and location a snapshot was created, as well as the speed and heading of the vehicle at that time. Table 2-4 provides a list of the snapshot header data generated by the probe vehicles used during the USDOT VII POC test program. The table also provides the measurement units for each parameter, the precision of the measurement if applicable, and a list of specific values that each parameter could take.

Table 2-4 – POC Snapshot Header Data

Parameter	Description	Use	Units	Precision	Value recorded in snapshot
Year	Year data was recorded	All Vehicles	Calendar year	n/a	Year in yyyy format
Mo	Month data was recorded	All Vehicles	Month name	n/a	Month of year (1 – 12)
Day	Day data was recorded	All Vehicles	Days of week	n/a	Day of month (0 – 31)
Hour	Hour data was recorded	All Vehicles	Hour of day	1 hour	Hour of day (0 – 24)
Min	Minute data was recorded	All Vehicles	Minutes within hour	1 min	Minutes from start of hour (0 – 59)
Sec	Second data was recorded	All Vehicles	Seconds within minute	0.001 s	Milliseconds from start of minute (0 – 59999)
Long	Geographical longitude	All Vehicles	Degrees	0.000125^{o}	Value between -7,200,000,000 and 7,200,000,000 representing a range of -90^{o} to +90^{o}
Lat	Geographical latitude	All Vehicles	Degrees	0.000125^{o}	Value between -14,400,000,000 and 14,400,000,000 representing a range of -180^{o} to +180^{o}
Elev	Elevation of vehicle	All Vehicles	Meters	0.1 m	Measured elevation minus 1000 m
Heading	Heading of vehicle	All Vehicles	Degrees	0.00459^{o}	Heading measurement (0-360^{0}) multiplied by 182.0417
Speed	Speed of vehicle	All Vehicles	Meters per second	0.01 m/s	Speed measurement multiplied by 100
Vehicle Type	Classification of vehicle in term of size	No vehicle	n/a	n/a	0 = Unknown 1 = Does not fit any category 2 = Special use 3 = Motorcycle 4 = Passenger car 5 = Four tire, single unit 6 = Bus 7 = Two axle, six tire single unit 8 = Three axes, single unit 9 = Four or more axle single unit 10 = Four or less axles, single trailer 11 = Five or less axles, single trailer 12 = Six or more axles, single trailer 13 = Five or less axles, multi-trailer 14 = Six axle, multi-trailer 15 = Seven or more axle, multi-trailer

Table 2-5 – Sample of Formatted Probe Messages from POC Test: Snapshot Data

SNAPSHOT HEADER																		VEHICLE STATUS DATA																													
Position Data											Time and Position Data Confidence						Vehicle Type	Data Count	PSN	Exterior Lights							Air Temp	Yaw	Throttle	ABS	Brakes		Stab	Trac	Steering		Lat Accel	Long Accel	Bar Press	Wipers			Tires				
Year	Mo	Day	Hr	Min	Sec	Long	Lat	Elev	Heading	Speed	Time	Pos	Elev	Heading	Speed	Throttle				Front	Turn	Hazard	Auto	Day	Park	Fog					Status	Boost			Angle	Rate				Status	Status	Rate	Pressure				Spare
								(m)	(degs)	(m/s)																	(C.)	(deg/s)							(degs)	(deg/s)	(m/s2)	(m/s2)	(PSI)	Front	Rear		FL (PSI)	FR (PSI)	LR (PSI)	RR (PSI)	
2008	8	27	0	2	32	-83.4329746	42.4241434	347.3	358.6266304	14.12	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	33633								24	327.68		on		off	on	on	-3	0	-0.16	0.56	200			0	37	37	37	36	1
2008	8	27	0	5	14	-83.43325350	42.4306831	349.4	358.2805558	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	50403								23	325.77		on	all on	off	on	on	13	0	-0.16	-0.16	200			0	37	37	37	36	1
2008	8	27	0	4	53	-83.4331874	42.4292175	347.9	358.5002857	15.68	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	5548								23	329.41		on		off	on	on	1	15	0.24	-0.16	200			0	37	37	37	36	1
2008	8	27	0	5	49	-83.43325350	42.4306831	349.4	358.2805558	9.60	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	64689								23	326.47		on		off	on	on	7	0	0.24	1.12	200			0	37	37	37	36	1
2008	8	27	0	24	59	-83.4343733	42.4426839	345.7	200.7781779	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	5	26972											n/a			n/a	n/a													
2008	8	27	0	23	57	-83.4352859	42.4449076	354.9	0.0000000	0.00	n/a	n/a	n/a	n/a	n/a	n/a		5	26972											n/a			n/a	n/a													
2008	8	27	0	23	29	-83.4352758	42.4449115	361.4	0.0000000	0.00	n/a	n/a	n/a	n/a	n/a	n/a		5	26972											n/a			n/a	n/a													
2008	8	27	13	38	54	-83.43170600	42.4390690	339.6	269.0262786	21.21	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	47324	Low	Off		Off	Off	On	Off	19	326.27		on		n/a	on	on	-1	0	0.30	0.38	200								
2008	8	27	13	39	45	-83.4356448	42.4389886	346.7	272.3496930	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	10460	Low	Off		Off	Off	On	Off	19	326.07		on	all on	n/a	on	on	1	0	-0.15	-0.17	200								
2008	8	27	13	41	17	-83.32689650	42.3839000	289.9	265.9555535	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	21461			On					21	327.01		on	all on	off	on	on	0	0	-0.08	0.00	205			0	31	33	33	33	1
2008	8	27	13	42	22	-83.32004650	42.3735283	294.7	0.0000000	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	34534	Low							20	327.68		on	all on	off	on	on	3	0	-0.08	0.16	205			0	36	32	32	30	1
2008	8	27	13	42	51	-83.32004650	42.3735283	294.7	0.0000000	4.81	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	51664								20	327.68		on		off	on	on	-3	-30	-0.08	0.08	205			0	36	32	32	30	1
2008	8	27	14	1	3	-83.4376083	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	14	0	47	-83.4376083	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	14	0	32	-83.4376083	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	14	0	17	-83.4376083	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	14	0	2	-83.4376083	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	59	47	-83.4376083	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	59	32	-83.4376083	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	59	17	-83.43760650	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	59	2	-83.43760650	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	58	47	-83.43760650	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	58	32	-83.43760650	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	58	17	-83.43760650	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	58	2	-83.43760650	42.4419550	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	57	47	-83.43760650	42.4419565	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	57	32	-83.43760650	42.4419565	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	57	16	-83.43760650	42.4419565	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	57	1	-83.43760650	42.4419565	359.4	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	56	46	-83.43760650	42.4419565	359.3	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	56	31	-83.4376083	42.4419550	359.3	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	56	16	-83.4376083	42.4419565	359.3	124.8724908	0.00	n/a	n/a	n/a	n/a	n/a	n/a		15	43186								20	324.98		on	all on	off	on	on	-42	-120	0.00	0.00	205			0	36	32	32	30	1
2008	8	27	13	56	28	-83.4375189	42.4420225	358.5	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	63269	Low	Off		Off	Off	On	Off	20	326.67		on		n/a	on	on	-62	0	0.35	0.07	200								
2008	8	27	13	56	14	-83.4375461	42.4419966	351.8	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	63269	Low	Off		Off	Off	On	Off	20	327.27		on		n/a	on	on	-62	0	0.36	0.10	200								
2008	8	27	13	56	4	-83.43754250	42.4420100	355.3	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	63269	Low	Off		Off	Off	On	Off	20	327.37		on		n/a	on	on	-62	0	0.29	0.04	200								
2008	8	27	13	55	44	-83.4375484	42.4419826	354.1	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	63269	Low	Off		Off	Off	On	Off	20	326.97		on		n/a	on	on	-62	0	0.30	0.10	200								
2008	8	27	13	55	33	-83.43755050	42.4420146	355.5	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	7424	Low	Off		Off	Off	On	Off	20	326.57		on		n/a	on	on	-62	0	0.36	0.07	200								
2008	8	27	13	55	14	-83.43754550	42.4420016	348.7	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	7424	Low	Off		Off	Off	On	Off	20	326.47		on		n/a	on	on	-62	0	0.33	0.05	200								
2008	8	27	13	54	59	-83.4375383	42.4420174	352.3	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	7424	Low	Off		Off	Off	On	Off	20	326.67		on		n/a	on	on	-62	0	0.35	0.05	200								
2008	8	27	13	54	48	-83.4375646	42.4419895	351.4	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	7424	Low	Off		Off	Off	On	Off	20	326.47		on		n/a	on	on	-62	0	0.33	0.08	200								
2008	8	27	13	53	29	-83.4375766	42.4420085	351.2	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	10325	Low	Off		Off	Off	On	Off	20	327.47		on		n/a	on	on	-62	0	0.30	0.07	200								
2008	8	27	13	53	14	-83.4375583	42.4420135	351.3	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	10325	Low	Off		Off	Off	On	Off	20	326.07		on		n/a	on	on	-62	0	0.35	0.08	200								
2008	8	27	13	52	59	-83.4375554	42.4420160	349.7	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	10325	Low	Off		Off	Off	On	Off	20	326.47		on		n/a	on	on	-62	0	0.33	0.05	200								
2008	8	27	14	5	2	-83.43481650	42.4420230	343.6	210.8527928	12.17	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	60425	Low	Off		Off	Off	On	Off	20	327.27		on		n/a	on	on	-6	0	-0.20	1.74	200								
2008	8	27	14	5	1	-83.4346086	42.4422766	343.8	208.9521294	6.72	n/a	n/a	n/a	n/a	n/a	n/a		13	60425	Low	Off		Off	Off	On	Off	20	328.37		on	all on	n/a	on	on	-12	0	0.68	-0.87	200								
2008	8	27	14	5	1	-83.43452400	42.4423920	343.8	206.4417155	3.45	n/a	n/a	n/a	n/a	n/a	n/a		13	60425	Low	Off		Off	Off	On	Off	20	328.37		on	all on	n/a	on	on	-12	0	0.68	-0.87	200								
2008	8	27	14	5	1	-83.4344169	42.4425505	343.3	204.0082071	5.95	n/a	n/a	n/a	n/a	n/a	n/a		13	60425	Low	Off		Off	Off	On	Off	20	328.37		on	all on	n/a	on	on	-12	0	0.68	-0.87	200								
2008	8	27	14	4	43	-83.43413100	42.4431431	342.1	193.5490648	13.51	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	60425	Low	Off		Off	Off	On	Off	20	328.37		on	all on	n/a	on	on	-12	0	0.68	-0.87	200								
2008	8	27	13	54	30	-83.4375514	42.4419924	353.3	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	7424	Low	Off		Off	Off	On	Off	20	326.27		on		n/a	on	on	-62	0	0.35	0.07	200								
2008	8	27	13	54	27	-83.43757750	42.4419660	350.0	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	7424	Low	Off		Off	Off	On	Off	20	326.47		on		n/a	on	on	-62	0	0.27	0.10	200								
2008	8	27	13	54	0	-83.43757700	42.4419770	351.5	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	7424	Low	Off		Off	Off	On	Off	20	326.87		on		n/a	on	on	-62	0	0.35	0.08	200								
2008	8	27	13	53	44	-83.4375784	42.4420025	357.0	113.9629023	0.00	n/a	n/a	n/a	n/a	n/a	n/a		13	7424	Low	Off		Off	Off	On	Off	20	326.67		on		n/a	on	on	-62	0	0.32	0.05	200								
2008	8	27	14	4	34	-83.4340324	42.4443993	352.3	177.4428646	13.44	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	1850	Low	Off		Off	Off	On	Off	20	336.47		on		n/a	on	on	-31	0	1.27	1.46	200								
2008	8	27	14	4	30	-83.43408050	42.4446483	355.2	141.8905700	4.91	n/a	n/a	n/a	n/a	n/a	n/a		13	1850	Low	Off		Off	Off	On	Off	20	339.57		on	all on	n/a	on	on	-290	0	0.66	-0.54	200								
2008	8	27	14	4	26	-83.4342169	42.4446868	356.6	87.1064177	3.13	n/a	n/a	n/a	n/a	n/a	n/a		13	1850	Low	Off		Off	Off	On	Off	20	324.57		on	all on	n/a	on	on	14	0	-0.23	-1.21	200								
2008	8	27	14	4	22	-83.43442900	42.4446889	357.6	91.7701844	5.32	n/a	n/a	n/a	n/a	n/a	n/a		13	1850	Low	Off		Off	Off	On	Off	20	326.47		on		n/a	on	on	0	0	-0.28	1.65	200								
2008	8	27	14	4	8	-83.4348406	42.4447011	355.5	93.6323951	0.00	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	1850	Low	Off		Off	Off	On	Off	20	325.97		on	all on	n/a	on	on	4	0	-0.23	-1.00	200								
2008	8	27	14	4	2	-83.43522800	42.4447188	355.9	89.2597705	8.92	n/a	n/a	n/a	n/a	n/a	n/a		13	1850	Low	Off		Off	Off	On	Off	20	328.17		on	all on	n/a	on	on	3	0	0.29	-0.04	200								
2008	8	27	14	3	57	-83.4354678	42.4447184	356.8	88.4302902	9.56	n/a	n/a	n/a	n/a	n/a	n/a		13	1850	Low	Off		Off	Off	On	Off	20	328.77		on		n/a	on	on	-22	0	-0.18	0.07	200								
2008	8	27	14	3	53	-83.43589050	42.4447070	358.2	87.4964382	7.71	n/a	n/a	n/a	n/a	n/a	n/a		13	1850	Low	Off		Off	Off	On	Off	20	327.07		on		n/a	on	on	5	0	-0.06	0.91	200								
2008	8	27	14	2	53	-83.43752450	42.4420773	355.6	32.0585895	8.60	n/a	n/a	n/a	n/a	n/a	n/a	unknown	13	40048	Low	Off		Off	Off	On	Off	20	309.67		on		n/a	on	on	176	0	-1.45	1.50	200								

Examples of snapshot header data are shown in Table 2-5, which details snapshot data from the probe vehicle messages shown in Table 2-1. Similar to Table 2-1, the data shown is not the raw data received from individual probe vehicles, but data that was formatted through post-processing analysis to allow meaningful measures to be displayed. The POC test vehicles typically collected all of the identified snapshot header parameters, except for the vehicle type, for which no data was recorded.

2.8.3. Vehicle Status Data Items

Table 2-6 lists the vehicle status data considered during the USDOT VII POC test program. The table also indicates whether each data item was collected by all test vehicles, some of the vehicles, or none, as well as the measurement units for each parameter, the precision of the measurement if applicable, and a list of specific values that each parameter could take. Contrary to the snapshot header data, not all test vehicles collected all the parameter. The specific status parameters collected by each vehicle were function of the onboard instruments available.

Examples of collected vehicle status data are shown in Table 2-5 presented earlier. Within each snapshot, the exact number of vehicle status parameters included is determined by the "Data Count" parameter. A data count of five indicates for instance that a vehicle is reporting five data items. However, more than five parameter values may be provided as some data items may include multiple measurements. For instance, the exterior light data item reports the status of all of the vehicle's exterior lights. Parameters reporting the status of headlights, daytime run lights, fog lights and turn signals are thus provided as part of this data item. As assessed in Chapter 3, the test vehicles used during the POC evaluations typically provided between 2 and 15 data items.

It can further be observed in Table 2-5 that all snapshots included within a specific message have the same PSN, as required by the SAE J2735 standard. An example can be found in the string of five messages containing snapshots with a PSN of 43186 sent at approximately the same time. Since PSNs are independently assigned by individual vehicles, the reception of messages containing snapshots featuring the same PSN indicates a high likelihood that they were sent by the same vehicle. However, because vehicles independently generate the PSNs, a possibility will always exists, albeit remote, that vehicles traveling in the same vicinity may tag snapshots with an identical PSN at the same moment.

Table 2-7 finally provides a listing of some of the vehicle status parameters that are currently defined in the SAE J2735 standard that could also be included in probe vehicle messages. These additional parameters include vehicle descriptors (length, width, weight), data that can be provided by various optional onboard sensors (rain sensor, sun sensor, radar systems), and data characterizing the operation of emergency response and maintenance vehicles (type of response, number of vehicles responding, use of sirens, status of light bars).

Table 2-6 – POC Snapshot Vehicle Status Data

Parameter	Description	Use	Units	Precision	Value recorded in snapshot
Data Count	Number of data items recorded in snapshots (excluding throttle position)	All vehicles	Data items	n/a	Count of data fields in snapshot (2 – 15)
PSN	Probe Segment Number	All vehicles	n/a	n/a	6-digit randomly determined number
Exterior Lights	Status of exterior lights	Some vehicles	System status	n/a	Eight-digit string representing the on/off status of various lights 0000-0000 = All lights off 0000-0001 = Headlights on, low beam 0000-0010 = Headlights on, high beam 0000-0100 = Left-turn signal on 0000-1000 = Right-turn signal on 0000-1100 = Hazard signal on 0001-0000 = Automatic light control on 0010-0000 = Daylight running lights on 0100-0000 = Fog lights on 1000-0000 = Parking lights on
AirTemp	Ambient air temperature	Some vehicles	Degree Celsius (^{o}C)	1 ^{o}C	Measured temperature + 40
Yaw	Yaw rate of vehicle	Some vehicles	Degrees per second	0.01 ^{o}/s	Yaw rate multiplied by 100
ABS	Anti-Lock brake status	Some vehicles	System status	n/a	2-digit number representing system status 00 = Not equipped 01 = Off 10 = On 11 = Engaged
Brake Status	Status of brake system	Some vehicles	System status	n/a	Series of four digits taking 0/1 value to represent the status of each individual brake. Application of all brakes would read "1111". 0001 = Left front brake active 0010 = Rear left brake active 0100 = Right front brake active 1000 = Right rear brake active
Brake Boost	Application of brake boost assist function	Some vehicles	System status	n/a	0 = Not equipped 1 = Off 2 = On
Stability	Status of stability control systems	Some vehicles	System status	n/a	2-digit number representing system status 00 = Not equipped 01 = Off 10 = On 11 = Engaged
Traction	Status of traction control system	Some vehicles	System status	n/a	2-digit number representing system status 00 = Not equipped 01 = Off 10 = On or active
Throttle	Position of throttle	No vehicle	Percent of range	0.5%	Percent of range multiplied by 2
Steering Angle	Angle of front steering wheel	Some vehicles	Degrees	0.02^{o}	Measured angle multiplied by 50 - Left value representing an angle to the left and right value and angle to the right

Table 2-6 – POC Snapshot Vehicle Status Data (cont'd)

Parameter	Description	Use	Units	Precision	Value recorded in snapshot
Steering Rate	Rate of change of angle of steering wheel	Some vehicles	Degrees per second	3 °/s	Measured rate of change divided by 3
Lat Accel	Lateral horizontal acceleration	Some vehicles	Meters per second^2	0.01 m/s^2	Acceleration measurement multiplied by 100
Long Accel	Longitudinal horizontal acceleration	Some vehicles	Meters per second^2	0.01 m/s^2	Acceleration measurement multiplied by 100
Bar Press	Barometric pressure	Some vehicles	PSI	5 PSI	Measured barometric pressure
Wiper Status	Status of wiper system	Some vehicles	Status	n/a	1 = Not equipped 2 = Off 3 = Intermittent 4 = Low 5 = High 256 = Automatic system present
Wiper Rate	Rate at which wiper sweeps	Some vehicles	Sweeps per minute	1 sweep /min	Actual sweep rate
Tire Pressure	Pressure of tires	Some vehicles	PSI	1 PSI	Measured pressure of front left (FL), front right (FR), rear left (RL) and rear right (RR) tire.
Spare Tire	Spare tire present	Some vehicles	Yes/No	n/a	Indicator whether a spare tire is available

Table 2-7 – Other Parameters Defined in SAE J2735 Standard

Parameter	Description
DSRC message type	Type of message (a la carte, basic safety, common safety, emergency, probe data, generic transfer)
Vehicle height	Height of vehicles in meters from the ground to the highest surface, with a precision of 0.05 m
Vehicle length	Length of vehicles in centimeters
Vehicle width	Width of the vehicle in centimeters
Vehicle mass	Mass of the vehicle in kilograms, with a precision of 25 kg; this mass should reflect the total gross weight of the vehicle and its contents, if known
Vehicle acceleration	Acceleration in m/s^2
Vertical acceleration	Measured acceleration in $meters/second^2$ along the vertical axis, with a precision of $0.08\ m/s^2$
Vehicle acceleration thresholds	Vertical acceleration thresholds used to define a vertical acceleration event; a separate threshold can be defined for each of the four wheels of the vehicle
Air bag count	Number of air bags
Brake applied pressure	Percent of brake pressure applied between minimum and maximum pressure
Obstacle direction	Heading of direction in which an obstacle is located
Obstacle distance	Distance in meters to an obstacle
Payload data	Information characterizing vehicle payload
Rain sensor	Measurement of rain intensity, recorded as <None>, <Light mist>, <Heavy mist>, <Light rain or drizzle>, <Rain>, <Moderate rain>, <Heavy rain> or <Downpour>
Sun sensor	Indicate the level of illumination from the sun, with eight levels ranging from <Complete darkness> to <Maximum sun light>
Siren use	Indicate whether any type of siren is in use, recorded as <Not equipped>, <Not in use> or <In use>
Response type	Indicate the type of response a vehicle is engaged to, recorded as <Not equipped>, <Emergency>, <Non-emergency> or <Pursuit>
Multivehicle response	Active to request a specific number of vehicles to respond to an incident or event, recorded as <Not equipped>, <Single vehicle>, or <Multiple vehicles>
Light bar in use	Status of optional light systems (arrow board, flashing lights, etc.), recorded as <Not equipped>, <Not in use> or <In use>

3. Summary of USDOT's Proof-of-Concept Tests Findings Regarding Probe Vehicle Data

The USDOT POC test program was initiated in 2005 to test the operation of a small-scale concept version of the envisioned VII system that was planned to be deployed starting sometime around 2010. The objectives of the program were to determine if the concept was sound, could provide an effective mechanism for wirelessly sending and receiving roadway information to and from vehicles, as well as between vehicles, and could support its intended use. Following completion of the test bed in 2008, quantitative assessments were performed of specific functional services and representative applications. Specific services that were tested included DSRC communications, vehicle positioning, communication security, and vehicle interface operations. Representative applications that were tested included geographic advisory messaging, probe data collection, vehicle-to- vehicle messaging, transactions involving local service providers communicating with an RSE outside the VII network, and network transactions involving OBE encounters with multiple RSEs. Details of the activities conducted during the POC test program and the main findings of test activities can be found in a six-volume report that has been published by the Research and Innovative Technology Administration (VIIC, 2009a, 2009b, 2009c; Booz Allen Hamilton, 2009a, 2009b, 2009c).

This chapter of the report summarizes the DUAP project activities that were conducted to evaluate the quality and usability of probe vehicle data generated during the USDOT POC test program. This includes both a summary of elements reported in the official POC test reports and additional analyses conducted at UMTRI using POC probe data. The specific elements presented include:

- Overview of data collection tests
- Quantity of snapshots collected
- Vehicle status parameters collected
- Summary of POC data collection test findings
- Evaluation of average snapshot latency
- Usability of collected data for DOT application evaluations

3.1. Data Collection Tests

During the POC test program, tests were conducted to verify the ability of the system to collect and transmit periodic, stop/start event, and special event snapshots according to various capture and transmit policies specified by network-side applications. Test activities focused primarily around the four following scenarios:

- **Single Vehicle Data Collection and Upload.** Baseline test aimed at determining the ability of the system to collect probe data from a single vehicle in a single RSE encounter.
- **Two Vehicle Data Collection and Upload.** This test aiming to assess the ability of the system to support uploads of probe data at a single RSE when two probe vehicles are present. This test was compromised by the discovery that the Internet Data Transport Layer Security (DTLS) standard on which communication security is based was unable to handle multiple parallel threads. As a result, the tests conducted using this scenario merely assessed the ability of the system to support two consecutive downloads.
- **Large Upload, Two Vehicles.** This test sought to assess the ability to support multiple large data uploads. This scenario was similar to the preceding one, but differed in that the maximum size

of the snapshot buffer for each vehicle was increased from 30 snapshots to 300 snapshots. Only a single buffer was utilized to capture all types of snapshots. As with the preceding test, this test was inhibited by the single thread ability of the secured communication channel.

- **Probe Data Management.** The objective of this test was to determine if it was possible to adjust Probe Data Collection parameters on the fly, through directives transmitted from the infrastructure to the probe data collection system. This test case focused on assessing whether Probe Data Management directive messages could be received by a vehicle and whether the receipt of these directives influenced the ability to generate and transmit snapshots. The vehicles were separated through the test route to limit one RSE interaction per vehicle.

One of the main characteristic of the above test scenarios is that they did not involve more than two vehicles communicating at a given time with an RSE. While was sufficient to evaluate communication protocols between vehicles and RSEs, it did not allow to test communication functions in situations that are likely to be encountered in real-systems, notable the likelihood that multiple vehicles may try to communicate simultaneously with a given RSE. In such a situation, there is a probability that communication delays may occur, which may then affect the quality of the collected data.

3.2. Quantity of Snapshots Collected

Table 3.1 summarizes the snapshots that were collected as part of the POC test activities conducted by Booz Allen Hamilton from May 6 to September 5, 2008. Testing activities during May, June, July and the first half of August focused on communication equipment testing and fixing up various technical issues.

Table 3-1 – Summary of Probe Vehicle Data Collected during POC Test

May 2008				June 2008				July 2008				Aug. 2008				Sept. 2008				Oct. 2008			
Date	Messages	Snapshots	Test Vehicles	Date	Messages	Snapshots	Test Vehicles	Date	Messages	Snapshots	Test Vehicles	Date	Messages	Snapshots	Test Vehicles	Date	Messages	Snapshots	Test Vehicles	Date	Messages	Snapshots	Test Vehicles
1				1				1				1	19	34	2	1				1	47	80	1
2				2				2				2				2	6,444	12,956	14	2	17	43	1
3				3	8	8	1	3				3				3	7,674	15,912	22	3	248	614	2
4				4				4				4	4	4	1	4	2,697	4,503	19	4			
5				5				5				5	35	41	3	5				5			
6				6				6				6	3	8	1	6				6			
7				7				7				7	1,381	2,822	18	7				7			
8				8				8				8	10	31	1	8				8			
9				9				9				9				9				9			
10				10				10				10				10	57	66	2	10			
11				11				11				11	3,630	7,164	21	11	623	852	25	11			
12	240	422	1	12				12				12	172	247	3	12	82	198	11	12			
13	7	26	1	13				13				13	29	33	2	13				13			
14				14				14				14				14				14			
15				15				15				15	90	118	2	15	36	74	1	15			
16	17	62	1	16				16	7	10	1	16				16	17	22	1	16			
17				17				17	33	65	1	17				17	6	15	1	17			
18				18				18				18	158	178	1	18				18			
19				19	1	1	1	19				19	995	1,713	11	19				19			
20				20	19	39	2	20				20	5,901	10,995	24	20				20			
21	50	84	1	21				21				21	3,787	7,583	26	21				21			
22	424	724	1	22				22				22	5,555	10,057	25	22				22			
23	180	303	1	23	104	147	1	23				23				23				23			
24				24	11	18	1	24				24				24				24			
25				25	4			25	39	93	1	25	5,756	9,841	23	25	111	163	2	25			
26				26				26				26	7,795	13,253	25	26				26			
27	517	815	1	27	92	212	1	27				27	2,775	5,417	22	27				27			
28	30	69	1	28				28				28	3,880	7,298	22	28				28			
29	1,496	4,708	3	29				29				29	5,826	13,443	19	29				29			
30	407	1,082	4	30				30				30				30	23	45	1	30			
31								31	34	50	3	31								31			

All messages:	69,599	Messages Aug. 20 - Sept. 4:	58,090
All snapshots:	134,761	Snpahosts Aug. 20 - Sept. 4:	111,258

Official testing of data collection processes started on August 20 and extended until September 4. Only limited tests then occurred after that date throughout September and October.

During the POC tests, UMTRI periodically retrieved the probe vehicle data that had been generated by two research vehicles that were lent to the program by the institute and that were periodically used in the test activities. The data was retrieved directly from an alternate computer system installed in the trunk of each vehicle that was designed to capture each of the generated snapshots. This data collection effort provided the total number of snapshots that had been generated by each vehicle prior to wireless transmission. The collected dataset thus potentially included snapshots that may have been later lost during wireless transmission due to communication problems or the application of protocols aiming to safeguard traveler privacy.

At the end of the testing, all of the probe vehicle messages that were received at the test SDN from all test vehicles through RSE communications were further obtained from Booz Allen Hamilton. Contrary to the data retrieved directly from the two UMTRI test vehicles, the recorded data items were in this case messages and not individual snapshots. As defined in the implemented protocols, each message could contain up to four snapshots. The snapshots were extracted from the recorded messages through a custom-built Visual Basic Excel macro and stored in a series of Excel files to facilitate data analysis.

As indicated in Table 3-1, the POC test generated a total of 69,599 messages and 134,761 snapshots. 58,090 messages containing 111,258 snapshots were notably collected between August 20, and September 4, during the main data collection and application test phase. These data were collected using a fleet of 31 test vehicles, with at most 26 vehicles used during a given day. While there were initial plans to conduct more extensive data collection, notably collecting data over a period of several weeks, these activities were scaled back following a series of delays brought on by technical issues associated with the development of RSEs. This resulted in only 11 days of data collection, primarily to evaluate the ability for vehicles to communicate and exchange data with RSEs.

3.3. Type of Data Collected

The number of vehicle status parameters collected from individual test vehicles varied from one vehicle to the next as not all vehicles had the same instruments or data reporting capabilities. Table 3-2 indicates the typical combinations of parameters that were returned by each test vehicle based on the reported number of parameters contained within each snapshot. As can be observed there was generally a unique combination of parameters for each data count value. The only exception is for vehicles returning 10 parameters, for which two sets of returned parameters were observed. At a minimum, all the collected snapshots contained GPS position data and a PSN value. The reporting of additional parameters then primarily depended on the specific instrumentation of each test vehicle.

Table 3-3 further compiles the number of snapshots containing specific vehicle status data that were collected by all test vehicles during the entire POC test period. Each cell in the table represents the number of instances in which a value was assigned to a specific parameter, including instances in which a “not equipped” status was assigned. When considering only the data collected during the main test period, i.e., between August 20 and September 4, it can be concluded that the test program was successful in demonstrating the ability to collect various vehicle status parameters.

The data of Table 3-3 further highlight a potential difficulty in obtaining certain data in sufficient quantities with a small fleet of vehicles if efforts are not made to replicate specific operating conditions deliberately. For instance, very few weather-related parameters were collected. This is in great part due to the good weather that generally prevailed during the test period. Of the 134,761 snapshots collected, there are only 125 indications that the wipers were engaged. Of this number, there is no report of wiper use in intermittent mode, 118 reports in low-sweep mode, and 7 in high-speed mode. Similarly, there are only 50 reports of traction system activation and 84 reports of ABS activation. There are also fewer than 200 reports of left or right turn signal activation. This is attributed to the fact that very few test vehicles could provide this data. This is a potential indication of the challenges that may lay ahead in ensuring that all vehicles are eventually equipped with the appropriate sensors and data-recording capabilities.

Table 3-2 – POC Vehicle Status Data Sets

Data Item Count	PSN	Position Data	Lights	Air Temperature	Yaw Rate	ABS Status	Brake Status	Stability Control	Traction Control	Steering	Lateral Acceleration	Longitudinal Acceleration	Tire Pressures	Barometric Pressure	Wipers
2	X	X													
5	X	X				X		X	X						
6	X	X	X	X		X			X						
8	X	X	X	X	X	X	X		X						
9	X	X	X	X	X	X	X		X			X			
10a	X	X	X	X	X	X	X		X			X			X
10b	X	X		X	X	X	X	X	X	X		X			
11	X	X			X	X	X	X	X	X	X	X		X	
13	X	X	X	X	X	X	X	X	X	X	X	X		X	
14	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
15	X	X	X	X	X	X		X	X	X	X	X	X	X	X

Table 3-3 – POC Vehicle Status Data Sets

Month	Day	Snapshots	Message Sizes					Latency per RSE		Air	Yaw
			Snapshots/message					Snap to	RSE to	Temp	Rate
			1	2	3	4	Avg	RSE	SDN		
May	12	422	161	21	13	45	21.9	77.6	-11.4	422	422
	13	26	0	1	0	6	3.7	234.6	-12.6	26	26
	16	62	1	1	1	14	9.5	216.7	-6198.5	62	62
	21	84	30	11	4	5	5.3	74.6	6933.4	84	84
	22	724	258	86	26	54	25.3	49.9	15.1	724	724
	23	303	117	29	8	26	6.5	42.8	2.0	303	303
	27	815	336	113	19	49	25.2	46.5	17.4	815	815
	28	69	12	6	3	9	7.7	64.5	22.0	69	69
	29	4708	292	155	90	959	61.5	112.2	25.7	2787	4708
	30	1082	127	66	33	181	56.7	64.4	30.8	921	1082
June	3	8	8	0	0	0	6.0	4.6	42.4	8	8
	19	1	1	0	0	0	1.0	15.0	11.0	1	1
	20	39	11	1	2	5	6.6	200.8	11.3	39	39
	23	147	85	6	2	11	18.3	63.6	-26.6	147	147
	24	18	8	0	2	1	8.3	114.4	-29.2	18	18
	27	212	39	14	11	28	15.1	63.6	-16.1	26	26
July	16	10	4	3	0	0	4.3	80.6	-22.4	10	10
	17	65	18	5	3	7	13.8	154.2	-22.9	65	65
	25	93	17	5	2	15	2.4	99.2	-68.8	93	93
	31	50	25	5	1	3	1.5	35.3	-51.3	50	50
August	1	34	11	4	1	3	1.8	309.8	158.4	34	7
	4	4	4	0	0	0	1.0	13.3	-41.3	4	4
	5	41	32	1	1	1	1.2	25.2	-40.3	41	41
	6	8	1	0	1	1	2.7	107.0	-40.3	8	8
	7	2822	732	201	104	344	2.0	105.9	-39.5	2822	2822
	8	31	1	2	2	5	3.1	733.2	-40.5	31	31
	11	7164	1972	576	288	794	2.0	109.0	16.2	7127	7094
	12	247	132	18	9	13	1.4	79.4	3063.0	182	143
	13	33	27	1	0	1	1.1	24.5	-88.2	33	5
	15	118	71	14	1	4	1.3	69.2	5.5	118	13
	18	178	147	6	1	4	1.1	42.3	132.4	178	0
	19	1713	632	153	65	145	1.7	138.8	538.9	1700	1607
	20	10995	3428	969	387	1117	1.9	122.9	4.3	9547	9547
	21	7583	2096	509	259	923	2.0	188.4	2.7	7579	7340
	22	10057	3358	880	329	988	1.8	151.9	7.7	9881	9634
	25	9841	3734	836	309	877	1.7	155.4	3.9	9073	9014
	26	13253	5052	1134	503	1106	1.7	105.9	3.2	12848	12798
	27	5417	1538	424	221	592	2.0	136.5	2.9	5201	5151
	28	7298	2185	676	315	704	1.9	115.4	9.4	7295	7295
	29	13443	2474	947	545	1860	2.3	40.2	2.2	12395	12395
Sept	2	12956	3364	1160	408	1512	2.0	60.6	4.2	12910	12910
	3	15912	3797	1338	717	1822	2.1	143.3	2.5	15868	15868
	4	4503	1794	383	137	383	1.7	122.1	3.6	4476	4476
	10	66	49	7	1	0	1.2	13.2	4.2	66	66
	11	852	500	61	18	44	1.4	54.3	5.0	820	724
	12	198	39	5	3	35	2.4	163.0	5.5	184	184
	15	74	19	5	3	9	2.1	96.9	2.7	0	0
	16	22	14	2	0	1	1.3	94.6	645.1	22	22
	17	15	2	1	1	2	2.5	299.5	4.2	15	15
	25	163	87	7	6	11	1.5	41.3	453.8	163	163
	30	45	14	2	1	6	2.0	187.4	3.4	45	45
Oct	1	80	30	9	0	8	1.7	117.6	3.1	80	80
	2	43	5	4	2	6	2.5	128.8	5.7	43	43
	3	614	81	53	29	85	2.5	89.5	2.8	34	34
TOTAL		134761	38972	10916	4887	14824	1.9			127493	128331

Month	Day	Lights									Brakes											
		Parking On	Fog On	Day On	Auto On	Left Signal	Right Signal	Hazard On	Low Beam	High Beam	ABS n/a	ABS On	ABS Engaged	Brake n/a	Brake On	Boost n/a	Boost On	Stability On	Stability On	Traction n/a	Traction On	Traction Engaged
May	12	0	0	0	0	0	0	0	0	0	0	422	0	0	125	0	51	0	421	0	420	2
	13	0	0	0	0	0	0	0	0	0	0	26	0	0	0	0	0	0	26	0	26	0
	16	0	0	0	0	0	0	0	0	0	0	62	0	0	43	0	0	0	62	0	62	0
	21	0	0	0	0	0	0	0	0	0	0	84	0	0	34	84	0	0	84	0	84	0
	22	0	0	0	0	0	0	0	0	0	0	724	0	0	312	724	0	0	222	0	226	0
	23	0	0	0	0	0	0	0	0	0	2	301	0	0	128	303	0	2	301	2	301	0
	27	0	0	0	0	0	0	0	0	0	0	815	0	0	376	815	0	0	815	0	815	0
	28	0	0	0	0	0	0	0	0	0	0	69	0	0	39	69	0	0	69	0	69	0
	29	1	1	0	0	0	0	0	1	0	0	4708	0	0	2763	0	1908	0	3811	0	3634	0
	30	155	0	0	0	0	0	0	158	0	44	1038	0	0	506	44	333	44	1006	44	1004	0
June	3	0	0	0	0	0	0	0	1	0	0	8	0	0	3	0	0	0	8	0	8	0
	19	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0
	20	0	0	0	0	0	0	0	19	0	0	39	0	0	11	0	0	0	39	0	39	0
	23	22	0	0	0	0	2	0	23	0	0	147	0	0	35	0	0	0	147	0	147	0
	24	0	0	0	0	0	0	0	0	0	0	18	0	0	5	0	0	0	18	0	18	0
	27	0	0	0	0	0	0	0	2	0	186	26	0	0	6	0	0	186	26	186	26	0
July	16	0	0	0	0	0	0	0	0	0	0	10	0	0	1	0	0	0	10	0	10	0
	17	0	0	0	0	0	0	0	4	0	0	65	0	0	26	0	0	0	65	0	65	0
	25	0	0	0	0	0	0	0	6	0	0	93	0	0	29	0	0	0	93	0	93	0
	31	0	0	0	0	0	0	0	2	0	0	50	0	0	14	29	0	0	48	0	48	2
August	1	0	0	0	0	0	0	0	0	0	27	7	0	0	3	0	0	0	7	0	7	0
	4	0	0	0	0	0	0	0	1	0	0	4	0	0	1	0	0	0	4	0	4	0
	5	0	0	0	0	0	0	0	3	0	0	41	0	0	14	0	0	0	41	0	41	0
	6	0	0	0	0	0	0	0	0	0	0	8	0	0	4	0	0	0	8	0	8	0
	7	1191	333	0	63	2	2	1	1653	0	35	2731	4	0	1093	1945	0	0	1642	0	1642	0
	8	0	0	0	0	0	0	0	0	0	0	31	0	0	5	0	0	0	31	0	31	0
	11	648	0	0	0	0	4	0	1033	0	332	6791	4	0	1658	4453	0	307	5054	299	5062	0
	12	0	0	0	0	0	0	0	22	0	39	142	1	0	46	121	0	0	143	0	143	0
	13	0	0	0	0	0	0	0	0	0	28	5	0	0	1	0	0	0	5	0	5	0
	15	0	0	0	0	0	0	0	1	0	105	13	0	0	4	0	0	0	13	3	13	0
	18	0	0	0	0	0	0	0	0	0	178	0	0	0	0	0	0	0	0	0	0	0
	19	9	0	0	0	2	0	0	719	0	191	1522	0	0	549	1355	0	93	498	93	1527	0
	20	769	0	0	0	5	7	0	2512	0	2763	8224	5	0	4032	6487	0	2726	4507	2763	8123	3
	21	337	327	0	0	2	6	0	777	0	879	6698	2	0	1790	4425	0	585	5221	640	6698	2
	22	1783	288	0	39	30	32	0	3589	0	1268	8783	6	0	2526	6338	0	710	6034	710	9008	2
	25	1120	40	0	0	8	23	0	2027	0	2786	7052	3	0	2089	7370	0	2386	4214	2383	7392	3
	26	3065	320	0	0	32	5	0	3813	0	1335	11872	12	0	3457	9087	0	1052	7672	1285	11881	3
	27	1101	370	0	0	10	12	0	1490	0	263	5143	8	0	2045	3234	0	216	3878	213	5151	0
	28	1867	693	0	0	6	11	0	3368	0	116	7175	4	0	2577	5966	0	111	4481	116	7172	7
	29	4949	550	0	0	26	76	0	5753	0	2024	11401	14	0	4223	11095	0	2004	5474	2024	11395	20
Sept	2	6	0	0	0	0	0	0	708	0	54	12886	10	0	4676	10980	0	66	8350	54	12896	0
	3	3118	725	0	57	18	10	0	5670	0	74	15828	10	0	5581	11555	0	74	11855	74	15832	6
	4	501	419	0	0	15	9	0	900	0	221	4254	1	0	1537	2755	0	224	3012	221	4255	0
	10	0	0	0	0	0	0	0	0	0	0	66	0	0	0	59	0	0	66	0	66	0
	11	77	1	0	0	0	0	0	193	0	149	703	0	0	211	579	0	41	376	53	703	0
	12	19	0	0	0	0	0	0	51	0	104	94	0	0	18	91	0	60	93	104	94	0
	15	0	0	0	0	0	0	0	0	0	74	0	0	0	0	0	0	74	0	74	0	0
	16	7	0	0	0	0	1	0	15	0	0	22	0	0	5	0	0	0	18	0	18	0
	17	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	15	0	15	0
	25	0	0	0	0	0	0	0	9	0	0	163	0	0	39	0	0	0	163	0	163	0
	30	45	0	0	0	0	0	0	45	0	0	45	0	0	6	0	0	0	45	0	45	0
Oct	1	0	0	0	0	0	0	0	3	0	0	80	0	0	17	0	0	0	80	0	80	0
	2	3	0	0	0	0	0	0	27	0	0	43	0	0	14	0	0	0	32	0	36	0
	3	0	0	0	0	0	0	0	6	0	0	34	0	0	12	0	0	0	34	0	34	0
TOTAL		20793	4067	0	159	156	200	1	34604	0	13277	120582	84	0	42689	89963	2292	10961	80338	11341	116636	50

Month	Day	Streering			Acceleration		Bar	Wipers					Tire Pressure					
		Angle	Rate	wheels value	Lat	Long	Press	Front Inter	Front Low	Front High	Rear On	Rate	Front Left	Front Right	Rear Left	Rear Right	Value of 1	Spare
May	12	422	422	422	422	0	0	0	0	0	0	0	0	0	0	0	0	0
	13	26	26	26	26	26	26	0	0	0	0	0	26	26	26	26	0	26
	16	62	62	62	62	62	62	0	0	0	0	0	62	62	62	62	0	62
	21	84	84	84	84	84	84	0	0	0	0	0	0	0	0	0	0	0
	22	724	724	724	720	720	720	0	0	0	0	0	0	0	0	0	0	0
	23	303	303	303	303	303	303	0	0	0	0	0	0	0	0	0	0	0
	27	815	815	815	815	815	815	0	0	0	0	0	0	0	0	0	0	0
	28	69	69	69	69	69	69	0	0	0	0	0	0	0	0	0	0	0
	29	4708	4708	4708	4708	1926	1926	0	0	0	0	0	5	5	5	5	0	5
	30	1078	1072	1074	1072	395	395	0	0	0	0	0	200	200	200	200	44	244
June	3	8	8	8	8	8	8	0	0	0	0	0	8	8	8	8	0	8
	19	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	0	1
	20	39	39	39	39	39	39	0	0	0	0	0	39	39	39	39	0	39
	23	147	147	147	147	147	147	0	0	0	0	0	147	147	147	147	0	147
	24	18	18	18	18	18	18	0	0	0	0	0	18	18	18	18	0	18
	27	26	26	26	26	26	26	0	0	0	0	0	26	26	26	26	0	26
July	16	10	10	10	10	10	10	0	0	0	0	0	10	10	10	10	0	10
	17	65	65	65	65	65	65	0	0	0	0	0	65	65	65	65	0	65
	25	93	93	93	93	93	93	0	0	0	0	0	93	93	93	93	0	93
	31	48	48	48	48	48	48	0	0	0	0	0	19	19	19	21	0	21
August	1	7	7	7	7	7	7	0	0	0	0	0	7	7	7	7	0	7
	4	4	4	4	4	4	4	0	0	0	0	0	4	4	4	4	0	4
	5	41	41	41	41	41	41	0	0	0	0	0	41	41	41	41	0	41
	6	8	8	8	8	8	8	0	0	0	0	0	8	8	8	8	0	8
	7	1666	1666	1666	1666	2822	1666	0	0	0	0	0	849	849	849	849	49	898
	8	31	31	31	31	31	31	0	0	0	0	0	31	31	31	31	0	31
	11	5361	5361	5361	5353	7082	5353	0	0	0	0	0	2633	2633	2633	2633	299	2932
	12	143	143	143	143	143	143	0	0	0	0	0	22	22	22	22	0	22
	13	5	5	5	5	5	5	0	0	0	0	0	5	5	5	5	0	5
	15	13	13	13	13	13	13	0	0	0	0	0	13	13	13	13	0	13
	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	19	578	578	578	578	1607	578	0	0	0	0	0	252	252	252	252	85	337
	20	5891	5891	5891	5889	9545	5889	0	0	0	0	0	3021	3021	3023	3023	1281	4302
	21	5806	5806	5806	5804	6851	5317	0	0	0	0	0	2371	2371	2373	2373	585	2956
	22	6575	6575	6575	6573	9632	6573	0	0	0	0	0	3294	3294	3296	3296	845	4139
	25	5833	5833	5830	5830	9009	5830	0	1	0	0	0	1641	1641	1641	1641	1763	3405
	26	8353	8353	8353	8353	12792	8353	0	0	0	0	0	3671	3671	3671	3671	269	3940
	27	3881	3881	3881	3878	4986	3716	0	0	0	0	0	1752	1752	1752	1752	0	1752
	28	4592	4592	4592	4588	7218	4517	0	0	0	0	0	1245	1245	1245	1245	107	1352
	29	6434	6434	6434	6434	12391	6434	0	43	0	0	0	1280	1280	1280	1280	960	2240
Sept	2	8376	8376	8376	8364	12898	8364	0	0	0	0	0	1918	1918	1918	1918	0	1918
	3	11885	11885	11885	11885	15656	11687	0	74	7	0	0	4115	4115	4115	4115	30	4145
	4	3236	3236	3236	3233	4016	2776	0	0	0	0	0	1261	1261	1261	1261	0	1261
	10	66	66	66	66	66	66	0	0	0	0	0	7	7	7	7	0	7
	11	446	446	446	385	696	357	0	0	0	0	0	105	105	105	105	0	105
	12	144	144	140	140	184	140	0	0	0	0	0	50	50	50	50	51	101
	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	16	22	22	22	22	22	22	0	0	0	0	0	22	22	22	22	0	22
	17	15	15	15	15	15	15	0	0	0	0	0	15	15	15	15	0	15
	25	163	163	163	163	163	163	0	0	0	0	0	163	163	163	163	0	163
	30	45	45	45	45	45	45	0	0	0	0	0	45	45	45	45	0	45
Oct	1	80	80	80	80	80	80	0	0	0	0	0	80	80	80	80	0	80
	2	43	43	43	43	43	43	0	0	0	0	0	43	37	43	43	0	43
	3	34	34	34	34	34	34	0	0	0	0	0	34	34	34	34	0	34
TOTAL		88523	88517	88512	88409	122960	83125	0	118	7	0	0	30717	30711	30723	30725	6368	37088

3.4. Summary of Reported POC Data Collection Test Findings

As indicated earlier, the POC test results are described in details in a six-volume report published by the Research and Innovative Technology Administration (RITA) of the USDOT (VIIC, 2009a, 2009b, 2009c; Booz Allen Hamilton, 2009a, 2009b, 2009c). This section outlines the primary evaluation results documented in these reports that regard the generation and collection of probe vehicle data.

3.4.1. Probe Data Generation

The POC program successfully demonstrated the feasibility to generate snapshots according to various intervals and triggering-event policies. In particular, the tests demonstrated the ability to generate snapshots according to a policy spacing snapshots in time according to the speed of the vehicle.

The tests further indicated that over 65% of snapshots were generated within 1 second of their intended time, and 77% within 4 seconds. When distance was used as the spacing criterion, 36% of snapshots were generated within 32 ft (10 m) past their intended distance, 75% within 65 ft (20 m), and 93% within 328 ft (100 m).

Significant limitations were finally found with the recommended 30-snapshot memory buffer. Test conducted with a 300 snapshot buffer indicated adequate operations and led to the recommendations that the memory buffer be increased to at least 300 snapshots.

3.4.2. DSRC Communication Range

Following various adjustments to fix initial poor test results, it was shown that solid radio communication could be established between a vehicle and an RSE up to a distance of 3600 ft (1100 m), with multipath effects degrading communications at 1971 ft (660 m), 2790 ft (850 m), 2950 ft (900 m), and 3280 ft (1000 m). This communications range was much larger than initial projections. The results further showed that a link imbalance with the vehicle-to-RSE communication is only present up to approximately 1300 ft (400 m).

3.4.3. Probe Data Transmission

The average vehicle-to-RSE data reception rate varied between 60% and 100%, with an average success rate of 87.8%. It was further estimated that 40 to 50% of the interactions between a vehicle and an RSE resulted in an incomplete data transfer due to the loss of the communication link before all data in a memory buffer could be sent. Connection losses were either due to a vehicle moving out of range or an unexpected termination while still within range caused by various technical issues.

About 10% of the snapshot losses following the termination of a communication connection were directly attributed to privacy requirements requesting that all remaining snapshots in a vehicle's buffer be deleted upon termination of a connection. On this issue, it was indicated that this performance could be improved if more stable connections could be established, if vehicles were provided with the ability to recognize that they are reconnecting to the same RSE, or if privacy requirements would be relaxed.

Test results further indicate that approximately 6% of all snapshots sent from an RSE were lost before reaching the SDN. These losses were attributed to some RSEs not being included in the probe data subscriptions and some RSEs not transmitting the collected data despite receiving a request for the information. A small amount of probe data was also determined to be lost between the SDN and a network user due to the need for sending an Address Resolution Protocol (ARP) message when sending the first probe data snapshot to the network user, as well as the use of User Datagram Protocol (UDP) for sending probe data snapshots.

A comparison of test results between scenarios involving one and two vehicles finally indicated that the addition of a second vehicle communicating with a specific RSE greatly reduced the performance of the probe data collection. This was explained by the design elements of the test system that allowed only one vehicle to establish a V-DTLS connection at a time.

3.4.4. Probe Data Transmission Latency

POC test activities looked at the latency resulting from sending probe vehicle data from a vehicle to a data server through a SDN. These evaluations focused on the delays induced by communication systems, from the moment a snapshot is ready to be sent to the moment it is received at a SDN. The evaluations did not look at the time that may elapse between the moment a snapshot is generated and the moment it is transmitted to an RSE.

Test results indicate that probe data typically took between 0.5 s and 1.5 s to travel from a vehicle OBE to a SDN after a vehicle has reached an RSE. The average latency when all systems were thought to operate normally was 0.8 s. No clear explanations were found to determine why the latency would vary from one day to another.

The evaluation also looked at the effects on latency of the type of backhaul system used to transfer data from an RSE to a SDN. The evaluations indicate that data typically took 0.46 s to reach a SDN from an RSE when using a wire line connection. With WiMax wireless communication, the average latency grew to 1.37 s. With a 3G wireless connection, the data took on average 1.57 s to reach the SDN.

3.4.5. Communication of Data Collection Directives to Vehicles

Tests assessing the ability to send probe data management directive to a vehicle resulted in only 5% of vehicles within range of an RSE receiving the directive. Since later tests conducted by Booz Allen Hamilton showed much better performance, it was assumed that the poor performance obtained during the test was likely the result of improper setting.

3.5. Evaluation of Overall Data Latency using Snapshot Time Stamps

This section reports on additional analyzes that were conducted at UMTRI to evaluate the potential latency of collected probe vehicle data. The test results documented in the POC report focus primarily on delays that could arise between the moment a piece of information is sent from a vehicle and the moment it is received at a data server located at a SDN. While useful, this information is insufficient to characterize fully the effects that data latency may have on application operations. For applications, the interest is on the total time that may elapse between the moment some piece of information is recorded and the moment it becomes available for use. This leads to the need to consider the following potential sources of latency:

- Time that elapses between the moment a snapshot is generated and the moment the onboard communication unit is ready to send the information to an RSE
- Time required to wirelessly transfer data from the vehicle to the RSE

- Time required for the data to travel from the RSE to the SDN or server hosting the application
- Time required for validating and preprocessing data after reaching an application server
- Time required by an application to extract and process data stored in the application server

Data collected from the POC tests only allow evaluating the latency associated with the first three elements. This can be done using the time stamp recording the moment a snapshot was generated, the RSE receipt time stamp that was appended to a snapshot message after it reached an RSE, and the SDN reception time that was recorded in the name of the file that was created when a message reached the test SDN. However, since there were no information indicating when a vehicle came within range of an RSE or became ready to transmit data after having established a secure communication with the RSE, it was not possible in this case to execute separate analysis for the first two delay elements.

3.5.1. Latency between Snapshot Generation and RSE Receipt

Data latency was assessed using only the snapshots that were collected during the application test phase between August 20 and September 4, as this data was thought to be more representative of what may happen in actual deployments. However, the assessments were also conducted with an understanding that latencies in actual systems may be somewhat different due to higher communication loads, the need to communicate with multiple vehicles simultaneously, and the operational efficiency of equipment used for wireless connection and processing data.

For each snapshot, the latency was determined by calculating the interval between the time stamp recording the snapshot generation and the time stamp recording its receipt at an RSE. Erroneous data, such as time stamps indicating RSE receipt before or multiple hours after a snapshot was generated, were removed to avoid biasing the evaluations. Since these situations occurred for only a small fraction of the total number of snapshots collected, it was not expected that such a removal would significantly affect the evaluation results.

Table 3-4 shows the calculated latencies for each RSE and each test day. As can be observed there is significant variability across all RSEs. While data retrieved at some RSEs have latencies of less than 10 s, data from other RSEs exhibit latencies of a few minutes. These large differences are due to the time needed to reach another RSE after leaving the range of an RSE. This is reflected in the fact that the longest latencies are typically observed at the same RSEs across all test days, such as RSEs number 10, 23, 34, 44, 62, and 81. These are RSEs located at the edge of the test area. RSEs that are far away from others, either in term of distance or time, are also likely to collect older snapshots and thus provide data with higher latency. Conversely, short latencies can be expected from areas with a high concentration of RSEs. The average latency of data collected within a network is thus likely to change if RSEs are added or positioned at different locations.

The data of Table 3-4 were obtained with a near-ideal system. During the POC tests, there was little competition for communication resources. Two vehicles were at most competing to communicate with the same RSE at a given time and vehicles only ran a single data generation application. Longer latencies can be expected from systems in which more vehicles attempt to communicate with each RSE and in which vehicles may run multiple applications simultaneously. It can therefore be inferred that applications relying on probe vehicle data collected by RSEs may only be able to operate in near real-time settings. In particular, the use of data that may be a few second old could result in an inability for applications to relying on the provided probe data to know the exact location of the vehicles surrounding a specific vehicle.

The range of latencies reported in Table 3-4 further indicate that data streaming to a central server may not always pertain to the same time window. While data from roadway segments that are close to RSEs may only be a few seconds old, data from segments that are further away may be a few minutes old. This creates a situation in which information about traffic conditions within different sections of a road network may have different latency. To compensate for this effect, the displaying and use of data may be delayed by a few minutes to enable analysis of each roadway segment on data pertaining to the same period. A more complex alternative may be to design algorithms allowing data analysis by sector. This approach would require knowing the period used for each sector, in addition to creating potentially difficult data processing for boundary areas between sectors.

Table 3-4 – Observed Data Latency between Snapshot Generation and RSE Receipt

RSE	20-Aug		21-Aug		22-Aug		25-Aug		26-Aug		27-Aug		28-Aug		29-Aug		2-Sep		3-Sep		4-Sep	
ID	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)
1	0		0		0		0		0		0		0		0		0		0		0	
3	132	15.9	156	18.8	233	14.8	267	14.3	393	15.0	76	20.4	78	11.8	296	22.0	460	21.9	0		0	
5	163	17.2	147	19.9	214			17.8	292	13.8	200	63.4	74	11.7	190	15.7	64	35.7	34	10.6	270	21.1
6	31	7.8	23	9.1	59	7.0	7	10.0	28	7.5	8	9.3	8	113.8	4	11.5	32	11.8	0		0	
8	127	22.5	61	74.3	209	73.6	542	72.2	876	84.0	303	94.7	544	54.2	564	44.8	398	65.9	0		0	
10	262	208.8	22	519.1	228	363.2	106	406.4	176	222.9	77	167.8	161	444.6	358	47.0	64	191.3	172	195.6	159	40.8
16	331	32.0	39	77.4	71	21.5	188	18.0	281	16.6	97	52.4	50	22.4	376	22.1	290	17.7	607	130.9	0	
17	0		0		0		0		0		0		0		0		0		0		0	
18	40	23.3	36	23.9	71	18.0	84	16.0	111	17.0	16	29.9	45	43.3	66	41.5	264	40.8	4230	151.1	0	
20	0		0		0		0		0		0		164	22.7	576	33.9	422	34.5	638	60.2	0	
21	136	32.3	136	48.0	319	55.2	182	62.3	274	67.9	82	53.4	135	38.0	108	78.6	238	73.6	29	74.7	0	
23	402	284.1	171	908.1	453	696.8	340	637.3	440	438.7	220	385.0	170	316.3	886	47.6	214	346.6	451	956.9	453	255.3
24	264	91.5	78	125.8	431	72.2	224	104.8	313	84.0	243	85.2	295	60.2	164	91.8	0		72	51.4	818	87.0
26	451	15.3	188	19.6	384	16.1	250	15.8	412	21.5	169	19.4	274	19.7	652	30.0	374	34.8	5	4.8	225	19.7
29	0		0		0		0		0		0		0		0		0		0		0	
30	208	115.0	171	32.8	325	119.9	92	51.2	195	47.5	78	48.4	118	40.2	0		240	47.3	0		0	
31	148	11.2	58	8.3	165	8.4	152	8.7	323	12.0	55	12.8	61	9.2	256	49.2	526	26.5	2883	33.7	0	
32	140	12.0	75	15.4	92	20.8	148	55.1	137	17.5	44	33.0	69	69.9	72	22.0	84	92.1	38	61.9	0	
34	3027	181.4	2173	208.9	507	130.2	1491	230.1	1661	128.9	1061	190.8	1220	161.5	1336	181.8	1726	145.8	2234	185.0	773	238.6
37	185	12.9	66	10.7	158	24.0	79	11.2	131	13.0	47	34.4	119	20.5	302	18.4	122	21.9	0		0	
38	0		0		0		0		0		0		0		0		0		0		0	
40	0		0		172	113.9	788	128.1	1094	143.9	621	138.8	519	143.4	1390	74.7	884	100.2	1068	147.7	278	10.6
41	17	15.4	78	32.9	73	13.3	108	31.0	48	15.3	25	43.5	56	22.5	22	38.7	0		127	39.4	82	14.8
42	107	9.3	80	77.5	112	32.7	61	86.6	196	92.3	106	84.9	147	123.8	170	48.1	0		0		58	38.9
43	204	20.0	64	51.5	155	32.2	147	23.0	134	17.4	53	14.6	72	25.5	110	21.0	74	26.2	0		0	
44	387	118.9	133	156.6	448	87.5	304	126.0	222	114.1	100	98.5	106	109.5	302	161.7	128	150.1	0		0	
45	52	42.0	100	141.6	180	196.2	118	72.8	91	111.8	34	44.1	48	45.5	44	64.0	60	55.9	124	45.3	48	24.8
46	45	72.0	354	76.5	20	128.9	354	61.1	598	70.8	143	92.7	340	65.1	426	77.1	616	73.7	0		0	
47	0		0		0		0		0		0		0		0		0		0		0	
49	0		0		0		0		0		0		0		0		0		0		0	
50	0		0		0		0		0		0		0		0		0		0		0	
52	402	52.2	198	72.2	123	29.6	351	50.2	323	37.1	120	37.3	111	37.5	254	64.0	214	58.4	0		0	
53	0		0		0		0		0		0		0		0		0		0		0	
54	59	75.1	36	89.2	124	63.4	47	51.4	34	82.3	34	82.2	4	29.0	16	46.6	0		94	141.8	152	89.5
55	170	85.3	224	64.6	617	204.7	228	78.0	294	46.4	91	19.6	55	119.1	149	54.9	274	27.8	183	14.6	23	10.0
57	233	18.8	170	30.6	408	36.2	206	11.0	359	14.7	0		89	14.4	314	30.0	426	21.1	0		82	94.3
58	320	59.0	506	83.6	374	61.2	320	40.3	661	46.8	246	47.0	270	116.0	598	118.6	1160	69.9	0		0	
59	115	31.2	97	21.9	88	9.4	80	8.4	138	8.1	26	8.7	79	7.8	142	45.5	206	19.1	0		0	
60	13	8.7	66	28.8	117	8.6	78	7.9	214	8.0	23	9.5	26	9.9	50	31.7	120	9.9	772	28.5	0	
61	149	21.6	50	66.4	113	28.1	131	20.7	92	20.4	46	19.4	46	17.8	88	15.1	58	12.9	0		0	
62	969	174.3	652	267.2	1192	262.5	677	154.0	915	137.5	512	205.8	592	217.7	762	105.7	534	65.9	117	37.5	372	20.3
64	191	71.7	206	71.2	317	67.6	249	78.3	230	56.1	66	28.9	115	59.6	342	80.4	464	72.4	0		0	
66	84	23.5	66	59.1	119	20.3	72	12.2	86	10.1	8	6.6	24	9.3	164	95.0	102	61.2	0		285	73.8
67	0		29	7.1	69	6.7	61	8.2	112	7.6	22	18.4	18	10.2	86	44.7	74	9.8	28	26.4	0	
68	433	63.2	118	93.3	287	72.0	135	79.4	252	57.4	82	42.3	217	60.3	248	88.1	88	60.5	0		0	
69	405	49.6	304	85.5	175	15.7	401	51.3	282	15.0	53	28.1	65	283.1	486	43.6	400	20.3	190	164.7	176	58.9
70	266	100.3	246	41.9	474	88.3	279	41.6	433	60.1	110	53.9	227	49.0	326	83.2	630	68.0	1795	105.5	0	
72	173	16.0	117	41.1	229	18.6	181	10.5	267	9.7	101	43.0	106	10.3	82	28.5	164	10.8	0		53	72.3
73	0		0		0		0		0		0		0		0		0		0		0	
74	35	8.3	31	12.4	45	164.7	11	7.7	31	16.8	19	11.0	8	9.6	40	128.4	50	41.8	0		0	
76	0		0		0		0		0		0		0		0		0		0		0	
77	0		0		0		0		0		0		0		0		0		0		0	
79	0		0		0		0		0		0		0		0		0		0		0	
80	0		0		0		0		0		0		69	62.7	360	46.0	48	83.9	21	6.6	0	
81	0		0		0		0		0		0		271	134.5	182	158.6	622	135.6	0		0	
82	119	24.4	58	69.7	107	33.2	76	19.5	104	13.0	0		33	10.5	84	46.5	42	7.2	0		196	35.8
Average		108.6		141.6		128.5		115.9		84.7		120.2		109.6		74.3		75.1		136.6		103.7

Table 3-5 – Data Latency between RSE and SDN

RSE	20-Aug		21-Aug		22-Aug		25-Aug		26-Aug		27-Aug		28-Aug		29-Aug		2-Sep		3-Sep		4-Sep	
ID	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)	Count	Avg (s)
1	0		0		0		0		0		0		0		0		0		0		0	
3	132	3.2	156	3.3	233	3.0	267	3.2	393	3.5	76	3.2	78	3.3	296	3.2	460	3.8	0		0	
5	163	3.2	147	3.5	214			3.2	292	3.8	200	2.5	74	3.2	190	2.8	64	3.0	34	3.4	270	4.0
6	31	2.8	23	2.6	59	3.3	7	3.7	28	3.9	8	4.5	8	2.3	4	2.5	32	3.7	0		0	
8	127	3.8	61	2.4	209	2.5	542	2.6	876	2.5	303	2.5	544	2.4	564	2.3	398	2.2	0		0	
10	262	3.3	22	2.9	228	2.4	106	3.6	176	3.8	77	2.3	161	2.5	358	2.0	64	3.0	172	2.7	159	5.4
16	331	11.8	39	5.9	71	5.4	188	19.7	281	4.6	97	3.1	50	3.6	376	2.1	290	20.5	607	2.8	0	
17	0		0		0		0		0		0		0		0		0		0		0	
18	40	6.2	36	4.7	71	4.3	84	6.2	111	4.9	16	5.3	45	3.4	66	4.1	264	2.9	4230	2.4	0	
20	0		0		0		0		0		0		164	2.7	576	2.3	422	2.9	638	3.4	0	
21	136	2.7	136	2.5	319	2.5	182	2.7	274	2.3	82	3.1	135	2.7	108	2.0	238	2.6	29	2.0	0	
23	402	2.8	171	1.8	453	2.6	340	2.3	440	3.0	220	2.5	170	134.3	886	1.5	214	2.0	451	1.7	453	3.8
24	264	8.8	78	3.0	431	9.3	224	3.8	313	4.1	243	3.0	295	3.3	164	4.7	0		72	6.1	818	3.5
26	451	3.2	188	3.8	384	3.5	250	3.3	412	3.4	169	3.6	274	3.6	652	2.1	374	2.3	5	2.4	225	3.4
29	0		0		0		0		0		0		0		0		0		0		0	
30	208	2.7	171	3.2	325	2.9	92	3.2	195	3.5	78	5.0	118	3.1	0		240	2.8	0		0	
31	148	3.3	58	3.6	165	3.3	152	3.4	323	3.5	55	4.2	61	3.3	256	2.4	526	2.5	2883	3.3	0	
32	140	3.3	75	3.9	92	4.4	148	3.0	137	3.9	44	3.7	69	3.4	72	3.5	84	9.5	38	4.6	0	
34	3027	2.5	2173	2.4	507	2.8	1491	2.5	1661	2.9	1061	2.6	1220	3.0	1336	1.1	1726	1.8	2234	2.1	773	2.4
37	185	3.7	66	3.7	158	3.7	79	3.7	131	4.1	47	3.4	119	3.5	302	3.0	122	3.1	0		0	
38	0		0		0		0		0		0		0		0		0		0		0	
40	0		0		172	3.3	788	2.8	1094	2.8	621	2.7	519	15.7	1390	1.5	884	2.2	1068	119.0	278	4.6
41	17	4.9	78	4.1	73	5.2	108	4.4	48	5.4	25	5.0	56	4.0	22	4.8	0		127	4.7	82	5.5
42	107	40.7	80	3.1	112	3.4	61	3.3	196	3.0	106	3.3	147	3.1	170	4.2	0		0		58	6.4
43	204	4.1	64	4.1	155	3.7	147	3.8	134	3.5	53	3.1	72	3.2	110	3.7	74	2.9	0		0	
44	387	1.9	133	2.8	448	2.6	304	2.2	222	2.6	100	2.1	106	2.4	302	2.0	128	1.4	0		0	
45	52	3.6	100	3.2	180	3.0	118	3.6	91	4.5	34	4.9	48	3.9	44	4.0	60	3.3	124	5.3	48	5.2
46	45	2.7	354	2.9	20	2.6	354	3.0	598	2.7	143	2.5	340	3.1	426	2.5	616	3.1	0		0	
47	0		0		0		0		0		0		0		0		0		0		0	
49	0		0		0		0		0		0		0		0		0		0		0	
50	0		0		0		0		0		0		0		0		0		0		0	
52	402	3.1	198	3.1	123	4.3	351	2.8	323	3.6	120	3.3	111	5.7	254	2.3	214	2.6	0		0	
53	0		0		0		0		0		0		0		0		0		0		0	
54	59	4.7	36	4.4	124	5.2	47	5.6	34	6.0	34	6.4	4	5.0	16	5.4	0		94	4.3	152	4.6
55	170	2.6	224	2.9	617	2.8	228	3.2	294	3.5	91	3.9	55	2.9	149	1.3	274	2.3	183	3.0	23	3.8
57	233	3.2	170	3.0	408	2.6	206	3.3	359	3.7	0		89	3.2	314	3.0	426	3.6	0		82	2.8
58	320	3.1	506	2.8	374	2.8	320	3.4	661	3.2	246	3.5	270	2.3	598	1.9	1160	2.6	0		0	
59	115	2.7	97	3.1	88	3.5	80	3.2	138	3.7	26	4.3	79	3.3	142	2.3	206	3.0	0		0	
60	13	3.5	66	2.4	117	2.8	78	2.9	214	3.4	23	2.9	26	3.5	50	2.0	120	2.8	772	2.9	0	
61	149	4.1	50	3.8	113	4.6	131	4.1	92	4.4	46	3.9	46	4.7	88	5.0	58	3.5	0		0	
62			652	2.3	1192	2.2	677	2.4	915	2.8	512	2.4	592	2.1	762	1.5	534	2.1	117	3.3	372	4.0
64	191	2.7	206	2.9	317	2.5	249	3.2	230	3.3	66	3.9	115	2.5	342	2.6	464	2.8	0		0	
66	84	3.5	66	2.6	119	2.6	72	3.8	86	3.9	8	4.0	24	3.5	164	2.3	102	3.2	0		285	3.3
67	0		29	3.9	69	4.0	61	3.5	112	3.5	22	3.0	18	5.2	86	2.0	74	3.2	28	3.8	0	
68	433	2.8	118	2.1	287	2.9	135	2.3	252	2.4	82	2.8	217	2.3	248	2.6	88	2.8	0		0	
69	405	4.1	304	3.0	175	1369.5	401	3.6	282	6.1	53	15.2	65	3.6	2203	2246.6	400	3.2	190	3.3	176	6.4
70	266	3.0	246	3.4	474	3.8	279	3.3	433	4.0	110	4.2	227	2.8	326	2.3	630	3.0	1795	2.6	0	
72	173	2.8	117	2.3	229	3.0	181	2.9	267	3.2	101	2.7	106	3.3	82	2.6	164	2.5	0		53	3.1
73	0		0		0		0		0		0		0		0		0		0		0	
74	35	3.4	31	2.7	45	2.4	11	3.6	31	4.3	19	3.6	8	3.6	40	2.4	50	5.7	0		0	
76	0		0		0		0		0		0		0		0		0		0		0	
77	0		0		0		0		0		0		0		0		0		0		0	
79	0		0		0		0		0		0		0		0		0		0		0	
80	0		0		0		0		0		0		69	2.3	360	2.2	48	1.4	21	4.0	0	
81	0		0		0		0		0		0		271	1.5	182	1.0	622	1.2	0		0	
82	119	3.9	58	3.3	107	3.5	76	3.9	104	3.8	0		33	3.0	84	2.9	42	4.1	0		196	3.6
Average:		3.8		2.8		3.2		3.3		3.3		3.1		3.8		2.1		3.0		2.7		3.7

Overall average: 3.06 s

3.5.2. Latency between RSE and SDN

The average observed latency between an RSE and a server hosting a probe data collection application was evaluated using the time stamp that records a snapshot message receipt at an RSE and the time stamp that records message receipt at the data application in the name assigned to each message data file. Similar to the evaluation of latency between snapshot generation and RSE receipt, only data collected between August 20 and September 4 were used for the evaluation.

Table 3-5 shows the results of the evaluation. As can be observed, the transfer of messages from an RSE to the data application typically added between 1 and 4 s of latency, with an average of 3.06 s. While data with significantly longer latency are observed on some days at some RSEs (for instance, the 1369 s latency from RSE number 69 on August 22 or the 2246 s latency from the same RSE on September 2), these situations are primarily attributed to technical problems and are assumed not to be reflective of normal operations. These erroneous results were obviously excluded from the calculations.

The POC test report indicates that the typical latency between a vehicle OBE and the data application server ranged between 0.5 and 1.5 s. This latency was significantly shorter than what is assessed using time stamps recorded with probe data snapshot and messages. The additional one to two seconds could be the result of changes in the backhaul system used to transmit the data from an RSE to the application server between the day the latency was assessed and the period during which applications were tested. The POC report also mentions that the type of backhaul system used affects transmission delay. There could be some added delay for the data application to record the incoming message. Overall, it can safely be assessed that only a few seconds are typically needed to transfer the data.

An important consideration here is that the POC test results are based on a very limited number of vehicles simultaneously attempting to communicate with RSEs and upload data. Actual system implementations will involve significantly more vehicles and higher data communication loads. Depending on the capacity of the backhaul system to process all the data communication requests, longer data latencies may be expected. Within this context, the results of the POC test provide only an indication of the fastest possible time that data could travel from an RSE to an application server.

3.5.3. Overall Latency between Vehicle and Data Application

Based on the above evaluations, it can be assessed that the primary source of latency will likely be associated with the time needed for vehicles to come within range of an RSE. Additional delays of a few seconds may be imposed during the transfer of data from a vehicle to an application server by the wireless and backhaul communication systems used. Overall, data latency of at least 5 to 10 s can be expected, with some data potentially reaching an application server up to a few minutes after having been generated. The main impact of such potential delays will be to limit IntelliDrive^{SM} applications relying on probe vehicle data to operate at best on a near real-time basis.

Another important point of consideration is the fact that data from different sections of a network may reach an application server with different latencies. This creates a potential need to wait for the longest delayed data to come in before using the data in applications, divide network data processing into different sections, or develop data processing algorithms implicitly considering differential latencies.

3.6. Usability of POC Data for DUAP Evaluations

The initial intent of the POC test project was to evaluate probe vehicle data collection capabilities across a range of applications. Unfortunately, while this program produced some data, it did not produce data in sufficient quantities to allow adequate evaluation of data uses in applications. The initial intent was to test applications and collect data over a period of three months. However, as shown in Table 3-1, various technical difficulties shortened to the data collection to a period of slightly less than 2 weeks. This resulted in partial application designs and data collection activities that primarily focused on testing the ability of vehicles to establish communication with RSEs and successfully to upload the snapshots they had been generating.

While the POC test programs generated over 100,000 snapshots, most of these snapshots were generated by vehicles traveling alone on a given roadway segment. At most two vehicles were present within the communication range of an RSE at any given time, with most of the interactions consisting of single vehicle-RSE communications. While the collected snapshots can be used to assess the capability to track individual vehicles over certain distances or to calculate parameters characterizing the movements of the vehicle, the limited quantity of data collected does not allow exploring the use of probe data to characterize average traffic behavior along specific roadway segments. For instance, while the data allows determining the average speed of a test vehicle over a given roadway segment, it did not allow exploring how probe data could be used to estimate the average travel time experienced by multiple vehicles along the same roadway link within a short interval or to assess travel time variability. Since most DOT applications rely on parameters attempting to characterize average traffic behavior, the data collected through the POC activities thus provide very little potential for evaluating how probe data could benefit DOT operations within a DUAP system.

4. DUAP Evaluation Framework

This chapter presents an overview of the context in which the evaluations detailed in this report were conducted. The specific elements covered include:

- Data processes of interest to the DUAP program
- Probe vehicle data as part of a multi-source information gathering system
- Proposed DUAP system
- Stakeholders
- Available data collection technologies
- Data sources of interest
- Applications of interests
- Potential operational constraints
- System evaluation approach

4.1. IntelliDrive^{SM} Processes of Interest

The purpose of the DUAP project is to support MDOT in evaluating the potential uses and benefits of the data that IntelliDrive^{SM} systems are envisioned to provide. The evaluations are therefore primarily conducted from a transportation agency standpoint, with a specific focus on how the collected data can be used to support the safety, mobility and network management goals typically faced by MDOT and other public transportation agencies. The program was notably designed to complement parallel efforts from the USDOT, car manufacturers and other stakeholders focusing on the design and testing of roadside infrastructure, vehicle equipment, and initial applications.

Figure 4-1 shows how the DUAP program relates to the IntelliDrive^{SM} operational framework. Elements of interest to the DUAP program are indicated by the blue and green bubbles. The focus is on processes supporting data collection, aggregation, storage, and uses in applications of interest to MDOT. The program thus generally covers processes aiming to collect information from vehicles traveling within a road network. There is generally no consideration of processes aiming to send information back to drivers or onboard vehicle systems, with the exceptions of processes supporting Advanced Traveler

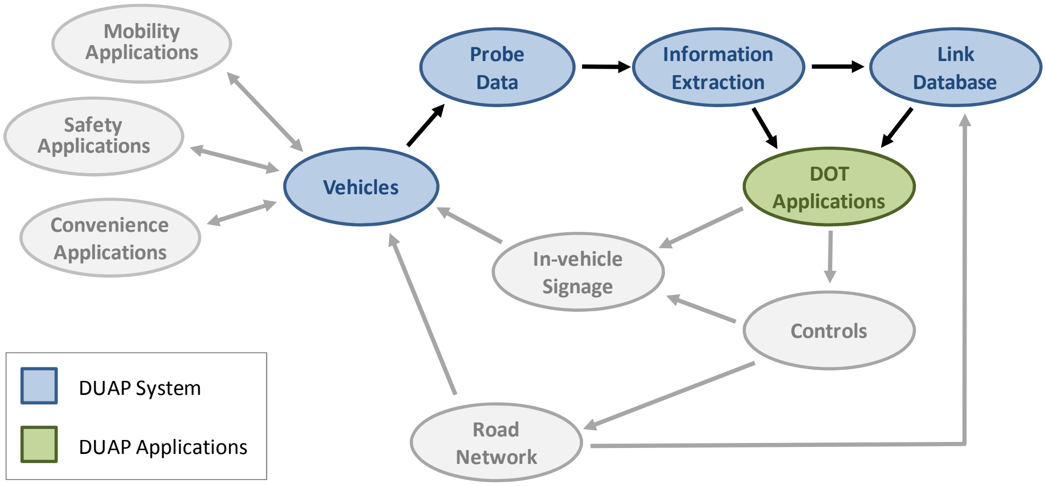


Figure 4-1 – IntelliDrive^{SM} Operational Scheme

Information Systems (ATIS) operated by MDOT. This includes processes supporting the use of changeable message signs and the displaying of traffic conditions information on the MI Drive website. All processes supporting applications that are to be developed by car-manufacturers, after-market device suppliers or private service firms are also typically outside the score of the DUAP program.

Applications to be considered program include those supporting surface transportation network operations, maintenance and planning. This include applications supporting traffic monitoring functions, the operation of Traffic Management Centers (TMCs), the operation of traffic control devices and ATIS operated by MDOT, regular network maintenance activities such as detection of potholes and other roadway surface defects, the management of inclement weather events, transportation system modeling, and demand forecasting. A more detailed list of applications of interest is provided later in this chapter.

4.2. Relation of DUAP Program to IntelliDrive^SM and Other Data Sources

Figure 4-2 illustrates the envisioned data flows within a DUAP system. It is expected that a DUAP system will draw data from various sources. This includes data from envisioned IntelliDrive^SM systems, sources currently maintained by MDOT, and relevant sources maintained by other agencies or entities. The vision is that a DUAP system will use all available data to enrich information used in existing applications and facilitate the development of new applications, both within and outside MDOT.

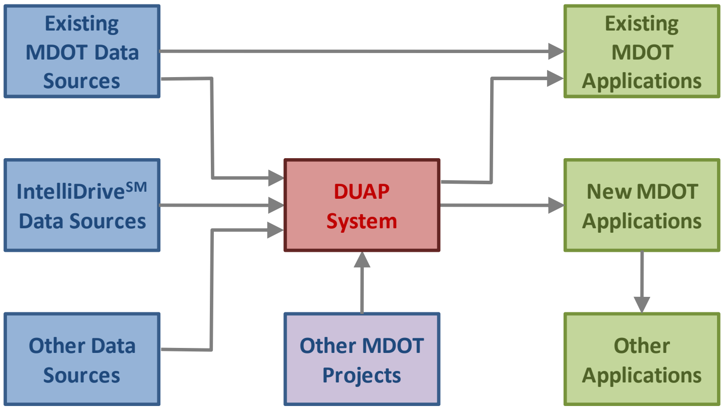


Figure 4-2 – DUAP Data Flows

One of the primary interests in IntelliDrive^SM systems is the potential to convert the vehicles used by ordinary travelers into traffic probes. The ability to collect data from a large number of vehicles will create the ability to collect data about travel and traffic conditions from every link in a network. However, IntelliDrive^SM systems are not expected to replace immediately existing data collection systems. Deployment will start with a few vehicles and data collection capability will gradually increase as the number of equipped vehicles on the roadway grows. When this project was executed, the preferred path for the deployment of IntelliDrive^SM systems was still being heavily discussed. Significant uncertainty thus still existed regarding when actual system deployments would be initiated and how these deployments would be executed. One option was to require all new vehicles starting with a specific model year to be equipped with IntelliDrive^SM systems. Another option promoted instead a deployment through the selling of after-market devices.

How fast IntelliDrive^{SM} systems will be deployed will have important implications on the assessed benefits. While some applications may provide benefits with very low market penetration levels, others may only yield benefits if data can be collected from a relatively high proportion of vehicles. It was for instance estimated that it could take up to 20 years to have IntelliDrive^{SM} devices installed in all vehicles under a deployment path only mandating that the devices be installed in all new vehicles starting with a given model year. This was judged by many as being a too slow deployment. For this reason, various proposals were also floated around promoting a parallel deployment path through the selling of after-market devices.

Regardless of the approach considered, it should be kept in consideration that system deployments are only likely to get traction if there is a clear vision of what the potential benefits may be over short-, medium-, and long-term ranges. Because of the importance of demonstrating benefits with early deployments to justify further system expansions, the first deployed applications are likely to be those that can provide almost immediate benefits.

4.3. Proposed DUAP System

Figure 4-3, reproduced from the DUAP Concept of Operations document produced by Mixon/Hill (Mixon/Hill, 2007a), provides a simple representation of the envisioned DUAP system as a set of services. Based on this vision, the following services would be provided:

- **Input Services:** Services providing the ability to interact with other systems that might have data of interest to the DUAP system.
- **Dynamic Data Services:** Services representing the active memory of the DUAP system. Data obtained by the Input Services are to be store within this module. A buffering service will also be provided to increase data longevity and provide an opportunity for services with complex data needs to process the data completely.
- **Persistent Data Services:** Services representing the long-term memory of the DUAP system.

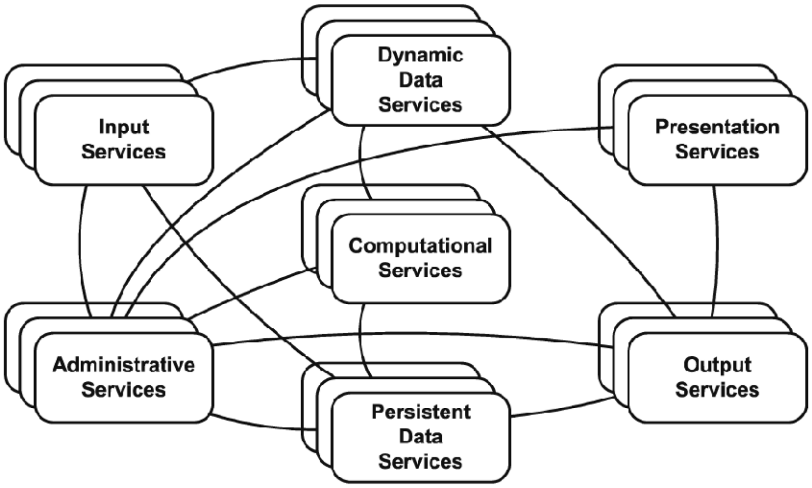


Figure 4-3 – DUAP Data Flows
(Source: Mixon/Hill, 2007a)

- **Computational Services:** Services applying logical algorithms to incoming vehicle and traffic observations to transform them into data directly applicable to transportation management and operations processes. These services will operate on both the dynamic and persistent data to derive new and useful information about what is occurring within the transportation network.
- **Output Services:** These services will structure and format data used by the Dynamic and Persistent Data Services modules for use by other services, either inside or outside the DUAP system.
- **Presentation Services:** These services are meant to support various data presentation needs, such as data outputs to a traveler information webpage or the issuance of traffic alerts for staff in a traffic operations center.
- **Administration Services:** Services used to configure and administer other DUAP services.

4.4. Stakeholders

Stakeholders in the DUAP system include all those who are expected to provide, create, or use the data and applications hosted by the system. In this case, stakeholders are predominantly MDOT staff, but also include individuals and entities who work with MDOT or who exchange data with it.

Primary stakeholder groups within MDOT include:

- **System Operators:** Individual tasked with monitoring system operations, primarily at Traffic Operations Centers, and making traffic management decisions in response to incidents, unusual congestion, or other events.
- **Asset managers:** Individuals responsible for monitoring the status of transportation system infrastructure and optimizing the preservation, upgrading, and timely replacement of highway assets through cost-effective management, programming, and resource allocation decisions.
- **Transportation system planners:** Individual tasked with evaluating transportation system needs and potential future actions to improve the movement of people and goods by motor vehicles, public transportation, walking and cycling.
- **Maintenance personnel:** Individuals responsible for maintaining roadways and bridges in adequate operating conditions; this includes individuals charged with providing snow removal and pavement treatment in the winter, performing routine reactive maintenance, and cleaning up and repairing roadway as needed in response to incidents.
- **MDOT executives:** Individuals responsible for providing oversight and for making final decisions on investments in Michigan’s transportation infrastructure; this includes MDOT’s Director, MDOT’s Executive Bureau, and the State Transportation Commission.
- **Information system administrators:** MDOT’s information system administrators are part of the Michigan Department of Information Technology (MDIT). These individuals are responsive for ensuring that data collection efforts meet policies, standard and procedures set by the department. Their overall goal is to facilitate data sharing and uses among stakeholders and ensure that certain consistency, efficiency, and effectiveness standards are met in the delivery of information supporting various state agencies.

Transportation agencies interacting with MDOT, as well as various other governmental agencies, may also benefit from the data collected by a DUAP system. Stakeholders in this group include:

- **Regional county road commissions and local departments of transportation:** Road commissions and local departments of transportation may use traffic condition data collected on major roadways crossing their jurisdiction to improve traffic management plans and support infrastructure safety programs.
- **Transportation planning organizations:** Regional and local planning organizations will benefit from the collection of data supporting the characterization of travel patterns and the determination of multi-year and seasonal travel trends within an area.
- **Transit Service Providers:** Transit service providers may use traffic condition data to plan transit route schedules. Real-time traffic conditions reports may also be used to provide on-the-fly route adjustments in response to incidents or unusual congestion.
- **Emergency Service Providers:** Emergency service providers may use traffic condition data to help them get to an incident rapidly. The data may also be used to evaluate the impacts of an incident on current traffic, plan traffic diversion strategies, and determine what resources may be needed to address and appropriately mitigate impacts on network operations.
- **U.S. Department of Transportation:** Data collected by a DUAP system will support research efforts promoting the development and deployment of applications supporting the department's goal of developing a more efficient, safer and sustainable national transportation system. Collected data may also enhance reporting capability on the status of transportation network elements, which may have subsequent impacts on the prioritization of state projects funded with federal dollars.

Non-governmental stakeholders further include:

- **Travelers:** As users of the transportation system and customers of MDOT services, travelers rely on information about traffic conditions to schedule daily commute or other activities.
- **Commercial fleet operators:** Similar to travelers, commercial fleet operators use information and roadway and traffic conditions to schedule goods shipments and manage fleet operations.
- **Commercial information service providers (ISPs)**: These entities use data from existing traveler information systems or proprietary monitoring systems to provide travel-related services to individuals and enterprises.
- **Vehicle and original equipment manufacturers:** The ability to collect probe vehicle data will depend on the willingness of car manufacturers to put the appropriate equipment in vehicles or original equipment manufacturers to produce after-market devices. The ability for vehicles to communicate with smart roadside infrastructure and other vehicles may also enable the development of new safety and mobility applications that could be marketed by car and equipment manufacturers.
- **Universities and research community**: Improved traffic and transportation system monitoring capabilities will enable researchers to better characterize traffic flow behavior and to more accurately determine how proposed mobility and safety applications may affect transportation system operations.

4.5. Available Detection Technologies

Table 4-1 provides a comparative summary of the various technologies that can currently be used to collect information from surface transportation networks. This review includes:

- Embedded point traffic detectors
- Non-intrusive traffic detectors
- Weather stations
- Automated Vehicle Identification (AVI) systems
- GPS tracking devices
- Cellular phones
- Bluetooth devices
- Instrumented probe vehicles

4.5.1. Embedded Point Traffic Detectors

Over the past 50 years, traffic surveillance systems have extensively relied on inductive loop detectors to obtain information about traffic conditions on specific roadway segments. These detectors consists one or more turns of insulated wire buried in a shallow cutout in the roadway and connected to a data recorder device. Vehicles are detected by monitoring changes in the oscillation frequency or period associated with the loop electrical output current that is produced when a vehicle passes over it. Other embedded vehicle sensing technologies that have been used to monitor traffic include magnetometers, magnetic induction coils, and piezoelectric detectors.

Table 4-2, adapted from a recent FHWA report on traffic detectors (Klein, Mills and Gibson, 2006a), summarizes the capabilities of available commercial sensors. All embedded sensors typically operate in presence mode. In this mode, the sensor turns on and stays on as along as a vehicle is standing above. Vehicle counts are obtained by simply summing the number of times a detector has been activated. While all types of sensors are shown in the table as being capable of measuring speed, this is technically true only for cases in which two sensors are used to create a speed trap. Installing two sensors a few feet apart allows direct speed measurements by monitoring the time the interval between the successive activation of the two loops. Single sensors cannot directly measure speed. With such sensors, traffic speeds are estimated by using a formula that considers the percentage of time a detector has been activated by vehicles and by assuming an average vehicle length. Some sensors finally offer the capability to classify vehicles (for instance, distinguishing passenger cars, motorcycles, 2-axle trucks, 3-axle trucks, etc.). Depending on the instrumentation, classification is done either by detecting specific sequences of axles or the specific magnetic signature of each type of vehicle.

A significant limitation of embedded sensors is their inability to provide direct information about traffic conditions between detection stations. Conditions between stations are typically inferred based on the conditions observed at each station. There is also no capability for uniquely identifying each passing vehicle, unless special equipment is installed onboard. This generally prevents tracking data to be collected. All that is provided is that a vehicle has passed over a detector at a given time. There is further no capability for obtaining data characterizing the status of onboard vehicle systems. Many surveillance systems based on loop detector have finally been plagued with poor reliability. Loop detectors may be affected by a crumbling road surface, a failure of the sealant protecting them from moisture, the introduction of foreign substances into the slot of the loop, or any work requiring cuts to be made in pavement. When a failure occurs, no data is collected from of the detection station, thus creating a blind spot in network coverage.

Table 4-1 – Comparison of Available Detection Technologies

Technology	Technologies	Advantages	Disadvantages
Intrusive traffic detectors	• Inductive loops • Magnetometers • Piezo-electric detectors	• Well understood detection data • Primary type of technology used by traffic surveillance systems • Can capture all vehicles passing within detection zone • Operations not affected by weather conditions	• Typically only provide basic traffic flow measures (count, speed, occupancy) • Cannot uniquely identify vehicles • Cannot obtain data characterizing the status of onboard systems • Can only provide information where detectors are installed • Detector failure results in complete loss of local detection capability
Non-intrusive traffic detectors	• Pneumatic tubes • Infrared sensors • Radar sensors • Doppler microwave sensors • Pulse ultrasonic sensors • Passive acoustic sensors • Video image detection systems	• Well understood detection data • Type of technology increasingly being used • Can capture all vehicles passing within detection zone • Many sensors offer the ability to detect traffic across multiple traffic lanes	• Inability to track vehicle movements • Can typically only provide basic traffic flow measures (count, speed, occupancy) • Cannot obtain data characterizing the status of onboard systems • Can only provide information where detectors are installed • Operations of some sensors may be affected by weather conditions (fog, snow, night conditions, etc.) • Detector failure results in complete loss of local detection capability • Sensors based on acoustic and Doppler principles may not accurately sense stopped or slow moving traffic
Weather stations	• Ambient air/wind sensors • Pavement sensors	• Augment traffic data with local and regional environmental condition data	• Does not provide vehicle-related information • Can only provide information where detectors are installed • Detector failure results in complete loss of local detection capability
Automated Vehicle Identification (AVI) systems	• Radio-frequency identification tag • License plate recognition	• Allow unique identification of passing vehicles • Allow tracking of vehicle movements from a detection to another • Commonly used for toll collection systems • Operation not affected by weather conditions	• Require installation of roadside infrastructure • Require vehicle to be equipped with identification tags • Does not provide information about traffic conditions between detection stations • Potential traveler privacy concerns
GPS tracking systems	• GPS receivers linked to data storage and/or communication devices	• Provide real-time position (latitude/longitude) and speed data • Allow unique identification of vehicles • Allow second-by-second data to be recorded • Allow positioning of vehicles on specific roadway segments when linked to mapping software	• Data collection may be suspended if line of sight to satellites if blocked (urban canyons, bridges, tunnels, dense foliage) • Potential traveler privacy concerns

Table 4-1 – Detection Technologies (cont'd)

Technology	Technologies	Advantages	Disadvantages
Cellular phones	• Any active cellular phone	• Use existing communication infrastructure • Ability to continuously send data, provided the vehicle is in a communication coverage area • High likelihood that an active cell phone is present in a vehicle • Can be used to possibly collect data from all roads vehicle travel • Smart phones may offer the opportunity to develop interfaces with onboard vehicle systems and various external sensors	• Potential for multiple detections from a single vehicle • Inability to obtain vehicle status data • May not be able detection of all vehicles • Potential traveler privacy concerns
Bluetooth devices	• Any active device equipped with Bluetooth communication capability	• Communication technology used with a wide variety of devices • Allow tracking of vehicle movements from a detection station to another • Many devices offer the opportunity to develop interfaces with onboard vehicle systems and various types of external sensors • Growing fraction of vehicles equipped with Bluetooth devices • MAC address of each device not linked to a specific user account	• Requires the installation of roadside units • Relatively short communication range (1 to 100 m) • Still relatively small fraction of vehicles with onboard Bluetooth devices • Can only provide data about traffic conditions between detection stations if intermediate data can be recorded in an onboard devices • Short communication range may limit data retrieval from moving vehicles • Potential for multiple detections from a single vehicle • Potential traveler privacy concerns
DSRC probe vehicles	• Wireless devices using the 5.9 GHz frequency band	• Ability to communicate data via restricted licensed wireless channels • Opportunities exist to develop interfaces with onboard vehicle systems and external sensors	• Requires installation of specialized onboard devices • Requires dedicated roadside infrastructure • Potential traveler privacy concerns

Table 4-2 –Detection Capabilities of Point Vehicle Detectors
(Adapted from Klein, Mills and Gibson, 2006a)

Sensor technology	Presence	Count	Speed	Output data	Classification	Multiple lane or detection zone	Communication bandwidth	Purchase cost [a] (1999 US$)
Pavement Embedded Sensors								
Inductive loop	X	X	X [b]	X	X [c]		Low to Moderate	$500-$800 [i]
Magnetometer	X	X	X [b]	X			Low	$900-$6,300 [i]
Magnetic induction Coil	X [d]	X	X [b]	X			Low	$385-$2,000 [i]
Roadside or Overhead Sensors								
Microwave Radar	X [e]	X	X	X [e]	X [e]	X [e]	Moderate	$700-$2,000
Active Infrared	X	X	X [f]	X	X	X	Low to Moderate	$6,500-$3,300
Passive infrared	X	X	X [f]	X			Low to Moderate	$700-$1,200
Ultrasonic	X	X		X			Low	$600-$1,900
Acoustic array	X	X	X	X		X [g]	Low to Moderate	$3,100-$8,100
Video image processor	X	X	X	X	X	X	Low to High [h]	$5,000-$26,000

[a] Installation, maintenance, and repair costs must also be included to arrive at the true cost of a sensor solution as discussed in the text.
[b] Speed can be measured by using two sensors a known distance apart or estimated from one sensor, the effective detection zone and vehicle lengths.
[c] With specialized electronics unit containing embedded firmware that classifies vehicles.
[d] With special sensor layouts and signal processing software.
[e] With microwave radar sensors that transmit the proper waveform and have appropriate signal processing.
[f] With multi-detection zone passive or active mode infrared sensors.
[g] With models that contain appropriate beam forming and signal processing.
[h] Depends on whether higher-bandwidth raw data, lower-bandwidth processed data, or video imagery is transmitted to the TMC.
[i] Includes underground sensor and local detector or receiver electronics. Electronics options are available to receive multiple sensor, multiple lane data.

4.5.2. Non-intrusive Point Vehicle Detectors

To alleviate some of the problems associated with in-pavement detectors, various technologies allowing vehicle sensing from the side of the road or an overhead location have emerged over the past two decades. One the most visible is video detection, which is now commonly used to detect vehicle queues or approaching vehicles at signalized intersections. Other technologies that have surfaced include sensors based on infrared, radar, laser and acoustic principles.

While non-intrusive detectors use different sensing technologies, they generally have the same data collection capabilities as traditional loop detectors as they are also primarily designed to monitor vehicles passing within a relatively narrow detection zone. As shown in Table 4-2, data collection capabilities again include vehicle presence, vehicle count. Direct speed measurement is also possible with sensors using Doppler radar principles or capable of defining multiple detection zones within their sensing field. Some sensors can also classify vehicles by analyzing the length or vertical profile of each passing vehicle.

4.5.3. Weather Stations

In recent years, many weather-monitoring stations have been installed along major roadways to provide local environmental data for assessing pavement and travel conditions. These systems typically provide air temperature, humidity, rain and wind information. Some stations may also provide pavement surface and subsurface conditions from sensors embedded in the pavement. The information is used to assist with roadway management decisions and help motorists make travel decisions during severe weather events. While useful, these stations only provide information about their location. If the stations are relatively far apart, weather conditions between the stations can only be inferred. Any equipment failure further results in a temporary blind spot within the measurement system.

4.5.4. Automated Vehicle Identification (AVI) Technologies

Automated Vehicle Identification (AVI) systems are vehicle-based detection systems allowing the unique identification of each passing vehicle. Because of this detection capability, they are extensively used around the world to support toll collection. Examples in the United States include the EZ-Pass and FasTrak systems. Both systems use radio-frequency identification (RFID) tags to identify uniquely vehicles passing through a toll plaza. Some systems may also rely on license plate recognition technology.

The data that can be obtained from each detection station typically include a vehicle identification number and a time of passage. Vehicle tracking across a network can be done by correlating the detections made at different stations. This allows obtaining the average travel time between each station, but does not provides information about the specific traffic conditions that may have been encountered in between. Origin-destination flow patterns can also be obtained along freeways equipped with toll plazas on entry and exit ramps. Since each vehicle is uniquely identified, vehicle classification can further be obtained by storing the vehicle type in each vehicle’s records.

4.5.5. Global Positioning Systems

Since its completion in the mid 1990s, the Global Positioning System (GPS) system has increasingly been used to provide positioning data. Data provided include latitude and longitude coordinates, speed and heading. Acceleration rate is also frequently provided by compiling speed differentials between successive measurements. The primary benefit of using GPS devices is the ability they provide to obtain position measurements from virtually anywhere. Unlike fixed detectors, a receiver can be carried around to generate information about each portion of a trip. Following a significant reduction in their cost, GPS receivers are now being used in a wide range of devices, such as cellular phones. They have also become a basic component of virtually all mobile data collection systems.

In most systems, data can be collected at least once every second. This allows the capture of detailed speed profiles that can be used to analyze driving behavior at specific locations. When linked to an electronic map, the position data returned by GPS devices can be used to obtain information about the link on which a vehicle is traveling or generate routes from which a vehicle can reach a particular destination from its current location.

GPS accuracy is affected by a number of factors, such as slight variations in satellite position, signal noise, atmospheric conditions, and natural barriers. The most accurate determination of position occurs when a receiver has a clear view of multiple GPS satellites and no other objects interfere with signal transmission between receiver and satellites. Noise results from interference from objects near the receiver or emitting signals on the same frequency and can create errors of 3 to 32 ft (1 to 10 m). Objects such a mountains or buildings between the satellite and the receiver can also produce errors, sometimes up to 100 ft (30 m).

To reduce potential measurement errors, various enhanced GPS systems have been developed. A first example is Assisted GPS. This system is typically used at locations where the reception of radio signals from GPS satellites is poor or non-existent. To aid with GPS accuracy, GPS receivers are installed on cell phone towers to collect satellite information. A ground wireless network is then used to relay the information to the GPS receivers located in poor reception area.

Differential GPS is another example. This system also relies on the use of fixed ground stations to send information to GPS receivers. However, information from both satellites and fixed ground stations are used to determine measurement correction factors. These factors are then broadcast to receivers via a ground wireless network. Differential GPS has been found to be particularly helpful in situations in which atmospheric conditions interfere with reception.

The most recent innovation is the Wide Area Augmentation System (WAAS), which has been developed by the Federal Aviation Administration and Department of Defense to augment GPS accuracy for air navigation. Using a network of ground-based stations protected from the public, this system transmits correction factors to geosynchronous communications satellites, which then transmit them to the receivers. Over the United States, WAAS has achieved a practical lateral accuracy of about 3 ft (1 m), which is almost sufficient for accurately positioning vehicles within specific traffic lanes.

4.5.6. Cellular Phone Tracking

To take advantage of the large number of persons carrying cellular phones, various research efforts have looked at how these devices could be used to obtain traffic flow data. In early research efforts, tracking was done by monitoring the signals sent by phones to communication towers. The location of a particular phone, and thus specific vehicle, was determined through triangulation techniques by processing lines of bearing and differences in the arrival time of wireless signals at various communication towers. This allowed following the movement of individual phones from one tower to another. Vehicle position and travel speed could further be obtained by correlating the collected data to highway maps. In recent years, however, an increasing number of cellular phones are equipped with an embedded GPS receiver. The availability of the GPS receivers allows tracking the position of a phone by simply recording the location measurements returned by the GPS receiver.

The attractiveness of cellular phone tracking over previous detection methods is the potential ability to follow vehicles on every road traveled without requiring additional infrastructure deployment. If the phone remains within a cellular system coverage area, data collected by the phone could be sent continuously to a data server over the cellular network. Alternatively, data could only be sent when vehicles pass specific locations. Smart phones also offer the ability to interface with various external systems. This allows for instance to collect and broadcast information from onboard vehicle systems.

Because cellular phones are attached to specific user accounts, some privacy concerns exist. These have so far typically been addressed by stripping any identity information from the collected data or collecting sensitive data only if the owner of the phone has agreed to the data collection (opt-in agreement). Another potential issue is the fact that multiple phones may be carried by the occupants of a vehicle. This creates a potential for double or triple counting some vehicles and thus biasing traffic statistics derived from the data. An issue also exists on how to distinguish between vehicles and cyclists on streets where both type of vehicles may travel at similar speeds.

4.5.7. Bluetooth Device Tracking

In addition to cellular phones, there is interest in using Bluetooth-enable devices for vehicle detection. This option aims to take advantage of the fact that the majority of consumer electronic devices produced today come equipped with Bluetooth wireless capability to enable communication with other devices, as well as the fact that Bluetooth is has become the primary means to enable hands-free cellular phone uses.

Depending on the power associated with each Bluetooth device, communication may be possible with other devices within a range of 3 to 300 ft (1 to 100 meters). Since each Bluetooth device uses an electronic identifier, called a Media Control Access (MAC) address, each device can be uniquely identified. Correlating detections from various locations thus potentially allows tracking vehicles carrying a specific device across a network. Since MAC addresses are not typically associated with a user-account, there are theoretically less privacy concerns than with cellular phone tracking. However, since multiple Bluetooth devices may be present in a vehicle, there remains a potential for double counting vehicles that can lead to some biases in the estimated traffic statistics.

4.5.8. Probe Vehicles

Probe vehicles have long been used to collect data within transportation networks. Most of the early uses focused on the collection of travel time data. Vehicles would be sent out to travel along specific roads and an observer in the vehicle would record the time at which the vehicle passed specific points. Over time, automated electronic data collection systems replaced manual data entries. Data collection has further expanded beyond travel time surveys as GPS systems can now be used to record position and speed data on a second-by-second basis. Various onboard instruments can also be used to capture data from various vehicle systems, such as data from the vehicles CAN network characterizing engine operations, wiper uses, etc.

In early systems, captured probe data would be stored in an onboard memory until the vehicle would return to its garage, where it would manually be retrieved. Over time, various approaches have been introduced to enable automated data uploads from vehicles. This included systems using Bluetooth devices to communicate with a data server when a vehicle would return to its garage, or cellular phones to enable periodic data upload while the vehicle would be traveling.

Envisioned IntelliDrive^{SM} systems further expand the use of probe vehicles by introducing the ability to communicate directly with roadside infrastructure, neighboring vehicles and other mobile devices. While probe vehicles were in the past primarily custom-built vehicles, IntelliDrive^{SM} systems further offer the opportunity to convert every vehicle into a probe. While early development efforts exclusively focused on using roadside DSRC devices to communicate with vehicles, current communication options encompass a wider range of technologies.

The primary advantage of using DSRC roadside devices is the ability to use a restricted communication band. The licensing requirement eliminates potential interferences from non-transportation related wireless devices and increases communication reliability by limiting data traffic over the communication channels being used. These benefits can be particularly advantageous for applications having low data latency tolerance, such as safety applications requiring accurate information about the position of surrounding vehicles. However, a potential disadvantage is that communication with other devices is only possible within a certain range. Early IntelliDrive^{SM} deployment tests have indicated an effective communication range of about 1300 and 1600 ft (400 to 500 m), with communication possible up to

3280 ft (1000 m) depending on local conditions. This is much better than the 3 to 327 ft (1 to 100 m) range typically offered by Bluetooth devices

A potential difficulty with the use of DSRC technology is the challenge of providing adequate communication coverage. Data can only be retrieved from probe vehicles when they are within range of at least one RSE. RSEs must therefore be placed at various locations within a road network to provide adequate in-network data collection capabilities. Deploying too few RSEs may result in difficulties to collect data from certain areas. This situation may also results in larger data uploads from probe vehicles and in a greater potential for data losses due to transmission problems. For these reasons, various recent research efforts have also looked at the possibility of using cellular phones for transmitting data collected by probe vehicles, as this approach would provide nearly ubiquitous communication coverage. While it may also results in higher data latency, this would be of little consequence is the collected data is not used to support real-time applications.

4.6. Data Sources of Interest

As indicated earlier, the focus of the DUAP program is on assessing how new IntelliDrive^{SM} data can be used to enhance how MDOT conduct its operations. The program considers not only how IntelliDrive^{SM} probe data can be used, but also how it may be used in parallel to other data sources. While it can be envisioned that probe vehicle data may someday become a primary source of transportation system data, such a situation is not likely to be realized in the short term. In some cases, IntelliDrive^{SM} data may provide additional information that is not currently available through existing data sources and used to develop new applications of expand existing ones. In other cases, the data may overlap already existing data and thus primarily be used to enhance existing applications.

The following subsections provide a summary of data sources that can be tapped to support DUAP applications. These sources, illustrated in Figure 4-4, can be categorized into the five following groups:

- MDOT data sources
- Data sources from other State of Michigan agencies
- Data sources from public transportation agencies across the state (metropolitan planning organizations, county road commissions, transit agencies, etc.)
- Data sources from federal government agencies and federal programs
- Data sources from private enterprises

Collected data can further be categorized into four broad groups:

- **Continuous data:** Data collected on a continuing basis, such as data from permanent traffic detection stations
- **Periodic data:** Data collected repeatedly, but only for short periods at a time, such as traffic counts conducted once every year over a period of a few days or yearly inventory data
- **Occasional data:** Information collected on an irregular basis, often to satisfy specific projects
- **Static/Semi-static data:** Information that remains fixed or changes infrequently, such as road or bridge inventory data in a GIS database

The primary focus of a DUAP system is on collecting and processing continuous data. However, periodic, occasional, semi-static and static data are not to be excluded as such information can provide additional valuable information to specific applications.

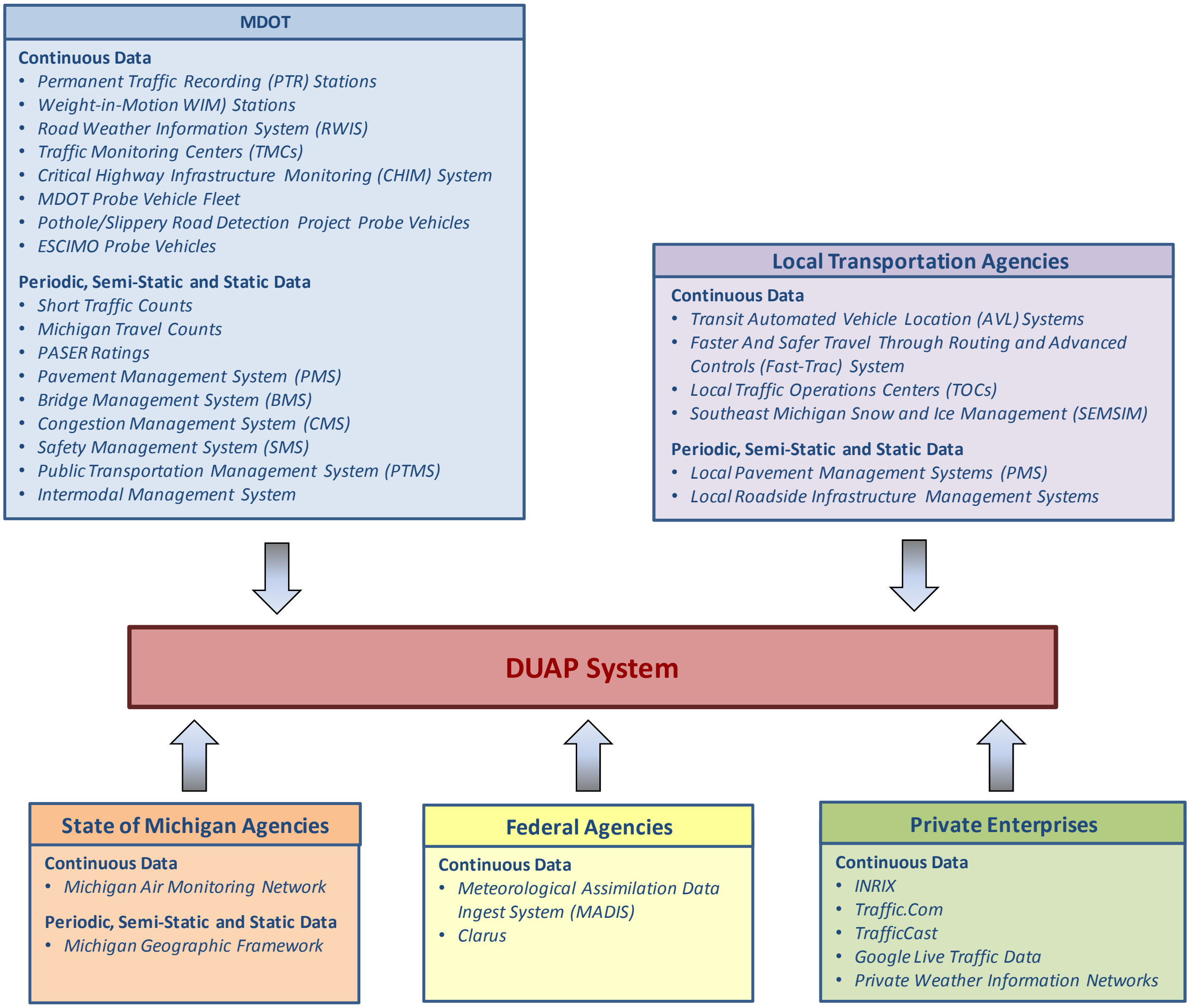


Figure 4-4 – Data Sources of Potential Interest

4.6.1. MDOT Data Sources

MDOT primary responsibilities are to operate and maintain state trunk lines. This includes freeways and all U.S. and Michigan numbered routes. To satisfy various operational, safety, planning and maintenance needs, a wide array of continuous and periodic data are collected for the purpose of characterizing traffic conditions on roadways, regional travel demand patterns, or the operational status of pavement, bridges and other infrastructure asset elements.

Sources of continuous data currently generated by MDOT traffic and roadway surveillance systems that are of potential interest to the DUAP system include:

- **Permanent Traffic Recorder (PTR) stations:** MDOT currently maintains a network of fixed vehicle detection stations to monitor traffic along major roads across Michigan. Detection is mainly done using loop detectors embedded in the pavement, but with an increasing number of sites using microwave, infrared or other roadside sensing technologies. Basic stations provide vehicle counts and hourly traffic volumes binned in 15 speed groups. Stations with more advanced sensors may also provide vehicle classification and truck characteristics data such as axle weights and spacing. Most of the detection stations are located on freeways around the Metropolitan Detroit area (2500 reported detectors covering 200 miles of freeway), with additional stations in Grand Rapids (23 reported detectors) and at key strategic locations across the state. While stations are meant to operate continuously, it is not exceptional to have a significant proportion of detectors being non-operational at any given time, particularly at stations with embedded sensors located on roads with bad pavement.

- **Weight-in-Motion (WIM) stations**: WIMs are sensors embedded in the pavement that enable to measure the weight of passing trucks without requiring them to stop. Weight sensors have traditionally been installed at fixed truck inspection stations located on the side of the road. Data collected at WIM stations typically include vehicle speed, axle weights, axle spacing, and vehicle classification based on axle configuration. Since 2007, MDOT and the Michigan State Police have also started installing WIM equipment with wireless communication capability directly on roadway traffic lanes to enable remote monitoring of truck weights. Approximately 20 wireless detection sites were reported to be in use across the state as of February 2009.
- **Road Weather Information System (RWIS):** RWIS are meteorological stations installed near highways for detecting hazardous roadway conditions and supporting weather-related decision-making. An RWIS typically consists of three main elements: an Environmental Sensor System (ESS), models and processing systems used to develop forecasts and tailor the information into an easily understood format, and dissemination platforms on which to display the tailored information. While monitoring capability at individual sites depends on available instrumentation, RWIS are generally designed to collect atmospheric and surface data. Common types of atmospheric data collected include air temperature, amount and type of precipitation, visibility, dew point, relative humidity and wind speed and direction. Video cameras may also be used to provide visual confirmation of roadway conditions. Surface data frequently include pavement temperature, subsurface temperature, surface condition (dry, wet, frozen), amount of deicing chemical on the roadway, and freezing point of road surface.
- **MDOT Traffic Management Centers (TMCs):** MDOT currently operates three TMCs across Michigan: the Michigan ITS Center (MITSC) in Detroit, the West Michigan TMC in Grand Rapids, and the Blue Water Bridge Operations Center in Port Huron. Plans are also made to deploy a fourth center in Lansing. These centers often act as focal operation points where data collected by various surveillance systems is sent and stored. The MITSC currently oversees 200 miles of freeways within the Metropolitan Detroit area and is connected to 166 closed-circuit television (CCTV) cameras, 72 dynamic message signs, one over-height detection system, one speed warning system, and 99 PTR stations. A planned expansion is expected to add connections from 17 CCTV cameras and up to 53 detection stations. The center is also connected to the Road Commission for Oakland County (RCOC) Traffic Operations Center through a center-to-center link. The Western Michigan TMC further oversees 24 miles of freeways instrumented with 42 vehicle detectors, 23 CCTV cameras, 11 dynamic message signs, and 4 variable speed limit signs. A planned system expansion is projected to bring connections to a total 70 vehicle detectors, 40 CCTV cameras, 30 dynamic message signs, and a number of signalized intersections by 2011.

Additional sources of continuous data that may be provided by various ongoing development and research projects include:

- **Critical Highway Infrastructure Monitoring Project (CHIMP):** This project uses wireless communication to retrieve data from sensors installed on bridge decks and to backhaul it to a central server. The system currently monitors sensors on the Mackinac and Cut River bridges and could be expanded to other bridges in the future. Data from the Mackinac Bridge include measurements from eight wireless strain gages installed near the south tower to monitor live load activity. The Cut River Bridge data include measurements from strain gages and sensors monitoring bridge deck moisture, temperature, chloride content, and icing conditions. Data is also collected from traffic point detectors installed in each of the eastside approach lanes to the bridge to determine traffic speed, volume, and occupancy, as well as from a wireless WIM station collecting data on vehicle weights one mile east of the bridge on US-2 and from a Road Weather Information System (RWIS) station installed near the bridge.

- **MDOT Probe Vehicle Fleet:** MDOT is currently working with Motorola to provide telemetry onboard devices for 70 MDOT vehicles. Time and vehicle position is to be captured from a GPS unit. Vehicle speed, engine RPM, coolant temperature, throttle position, and time since engine start are to be further collected through interfaces with onboard systems. Additional external sensors will also be used to collect accelerometer data, barometric pressure and ambient air temperature. The collected data will be stored in an onboard memory until the vehicle will come within range of one of eleven 802.11 wireless access point installed at strategic locations across the state.

- **Pothole/Slippery Road Detection Project:** MDOT is currently working with UMTRI to instrument two vehicles that will be used to test the feasibility of using onboard vehicle instrumentation to detect potholes and slippery road conditions. Data from these vehicles will include GPS positioning, vehicle speed, road surface temperature, ABS brake activation, accelerometers, and data from other relevant vehicle systems. Data is to be collected by a smart cellular phone communicating via Bluetooth with various onboard devices. Use of a cellular phone will allow frequent, if not continuous, data communication with a central data server.

- **Eliminating Slippery Conditions by Implementing Mobile Observation (ESCIMO) Project:** Daily observations of the actual road surface conditions are needed to compare and correlate between the information and data collected from RWIS. As part of this project, MDOT vehicles will be instrumented to collect weather data. These vehicles will then be used to record actual road surface conditions during periods in which icing conditions could occur. The collected data will then be compared to information provided by nearby RWIS stations to determine how much error exists between the slippery road conditions that were actually observed and the conditions recorded by the RWIS stations. Most of this data collection is to be done in Michigan's Upper Peninsula region. All collected data will be sent to a central server and commingled to provide useful information to the end users (maintenance garage staff, traffic operation center, travelers, transportation system planners, etc.).

Sources of periodic data and static/semi-static data that could further support DUAP applications include:

- **Short Traffic Counts:** To support various reporting and study needs, MDOT conducts more than 3500 short-term traffic counts each years on state trunk lines. Collected data typically include hourly volume counts over a 48-hour period and 15-minute counts over a 24-hour period. The most common method for counting traffic is by using a pneumatic hose placed across the road attached to a portable recording device. These devices primarily count the number of axles passing on the pneumatic hose. Vehicle counts are then obtained by applying axle-to-vehicle conversion factors. Some devices may also classify vehicles according to their sequence of axles.

- **Michigan Travel Counts:** Travel counts are statewide surveys in which individuals are asked to describe their travel habits. A survey involving more than 14,000 households across the state was conducted in 2004. This was the first time that travel data had been collected in an urban area in Michigan since the 1970s. A second survey was executed in 2009 to understand the changes in household travel that may have occurred since the first study.

- **Pavement Surface Evaluation and Rating (PASER) Data:** Current Michigan laws require MDOT, county road commissions and cities to report annually to the Transportation Asset Management Council (TAMC) the condition of roads and bridges under their jurisdiction. To fulfill this requirement, pavement condition data is collected every year using the PASER rating system. This system consists of a 1 to 10 ride-quality rating based on a visual assessment of pavement condition. Ratings are typically collected for individual road segments. Currently, data is collected for approximately 50% of all federal-aid eligible roads every year, with some counties and cities conducting surveys that are more extensive. All the data collected across the state is stored within the RoadSoft software and reported back to the TAMC.

- **MDOT Pavement Management System (PMS):** MDOT maintains a database of pavement-related information that is used for assessing and prioritizing roadway maintenance needs. Information stored within the system typically includes inventory, construction, traffic, condition, and treatment data. Inventory data provide information about each roadway segment, such as road name or route number, segment location, number of lanes, width of road, number of lanes, pavement type, thickness of pavement layers, and drainage conditions. Construction data contain information about the history of the pavement, such as year built, design service life, date and type of rehabilitation, maintenance projects, materials used in construction activities, and cost of maintenance activities. Traffic data typically include vehicle and truck counts in the form of Average Annual Daily Traffic (AADT). Condition data refer to information about the past and present surface condition. This may include physical distress, roughness, structural capacity, and friction data. Treatment data finally provide information about the cost and performance of different maintenance, rehabilitation, and reconstruction treatments. Data for the system is collected over a two-year period using specially equipped vehicles and used to assess pavement distress and the Remaining Service Life (RSL) for each roadway section on the road network operated by MDOT.

- **MDOT Bridge Management System (BMS):** MDOT’s BMS includes an Oracle database storing asset inventory data for bridges and culverts throughout the state. This system, which is compatible with the AASHTO Pontis Bridge Management System, is used as a decision-support tool for managing the inspection, analysis, and maintenance of bridges and culverts. It includes data on more than 12,500 bridges, of which 4,500 are under MDOT responsibility while the others are maintained by local jurisdictions. For each bridge, the system stores information characterizing the location and type of structure, periodic inspection reports, maintenance recommendations, and records of executed work.

- **MDOT Congestion Management System (CMS):** MDOT’s CMS provides access to current system level conditions and identify roadway segments on which congestion is currently occurring or expected to occur in the future. The system also incorporates travel demand forecasting capabilities for 14 urban and numerous rural areas throughout Michigan. Its database incorporates historic traffic data and future traffic forecasts from both statewide and urban area models. It also contains historic and forecasted socioeconomic data from the U.S. Census Bureau aggregated both at a traffic analysis zone and at the county level. The system can further provides summary statistics and performance measures for user-selected routes based on geographical area or road classification.

- **Safety Management System (SMS):** The SMS is a decision support tool used for analyzing vehicular crashes and the roads on which they occur. This system provides users with data on both roadway features and crashes. Crash data are pulled monthly from the Traffic Crash Reporting System, which stores crash reports filled by the Michigan State Police, with an average 30-day delay in loading. Inventories of roadway elements that may affect safety evaluations, such as guardrails and markings, may also be included.
- **Public Transportation Management System (TRMS):** The PTMS provides access to data characterizing public transportation ridership, finance, vehicles, and performance from about 100 transit agencies across Michigan. It also includes a statewide vehicle inventory used for forecasting needs and a financial database used for both budgeting and obtaining state funds.
- **Intermodal Management System:** This system is a data management and information analysis tool used to assess passenger and freight access to and use of air, marine, non-motorized, and rail transport modes. It is designed to support the day-to-day functions of modal specialists, while providing user access to data on intermodal assets.

4.6.2. Data from other State of Michigan Agencies

Continuous data sources of potential interest from State of Michigan agencies other than MDOT include:

- **Michigan Air Monitoring Network Data:** The Michigan Department of Environmental Quality operates a network of 26 stations located throughout Michigan. These stations all provide hourly observations of air temperature, wind speed, and wind direction. Twelve of them further provide barometric pressure, while five also provide relative humidity and three record solar radiations.

Inventory data of potential interest state agencies other than MDOT include:

- **Michigan Geographic Framework (MGF):** The MGF is maintained by the Department of Information Technologies (MDIT) and serves as the digital base map for governmental agencies in the State of Michigan. It includes road features and attributes based on current TIGER/Line files, as well as an enhanced linear referencing system built from MDOT's Michigan Accident Location Index (MALI). Geographic features are modeled within the framework at a scale of 1:24,000, which corresponds to a horizontal accuracy of +/- 40 feet.

4.6.3. Data from Local Public Transportation Agencies in Michigan

Various data of interest may be collected by local road commissions, metropolitan planning organizations, and cities. While MDOT is primarily only responsible for freeways and state trunk lines, county road commissions are often responsible for the majority of roads within a region. In Michigan, non-trunk line roads within a township are typically under control of the county, while cities are normally responsible for roads within their boundaries.

Potential continuous data streams from local transportation agencies that may benefit DUAP applications include:

- **Transit Automated Vehicle Location (AVL) Systems:** Many transit agencies have implemented GPS-based automated vehicle location systems to enable them to track the location of their vehicle fleets. Depending on the system being used, data are either continuously sent to a central computer or only sent when buses pass pre-set locations. Transit agencies in Michigan with deployed AVL systems include SMART, the Ann Arbor Transportation Authority, and Grand Rapids Transit. Additional deployments are also planned by the Capital Area Transit Agency in Lansing, Battle Creek Transit, and the Kalamazoo Transit Authority.
- **Faster and Safer Travel through Routing and Advanced Controls (Fast-Trac) System:** FAST-TRAC is a traffic monitoring system that has been developed by the Road Commission for Oakland County (RCOC). At the heart of this system are advanced traffic management technologies that allow traffic signals to respond in real time to observe traffic flows at each intersection. Traffic demand is sensed through overhead video imaging devices. These devices detect approaching traffic and monitor flow rates at intersection stop lines. The collected traffic flow information is then sent to a regional computer, which in turn analyzes observed traffic patterns and adjusts the signal timings at individual intersections to match the observed traffic flows. The system currently collects data from over 600 intersections. This data is managed by seven regional computers that are connected to a central management computer at the RCOC's Traffic Operations Center. In addition to monitoring system operations, the system stores collected information in a database that can be queried for future uses. The system also features automatic traffic signal operations diagnostic capabilities that allow many problems to be repaired remotely.
- **Local Traffic Operations Centers:** As cities are increasingly implementing centralized traffic signal control systems, there are increasing opportunities to collect real-time data on traffic signal control operations and traffic flow conditions around signalized intersections. As an example, the Road Commission for Oakland County (RCOC) has access to more than 600 intersections through its Fast-Trac system. The Road Commission of Macomb County (RCMC) has further access to approximately 175 signalized intersections within the county. The potential for collecting data from individual TOCs will depend on local communication capabilities with traffic detectors and traffic signal control cabinets. The type of traffic signal control used will also affect data availability. Fully actuated systems require for instance traffic detectors to be installed on all legs of an intersection, while semi actuated systems only use detectors on cross streets. The type of data provided by each detector will also depends on whether it is installed with the intent to count vehicle or simply detect vehicle presence.
- **Southeast Michigan Snow and Ice Management (SEMSIM):** SEMSIM is a collaborative project between the Road Commission for Oakland County (RCOC), the Wayne County Department of Public Services, the City of Detroit and the Road Commission of Macomb County. This project sought to equip approximately 500 snow plows/salt trucks with various sensors supporting the operation and management of these trucks. Sensors installed onboard vehicles typically include a GPS tracking device, an air temperature sensor, an infrared pavement temperature sensor, sensors indicating whether the front and underbelly plows are up or down, and sensors monitoring the operation of salt spreading equipment. Collected data is continuously send back to an operation centers using a 900 MHz- radio communication infrastructure operated by the Suburban Mobility Authority for Regional Transportation(SMART).

Periodic, semi-static and static data of potential interest collected by local transportation agencies include:

- **Local Pavement Management Systems (PMS):** Similar to MDOT, many county road commissions and cities maintain a database of pavement-related information for assessing and prioritizing roadway maintenance needs. While differences may exist, collected information will typically cover inventory, construction, traffic, condition, and treatment data similar to what can be found within MDOT's system. Depending on available resources, supporting data collection may be conducted annually, every two to three years, or every five years.
- **Local Roadside Infrastructure Management Systems:** Many cities and local transportation agencies maintain inventories of roadside infrastructures, such as locations of guardrails, traffic signs, traffic signals, bus shelters, or landscaping elements.

4.6.4. Data from Federal Government Agencies

Potential continuous data streams of interest from federal governmental agencies include:

- **Meteorological Assimilation Data Ingest System (MADIS) data:** The National Oceanic and Atmospheric Administration provides through MADIS access to a database containing real-time and archived observational weather datasets. The MADIS meteorological surface dataset includes reports from many observing networks run by different providers. Collected data include basic weather measurements such as temperature, relative humidity, wind, precipitation, as well as various types of weather occurrences such as hail, fog, and thunder. Data is processed in 5-min increments and typically become available two hours after observation.
- **Clarus data:** The Clarus initiative was launched in 2004 by the FHWA Road Weather Management Program in conjunction with the ITS Joint Program Office. This initiative aims to provide weather information support for surface transportation system operators through the deployment of a national weather data collection system complementing NOAA's MADIS data. Its goal is to create a robust data collection and dissemination system that can provide near real-time atmospheric and pavement observations**.** Data for the system is provided by participating agencies, with most of the collected data currently pulled from RWIS stations maintained by state departments of transportation. While Michigan is listed as a contributor, no Michigan data were yet shown on the Clarus website (http://www.clarus-system.com) as of April 2010.

4.6.5. Data from Private Enterprises

The following lists additional sources of streaming data that may be available from private enterprises:

- **INRIX traffic and probe vehicle data:** INRIX is a provider of real-time, historical and predictive traffic information data. Through its Smart Dust Network, INRIX acquires real-time and historical data from hundreds of public and private sources. This includes road occupancy and speed measurements from roadway sensors operated by departments of transportation around the country, as well as vehicle detections from tolling systems. Anonymous probe data is also collected from over one million vehicles within commercial, delivery and taxi fleets. This data is obtained by either communicating with an onboard GPS tracking device or tracking cellular phones carried onboard vehicles. Information about incidents, roads construction, road closures, sports games, entertainment events, school schedules and weather forecasts are also collected and compiled. Real-time traffic flow data is said to be currently available from over 160,000 miles of roads in 126 markets across the United States, Canada, and European countries.

- **Traffic.com data:** NAVTEQ, which operates the Traffic.com website, collects and processes data from various sources to provide real-time traffic information to travelers. While the system heavily relies on data provided by point detectors operated by state departments of transportation, supplemental roadside detectors are installed where additional detection capability is required. These supplemental detectors typically consist of infrared, radar or passive acoustic sensors. In some areas, data from GSP-equipped probe vehicles or cell phone tracking may also be fused with the point detector data to enhance traffic information.

- **TrafficCast data:** TrafficCast is another provider of real-time traffic condition data. In markets served by the company, traffic data is currently primarily obtained from public traffic sensors. However, the company is actively seeking to develop fleets of probe vehicles from which real-time and near real-time speed measurements could be obtained. The company is the exclusive real-time traffic provider for Yahoo Maps and recently signed a contract to provide real-time data to TomTom navigation applications. It is also developing applications enabling cellular phone tracking and testing the use of Bluetooth detection devices to track vehicle movements between fixed detection points.

- **Google Live Traffic:** Google started to display live traffic speed data from major highways on Google Maps in February 2007. The displayed data primarily come from local highway authorities. Google is also tapping into probe vehicle speed measurements it receives from GPS-enabled phones using Google Maps with the My Location feature. Where available, probe vehicle data is used to expand traffic condition monitoring beyond major highways on Google Maps. Spot speed measurements are also directly displayed on Google Earth, as shown in the example of Figure 4-5. As of March 2010, there appeared to be yet relatively few vehicles contributing data to the system.

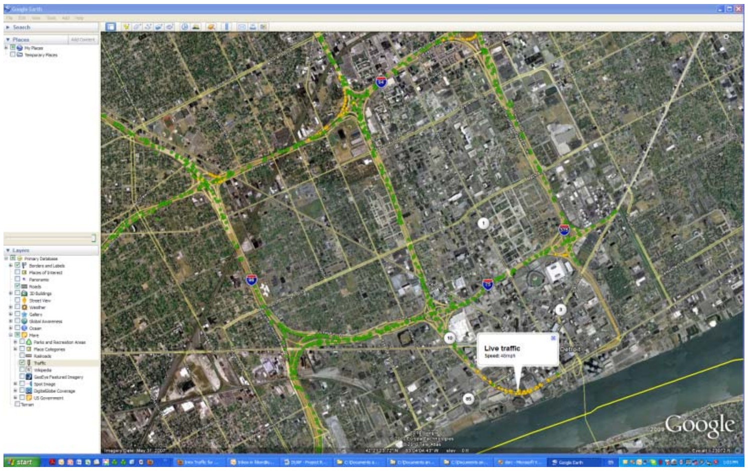


Figure 4-5 – Probe Vehicle Data from Google Live Traffic Data Displayed on Google Earth Map

- **Private Weather Information Networks** – Various enterprises have deployed weather-monitoring stations throughout Michigan, primarily for providing weather information to television stations and websites. Many of these stations can provide up to 1-minute observations of air temperature, relative humidity, wind speed, wind direction, precipitation, and barometric pressure.

A potential issue with the Traffic.com, INRIX, TrafficCast and Google Live Traffic data is the accuracy of some of the measurements. In each case, data collection is primarily executed for supplying traffic condition information to travelers or information subscribers. This results in a focus on speed or travel time data. While roadside detectors installed by these enterprises may provide traffic counts, there are few incentives to ensure the validity of the counts. This has resulted in a certain hesitation by some transportation agencies, including MDOT, to rely on the supplied traffic counts.

4.7. Applications of Interest

MDOT operations cover a wide breath of activities. Figure 4-6, which is adapted from the DUAP concept of operations document produced by Mixon/Hill (Mixon/Hill, 2007a), illustrates the key high-level processes in MDOT operations that were identified by system stakeholders. These processes include:

- **Planning activities**: Activities seeking to identify, develop and select, within available funding and resources, programs and projects aiming to improve the efficiency of the transportation system, enhance access to goods and services, and fulfill travelers’ needs.
- **Design activities**: Activities focusing on the design of transportation projects that have been selected and established through the planning process.
- **Construction activities:** Activities related to the building of projects that have been planned and designed by MDOT or its consultants.
- **Maintenance activities:** Activities conducted to ensure that constructed roadways remain operational within the constraint of available funding and resources.
- **Operations activities:** Activities executed to ensure that roadways and other assets are being properly utilized.
- **Monitoring activities:** Activities conducted to assess how well the road network is operating. This includes evaluations of the condition of roadway pavement, bridge and other infrastructure elements, evaluations of system-wide safety performance, and evaluations of congestion levels.

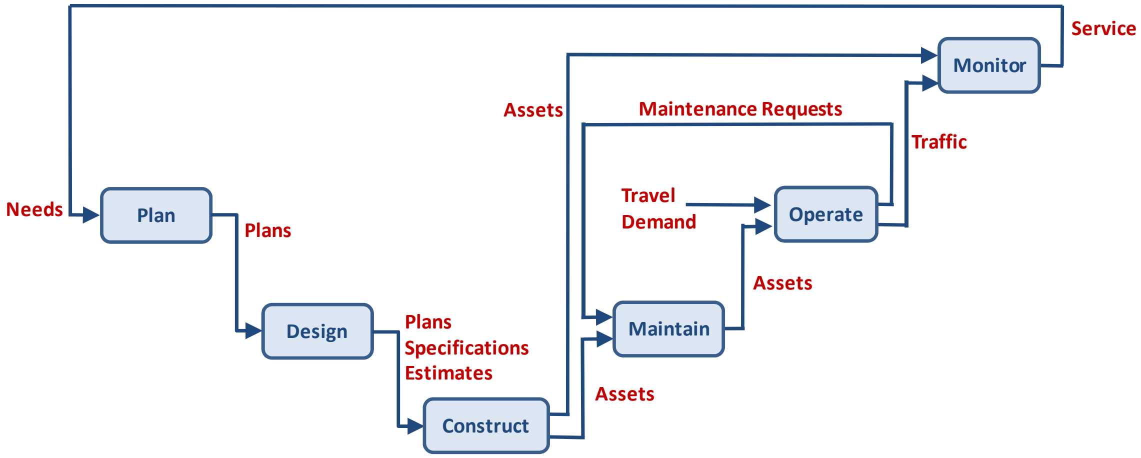


Figure 4-6 – MDOT Key Processes
(Adapted from Mixon/Hill, 2007a)

Table 4-3 – IntelliDrive^{SM} Application Reference Set

No.	APPLICATION	DESCRIPTION	Suitability of Data Collected						
			Embedded Pavement Detectors	Non-intrusive Traffic Detectors	Weather Stations	Automatic Vehicle Identification (AVI) systems	Bluetooth devices	Cellular Phones	IntelliDrive
Network flow monitoring									
1	Traffic flow monitoring	Monitor traffic on freeway and arterials to measure flow efficiency; use of collected data to profile normal and abnormal traffic patterns and bottlenecks; analysis of archived data to identify trends.	PM	PM	NA	PM	PM	FM	FM
2	Detection of unusual congestion	Monitor traffic flow and report abnormal situations and disruptions.	PM	PM	PM	PM	PM	FM	FM
3	Incident detection and response monitoring	Monitor and detect incident formation, duration and clearance intervals, capturing causal factors (via visual data) where possible.	PM	PM	NA	PM	PM	FM	FM
4	Monitoring of traffic around work zones	Evaluate work zone traffic flows and identify differences from planned flow.	PM	PM	NA	PM	PM	FM	FM
5	Monitoring of weather impacts on traffic	Monitor weather conditions and detect impact on road conditions and traffic flows. Report current situation and abnormalities to TOC.	PM	PM	PM	PM	PM	FM	FM
	Detection of icy/snowy/wet roads	Monitor weather conditions and correlate to vehicle data to determine if slippery roads conditions exist; Clarus, SEMSIM and MDSS are example programs.	NA	NA	PM	NA	NA	FM	FM
Network operations									
6	Special event planning and management	Plan and schedule special actions necessary to minimize impact on traffic of special events.	PM	PM	NA	PM	PM	FM	FM
7	Management of arterial / freeway corridors	Optimize traffic flow on freeway and arterial corridors by monitoring flow and adjusting signals and VMS messages as required.	PM	PM	NA	PM	PM	FM	FM
8	Traffic signal operations	Use traffic flow data to assess adequacy of existing signal timing plans and develop new plans when necessary	PM	PM	NA	PM	PM	FM	FM
9	Priority traffic signal phasing to transit and emergency vehicles	Use vehicle presence/tracking data to provide preferential treatment to transit and/or emergency vehicles at signalized intersections.	NA	NA	NA	FM	NA	FM	FM
10	Operation of ramp meters	Use information about gap between vehicles on freeway to optimize the release of entering vehicle from ramps.	PM	PM	NA	NA	NA	FM	FM
11	VMT-based fee collection	Use vehicle tracking data to assess mile-based usage fees along DOT-controlled roads.	NA	NA	NA	PM	NA	FM	FM
12	Toll collection	Use vehicle tracking data to assess and collect tolls from toll roads, toll bridges and high-occupancy toll (HOT) lanes.	NA	NA	NA	FM	NA	FM	FM
13	Congestion pricing	Use vehicle tracking data to assess fees associated with traveling on a congested link or area	NA	NA	NA	FM	NA	FM	FM
14	Evacuation planning and management	Emergency evacuation policies, practices and procedures designed to maximize quick evacuations where needed.	PM	PM	NA	PM	PM	FM	FM
Traveler information services									
15	Management of variable message signs	Management of messages given to the driving public through roadside variable message signs.	PM	PM	PM	PM	PM	FM	FM
	Traffic flow information to websites	Aggregated traffic flow information provided to web servers and 511 services to inform drivers of traffic flow conditions.	PM	PM	PM	PM	PM	FM	FM
System Planning									
16	Estimation of traffic flow patterns	Collect O-D for transportation planning purposes and congestion management optimization applications.	PM	PM	NA	PM	PM	PM	FM
17	Transportation system modeling	Development of models to simulate traffic flows and execute traffic demand studies using collected and archived traffic data to evaluate network system performance and needs.	PM	PM	NA	PM	PM	FM	FM
18	System needs assessment	Use of traffic flow and vehicle data to identify location of recurring bottlenecks and roadways with possible safety issues	PM	PM	NA	PM	PM	FM	FM
19	Air quality assessment	Collect air quality data from vehicles and traffic volume to monitor and assess air quality changes.	PM	PM	PM	PM	PM	PM	PM
Truck/cargor monitoring									
20	Hazardous cargo notification	Monitor and track hazardous material movements through a road network.	NA	NA	NA	PM	NA	NA	FM
21	Commercial vehicle safety Inspection	Monitor heavy truck safety conditions by inspections using non-intrusive wireless technologies.	NA	NA	NA	PM	NA	NA	FM
22	Commercial vehicle electronic weight inspection	Weigh-in-motion roadside equipment to monitor vehicles for excessive axle loading.	NA	NA	NA	PM	NA	NA	FM
Asset Management									
23	Management of salt and snow plow equipment	Salt and snow plow equipment scheduling by monitoring road conditions and deploying appropriately; e.g., MDSS, SEMSIM.	NA	NA	PM	PM	PM	PM	FM
24	DOT Vehicle tracking and work-order management	Track maintenance equipment to manage logistics and use scheduling.	NA	NA	NA	PM	PM	FM	FM
25	Pavement pothole/crack detection and mapping	Monitor and report road surface conditions using vehicle sensing while traversing road network.	NA	NA	NA	NA	NA	NA	FM
26	Bridge deck monitoring	Instrumentation of bridge structutures to monitor loading, stress and deteriotion.	PM	NA	NA	PM	NA	NA	PM
27	Sign inventory	Monitor roadside signage conditions and placement by special vehicle mounted cameras.	NA	NA	NA	NA	NA	NA	NA

FM = Needs fully met
PM = Needs partially met
NA = Needs not met

Table 4-3 provides a more detailed list of activities typically conducted by state departments of transportation. For each application, the table shows how the application's specific data needs can be met by the various sensing technologies surveyed in Table 4-1. Applications of interest to the DUAP program within the table are those envisioned to benefit from the availability of IntelliDrive^{SM} probe vehicle data.

From a conceptual standpoint, probe vehicle data can meet the information requirements of a wide range of applications. While many applications may benefit from the simple provision of vehicle speed and position data returned by GPS devices, others may only benefits if data from specific onboard sensors may only be obtained, such as data from the vehicle's Controller Area Network (CAN) bus. Some applications may further only benefit if information can be collected from a sufficient number of vehicles. For instance, while data from a single or few vehicles may be sufficient to assess whether traffic is experiencing delays on a road segment, applications aiming to use the data to obtain reliable estimates of average travel times and travel time variability may require data from certain minimum number of vehicles to ensure certain statistical accuracy. This requirement converts into a need to reach a certain IntelliDrive^{SM} market penetration level before certain applications may start to benefit from the availability of probe vehicle data.

While there are currently significant discussions on the possibility of using IntelliDrive^{SM} systems to enhance safety within transportation networks, many of the applications being considered, such as intersection collision avoidance and roadway congestion notification, are envisioned as onboard vehicle applications. As indicated in Figure 4-1, the focus of the DUAP program is on processes collecting information from vehicles. Since most of the safety applications currently being developed involve sending information back to vehicles, they are therefore outside the scope of the current project. In Table 4-3, safety goals are primarily considered through surveillance applications seeking to inform system operators of slippery or hazardous road conditions and asset management applications seeking to detect potholes or roadway link defects.

4.8. Potential Operational Constraints

A number of constraining elements may affect the development of IntelliDrive^{SM} applications and the practical benefits that can be obtained from them. Elements often cited as potential constraints are:

- Market penetration level
- Data latency
- Data quality
- Consistency of network coverage
- Data ownership
- Traveler privacy needs

4.8.1. Market Penetration Level

The amount of IntelliDrive^{SM} data coming into the DUAP system will depend on the number of vehicles supplying data, the amount of data collected by each vehicle, and how data is collected from individual vehicles. While these factors can be controlled during the evaluation of proposed applications, only the data collection process will be within the control of MDOT and other public transportation agencies, within certain limits, in real system deployments. While some applications may operate with a limited number of equipped vehicles, such as applications simply attempting to determine whether traffic is flowing at normal speeds along roadway segments, others may require data collection from a certain minimum number of vehicles to produce viable results. An example of the later case would be an application attempting to characterize travel time variability on specific roadway segments. Because of differing data needs, different applications may therefore start to provide benefits only after a specific market penetration is reached.

4.8.2. Data Latency

Within the context of probe vehicle data, latency characterizes the time that elapses between the moment a snapshot is generated and the moment it becomes available for use by applications. When considering the various steps involved in retrieving snapshots from individual vehicles, latency could enter into the data collection process in several ways:

- Time required by vehicles to generate the data (for instance, delays imposed by the interval schedule between snapshots)
- Time required by vehicles to reach a location allowing the data stored in the onboard buffer to be broadcast (for instance, reaching an RSE or getting within range of a cellular phone tower)
- Time required for transferring data from a vehicle to a roadside wireless communication unit
- Time required for transferring data from an initial roadside wireless receptor to an application server (for instance, backhaul data transfer from an RSE to a central server)
- Time required for data validation and preprocessing at an application server
- Time required by an application to extract and process the data stored in the application server

While probe vehicles may provide relatively timely information when compared to other data sources, the collected data may not necessarily be useful for real-time applications. As reported in the USDOT POC test results, probe vehicle data can take between 0.5 s and 1.5 s to travel from a vehicle to a SDN after a communication link has established with an RSE. Since these performance results were obtained for tests mainly involving a single vehicle uploading only probe vehicle data, longer latencies can be anticipated in situations in which RSEs and application servers have to handle large volumes of data transmitted by multiple vehicles. Data usability in real-time applications will then depend on the tolerance of each application. For instance, delays of a few seconds may already be too great for applications implementing collision avoidance or transit signal priority. However, such delays may still be acceptable for congestion management applications.

Another important consideration is the time needed by probe vehicles to come within range of an RSE or other data upload point. The POC tests mentioned above did not consider this important factor. As demonstrated later in the report (Section 6.8), the need for probe vehicles to come within range of an RSE before could impose additional delays in data collection ranging from several seconds to a few minutes, depending on the density of RSEs in the network under consideration and the protocols governing vehicle-RSE interactions. While the use of cellular phones or other technology offering ubiquitous communication coverage could significantly reduce these delays, it would not eliminate them as transmission delays of a few seconds could still be expected.

The potential for non-negligible delays in collecting probe vehicle data creates a need to evaluate carefully the sensitivity of each application to data latency and the suitability of each data element to each application. Probe data exhibiting too great latency should for instance not be used by real-time applications. Considerations must also be made of the fact that data from different areas of a network may arrive at an application server with different latencies. The need to reduce latency may further push for the use of specific communication technologies or system architectures to support real-time applications. An example may be to implement transit signal priority or intersection collision avoidance applications in a signal controller cabinet rather than at a central application server. Another example may to use cellular phones to collect probe data simply used for characterizing traffic conditions on roadways, but use DSRC to collect data supporting intersection collision avoidance or transit signal priority applications.

4.8.3. Data Quality

IntelliDrive^{SM} systems are likely to be deployed gradually over time. In early deployments, most of the data collected may still come from traditional sensing technologies. As time passes, a greater proportion of data would come from probe vehicles. This means that is likely that a range of sensing technologies may be used at any given time to collect data supporting various applications for the near future. Over time, sensors installed on probe vehicles may also lose their calibration and start to provide inaccurate information. Sensors exposed to ambient air may also become dirty or damage.

Since all sensing technologies and collected data will not necessarily share the same accuracy or reliability, a need exists to develop measures for quantifying the quality of information collected and for vehicles or application servers to assess the quality of collected data. A need also exists to develop processes allowing data exhibiting different precision, reliability or latency or aggregated.

4.8.4. Consistency of Network Coverage

Variations will likely exist in the amount and quality of probe vehicle data collected from various parts of a transportation network. For instance, it is widely anticipated that more RSEs will be deployed in urban areas than rural areas. This will result in much lower densities of RSEs in rural areas than urban areas. Snapshots collected in rural area may consequently exhibit significantly higher average latencies than snapshots collected in urban networks with dense RSE coverage. Even if data could be retrieved using cellular communication, slightly more time may be needed for data collected from rural areas to reach an application server than data collected in urban networks due to the potential need to transport the data over greater distances.

Consistency of network coverage may also be affected by socio-demographic factors, particularly in early IntelliDrive^{SM} deployment stages. Households with higher income or businesses with fleets of vehicles are likely to be early purchasers of vehicles with IntelliDrive^{SM} communication capabilities or after-market devices enabling such capabilities to be added to existing vehicles. This may result in early system deployments in higher concentration of probe vehicles in neighborhood with higher median income levels and industrial and commercial areas with significant truck fleet activities. It may lead to more data being initially collected from these areas and in an ability to deploy applications or obtain benefits from existing applications more quickly from these areas.

4.8.5. Data Ownership

The question of ownership of comingled data may become an issue. MDOT and its partner transportation agencies currently subscribe to selected traffic, vehicle location, and weather information services that are likely to be blended into the DUAP data streams. While the bulk of the data is eventually expected to come from IntelliDrive^{SM} data streams, other data sources may be used to expand and validate data collected by IntelliDrive^{SM} systems for the near future. Limitations on the use or redistribution of data from these third-party sources could hamper the usefulness of the DUAP system and will need to be considered when developing data uses agreements with data providers.

4.8.6. Traveler Privacy Needs

An area of significant concern from the traveling public regarding the collection of probe vehicle data is a fear that the collected information will be used to track their movements. While various traffic surveillance systems already use vehicle tracking to obtain information about traffic conditions on specific roads, the collected data is usually anonymized, i.e., processed in such a way that there is no capability to associate the collected data with a particular vehicle or driver outside authorized data users.

A similar approach is adopted with IntelliDrive^{SM} data collection systems. As outlined in Section 2.5, instead of using vehicle identification numbers, the snapshots generated by each vehicle are tagged with a temporary identification number (the PSN) that theoretically only allow tracking for 3280 ft (1000 m) or 120 s. However, as is demonstrated in Section 6.6, various factors may reduce the distance over which a vehicle can effectively be tracked. This may create situations in which relatively few vehicle tracks of usable length may be obtained, and thus limit the development of applications relying on such information, such as applications seeking to estimate turning proportions at intersections.

Another issue, particularly in early system deployments, is the potential to reconstruct vehicle tracks from collected snapshots. In the simplest case, collected snapshots with different PSNs could be uniquely correlated to a particular vehicle if this vehicle is the only one generating snapshots at a particular time. While this may not be an issue in later deployment stages, when significant proportion of vehicles have started to provide probe data, it could be in early system deployments. The perception by early probe vehicle participants that their privacy may not adequately be protected could have negative impacts on system acceptance and create delays in reaching market penetration levels allowing full benefits to be obtained from deployed data collection systems and applications.

4.9. Evaluation Approach

To fully evaluate and test applications using field data, an operational IntelliDrive^{SM} system must be available. Such a system requires the five following major components:

- Road network equipped with DSRC RSEs
- Vehicles equipped with OBEs
- Availability of probe data generation software in vehicles
- Algorithms for extracting relevant information from collected probe data
- A database storing collected information on a link-by-link basis, as well as a time basis

The initial plan for the DUAP evaluations was to use probe data collected during the USDOT POC test program to evaluate and test applications of interest to MDOT. However, as outlined in Section 1.3, changes in the POC test program resulted in partial application design and in the collection of significantly less data than expected. The lack of field data prevented the evaluation of application. To bypass this problem, a decision was then made to use UMTRI's Paramics virtual IntelliDrive^{SM} probe vehicle data generator as a substitute for field data. This generator, which had been developed by UMTRI under a separate research program, featured a modeling of the road network covering the USDOT POC test bed and of the 57 RSEs that were tested during the POC program. Its use allowed evaluating data collection capabilities and uses in a range of situation that could not be considered with actual POC field data.

While the adopted approach allows synthetic probe vehicle data to be used to evaluate potential data uses, it does not provide a mechanism to replicate real on-board vehicle sensor data that would be provided through CAN network. This results in an inability to replicate on-board sensor status data, such as information monitoring lights, wipers, ABS activation, etc. While these limitations are notable, they are not required by all applications of interest to MDOT. A majority of applications only requires vehicle position and speed data. This information, together with brake application, can readily be collected from traffic simulations.

Applications focusing on adverse weather management and the monitoring of pavement and bridge conditions are currently seen as the only major applications of interest to MDOT specifically requiring data from on-board vehicle sensors. At the time the report was written, these applications were already subject of separate field evaluations that could provide operational and evaluation data compensating for the limitations of UMTRI's virtual probe vehicle data generator.

4.10. Summary of Evaluations Reported in Subsequent Chapters

The remainder of this report is organized around the following nine sections:

- **Section 5:** Describes the Paramics IntelliDrive^{SM} Probe Vehicle Data Generator that was used to enable the evaluation of probe vehicle data uses over conditions not currently covered by existing test bed data.
- **Section 6:** Examines the effects of snapshot generation protocols and privacy policies on data latency, data quality, and the ability to track vehicles over effective distances.
- **Section 7:** Maps application data needs and describes general data processes that may be required to convert raw probe vehicle data into information usable by individual applications.
- **Section 8:** Evaluates whether or how flow rates, density, speed profiles, average travel times, delays, number of stops, queue parameters, turn percentages, vehicle classification, and vehicle occupancy could be estimated from collected probe vehicle data.
- **Section 9:** Develops a concept of operations for an enhanced traffic monitoring system integrating probe vehicle data collection to other data sources.
- **Section 10:** Investigates various issues that should be considered when selecting which applications to deploy and when developing application deployment plans.
- **Section 11:** Provides a summary of the primary findings of the projects and some recommendations for future work.
- **Section 12:** Provides general lessons learned regarding the collection and use of IntelliDrive^{SM} data.
- **Section 13:** Provides recommendations for future work to promote the development and deployment of IntelliDrive^{SM} applications of interest to public transportation agencies.

5. IntelliDrive^{SM} Probe Vehicle Data Generator

This chapter provides a description of the IntelliDrive^{SM} probe vehicle data simulator that was used to complement data collection activities from the USDOT POC test program and conduct operational data processing analyses that could not be executed through the sole processing of the USDOT POC data.

UMTRI's Probe Vehicle Data Generator is a collection of data processing functions that have been embedded within the Paramics microscopic traffic simulator (version 6.6) though its Application Programming Interface (API) [Quadstone Paramics Ltd, 2009]. These functions have been added with the intent to replicate the snapshot generation and vehicle-RSE interactions protocols implemented in the USDOT's Michigan POC test bed. Although some modifications to the simulator were made as part of the DUAP project, the majority of its development was executed as part of other research projects. Most of the functionalities described in this chapter were developed as part of an UMTRI research effort that was initiated in 2007, with collaboration from Western Michigan University. Some functionalities were further developed as part of an on-going National Science Foundation project that was initiated in 2008 to explore data latency issues surrounding safety applications relying on vehicle-to-vehicle communication [Dion, Yu and Biswas, 2009]. Additional developments can finally be credited to a MDOT project executed in 2008 and 2009 aiming to assess the benefits of including origin-destination data in VII data sets [Dion, Robinson and Morang, 2009].

The following sections describe the need for using the simulator, the Paramics road network that was used to conduct the evaluations, and a description of the traffic flow demand that was simulated to replicate typical weekday morning peak traffic across the modeled road network. This is followed by a description of the various probe vehicle data processing and vehicle-RSE interaction protocols that were implemented in the simulator to replicate the IntelliDrive^{SM} probe vehicle data processes defined in the SAE J2735 standard and implemented in the USDOT POC test bed. The last portion of the chapter finally describes dynamic routing, incident rerouting, and link flow projection functionalities that have been developed as part of other projects and that could be used to model various IntelliDrive^{SM} applications.

5.1. Need for Probe Vehicle Data Generator

The initial intent of the DUAP project was to develop prototype applications and data management software using preliminary probe vehicle data that were to be obtained through the USDOT Michigan VII POC test program. Unfortunately, while this program produced some data, it did not produce data in sufficient quantities to evaluate uses probe vehicle data uses. While the initial POC test program aimed to evaluate data collection capabilities across a range of applications, this goal was significantly modified due to technical issues. Instead of collecting probe vehicle data over a period of three months, data was collected only over a period of two and a half weeks, as shown earlier in Table 3-1. This resulted in partial application designs and in data collection activities focusing primarily on the ability for vehicles to establish communication with RSEs and to upload successfully the snapshots they have generated.

While the POC test programs generated over 100,000 snapshots, most of these were from probe vehicles traveling in isolation. At most two vehicles were communicating with an RSE at any given time. While the collected snapshots could be used to assess the capability to track individual vehicles over certain distances and calculate vehicle-specific trip parameters, there were no capability provided for characterizing traffic streams. For instance, while the collected data allowed tracking the progression of a vehicle across a given road segment, it did not allow estimating the link's traffic volume, flow rate, traffic density, or travel time variability.

To address the above limitations, the project team assessed whether other data sources could be tapped. The only source deemed to have the potential of providing usable data at the time was the fleet of 1500 probe vehicles operated by Chrysler as part of its Fast Feedback project. Vehicles within this fleet were used by Chrysler to help identify vehicle problems before the public release of new models and had the capability to report position and diagnostic data in real time. MDOT had already negotiated access to the data for the portion of the DUAP project being executed by Mixon/Hill. Unfortunately, proprietary constraints placed on the data by Chrysler significantly limited its usability for the current evaluations. This resulted in the use of the data not being pursued further.

Another potential source of probe vehicle data was from MDOT's own fleet of probe vehicles (see project description in Section 4.6.1). The probe vehicles were expected to capture data characterizing their movements while traveling. Since the vehicles would have been driving in isolation from each other, the collected data would have at least allow evaluating applications relying on data collected by specific vehicles, such as the use of a service vehicle to survey pavement condition and detect potholes or slippery conditions. Similar to the POC data, there would still have been no capability to evaluate how probe vehicle data could be used to characterize average traffic flow characteristics other than speed or travel time. Unfortunately, this data was only expected to start streaming in 2010 and was therefore not available when the DUAP evaluations were conducted.

In the above context, the use of a virtual probe data simulator appeared as the only viable solution to compensate for the limited amount of available field data. The primary benefit was allow evaluations of data collection processes and uses in situations and environments that could not be considered by existing test beds and test vehicle fleets. Specific advantages offered by the use of simulation models to conduct evaluations included:

- **Ability to consider alternate system configurations.** Field operational tests are developed to test a specific configuration of hardware and software devices. Once in place, the configuration is difficult or costly to modify to evaluate alternative configurations and processes. For example, after a specific piece of equipment has been installed, such as an RSE, moving this equipment to a new location often requires significant cost and time. Within a simulation environment, instrumentation can easily be moved around. This allows exploring relatively quickly and at low cost the use of alternate system components, methods and data processes. In turn, this capability allows for the rapid execution of optimization and performance quantification analyses that is not possible with fixed, physical system configurations.
- **Ability to consider large fleets of vehicles.** Contrary to field tests, inserting vehicles with specific instrumentation in a simulation environment typically only involves changing a few lines of codes. This easily allows expanding the number of probe vehicles or changing the instrumentation that vehicles are assumed to carry to meet the needs of specific analyses. Simulation further offers the ability to explore data processes and data uses in scenarios involving several thousands of vehicles. Field operational tests are still years away from having similar evaluation capability.
- **Ability to control the movement and placement of individual vehicles.** In field operational tests, the need to place vehicles at a specific location at a given time creates significant operational challenges, particularly if there are only a finite number of test vehicles. The time, and logistics needed to create a specific situation often limits the type of tests that can be executed or the number of times a specific test may be replicated. A simulation model allows instantaneously resetting vehicle placements. Simulation model users further have significant

flexibility to insert vehicles at specific locations for the purpose of creating or re-creating specific situations. This allows evaluating of scenarios that may be difficult to replicate in reality or exploring fully the stochastic effects associated with specific applications or scenarios.

- **Ability to consider scenarios that can potentially put the safety of travelers at risk**. Field operational tests cannot consider tests that may put the safety of vehicles at risk, particularly if tests are executed on public roads. A simulation model allows evaluations in potentially risky and dangerous situations. For instance, a simulation model can be used to preliminary test an algorithm for collision avoidance. Wrong recommendations from the algorithm would only cause virtual crashes. In this case, the simulation model could be used to refine the algorithm before attempting testing it in real-world settings.

While simulation models are never expected to replicate the full complexity of real-world systems, they can provide very reasonable approximations. Simulation models thus offer the opportunity to conduct preliminary application evaluations before committing to the development of real-world prototypes and initiating field operational tests. The use of simulation models thus offers opportunities to identify design flaws and refine proposed algorithms at an early application or system design stage, when the cost of initiating modifications remain relatively low.

5.2. Test Road Network

To complement evaluation activities from the USDOT VII POC test program, an effort began in late 2007 to create a Paramics simulation of the USDOT test bed. To facilitate comparisons between simulation and field test data, the objective was to code the primary road network near Detroit, Michigan, within which POC test activities were planned.

The network that has been developed is shown in Figure 5-1. The circles shown in the figure represent the location of the 57 RSEs that have been modeled. These RSEs are placed at the same locations as actual field equipment. When developing this network, efforts were made to ensure that all geometric roadway features have been adequately coded. Validation of roadway elements was done through

Figure 5-1 – Paramics Modeling of the USDOT IntelliDrive^{SM} Test Bed in Michigan

occasional drive-bys and by using the Google Map Street View application. This application was found to be particularly useful for determining posted speed limits and verifying lane markings. Where available, traffic signal timing data were also determined from actual signal timing plan provided by the Road Commission for Oakland County and manual signal observations.

5.3. Traffic Demand Modeling

To enable the evaluation IntelliDrive^{SM} applications using realistic traffic demand scenarios, a traffic demand model was developed to replicate the traffic flows that are typically observed during a weekday morning peak travel period. While efforts were made to develop simulated flow patterns that would be representative of observed patterns across the modeled area, no extensive calibration was conducted to ensure that a close match with reality was achieved. The rationale for this decision is based on the recognition that the IntelliDrive^{SM} simulator was not aiming to assess network performance but how IntelliDrive^{SM} applications may operate in situations that can be expected to occur in reality. Spending significant time to calibrate the simulation model to the actual traffic demand would therefore only yield limited practical benefits. However, even without extensive calibration, experimentations with the model have shown that congestion tend to occur in the same areas as in the real network, thus providing a certain degree of validation.

Paramics simulates traffic within a network using origin-destination flow matrices. Difference matrices can be used to reflect the differing movements of various vehicle types (for instance, passenger cars and trucks), as well as to model time-based changes in traffic patterns. Vehicles entering the network from a given zone are randomly assigned a destination zone based on target flow rates toward each destination listed in the matrix. Between the origin and the destination, vehicles determine their path based on a user-defined cost function considering travel distance, travel time and out-of-pocket expenses (for instance, tolls). For this project, a cost function emphasizing travel time was being used. However, a small weight was also assigned to the travel distance to avoid situations in which vehicles would choose a much longer route just to save a few seconds.

Figure 5-2 – Origin-Destination Zone Modeling

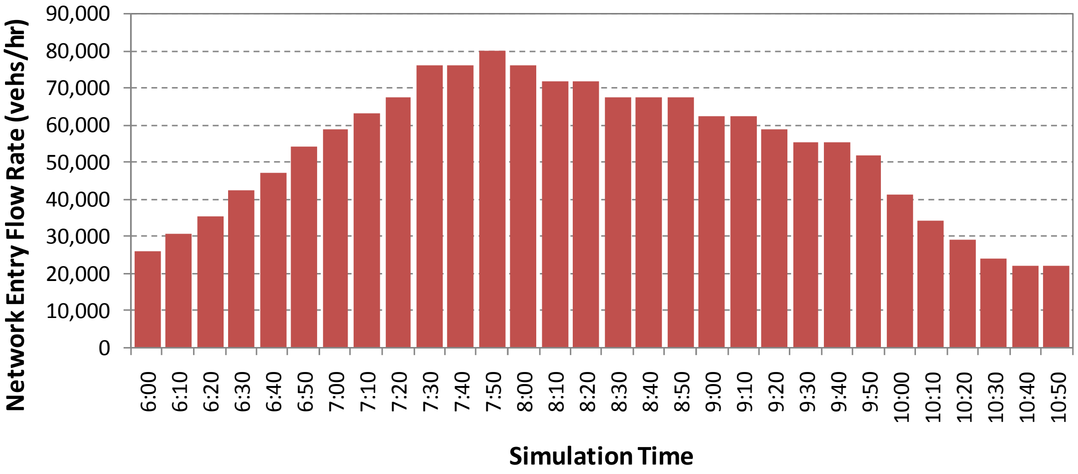


Figure 5-3 – Modeled Time-Dependent Traffic Demand

Figure 5-2 illustrates the zone system that was developed. The zones are the boxes shown in light color between the roadways. Based on the need to model traffic entering and exiting streets midway between two intersections, the preference was to use small traffic generation zones reflecting local land uses rather than large zones. This resulted in the modeling of 189 origin and destination zones and the need to define a 189x189 origin-destination matrices.

Figure 5-3 presents a profile of the resulting traffic demand modeling. The figure illustrates the equivalent hourly rate at which vehicles are inserted into the network for each 10-minute interval between 6:00 and 11:00 a.m. From 6:00 to 8:00 a.m., the demand gradually increases to simulate the buildup of traffic that typically occurs in the early part of the morning. After reaching a peak around 8:00 a.m., the demand then gradually reduces between 8:00 and 10:00a.m., before starting to level off at a mid-morning minimum flow rate around 10:30 a.m.

Within the illustrated five-hour period, origin-destination matrices were developed for each simulation hour (for instance, for 6:00 to 7:00, 7:00 to 8:00, etc.). This was done to better capture time-dependent effects in traffic flow demand. While the resulting matrices only allow origin-destination flow patterns to change once every hour, Paramics allows the rate at which vehicles are released along each origin-destination pair to vary across a series of shorter time intervals. This allows modeling the gradual increases and decreases observed in the profile of Figure 5-3.

The development of the origin-destination matrices was executed using the Paramics Estimator module. This module develops a matrix by gradually altering the flows assigned to each pair of origin and destination zones to allow the simulated flows on individual links to match observed link flows rates defined in a separate input file. In this case, the matrices were adjusted to reflect data from 400 intersection vehicle counts that had been conducted by the Southeast Michigan Council of Governments (SEMCOG) between 2000 and 2009. Adjustments were made to minimize the square root error between observed and simulated flows. Following completion of the calculations by the Estimator module, manual adjustments were then made to the calculated origin-destination flows to prevent unrealistic flows from being assigned to zones for which such flows would not exist or to correct obviously erroneous flow assignments.

Within Paramics each vehicle type can accelerate or decelerate according to vehicle-specific parameters. This allows considering the specific behavior of passenger cars, buses, and trucks. Since the flow counts used for demand modeling did not contain information about traffic flow composition, a single origin-destination matrix covering all vehicle types was generated for each one-hour period. Paramics was then instructed to generate specific proportions of cars, trucks, and buses along each origin-destination pair based on a fixed distribution of vehicles. In this project, all simulations assume that traffic is composed of 95% passenger cars and small delivery trucks, and 5% larger trucks and buses.

Traffic flow is finally simulated with a 5-min information feedback loop. Every 5 min, Paramics recalculates the travel cost associated with each roadway link based on a weighted average of the travel time experienced by vehicles that have traveled across the link within the past 5 min. These updated costs are then used to calculate the route that vehicles entering the network should follow. Although the option is available, vehicles already within the network do not have their projected route recalculated. This information feedback loop was introduced to allow Paramics to adjust flow assignments based on congestion and to replicate the learning process of regular commuters.

5.4. IntelliDrive^{SM} System Modeling

IntelliDrive^{SM} functionalities were introduced within Paramics using the software's Application Programming Interface (API). This interface provides a library of pre-defined C-language functions that enable model users to query or set various parameters during the course of a simulation, add model functionalities, and even replace default driver behavioral models.

Figure 5-4 illustrates the architecture of the IntelliDrive^{SM} Probe Vehicle Data Generator. In developing the simulation model, attempts were made to replicate as closely as possible the data generation and collection activities that would occur in real-world systems. As indicated in Figure 5-5 and Figure 5-6, efforts were made to develop IntelliDrive^{SM} functionalities in the simulation objects that would most

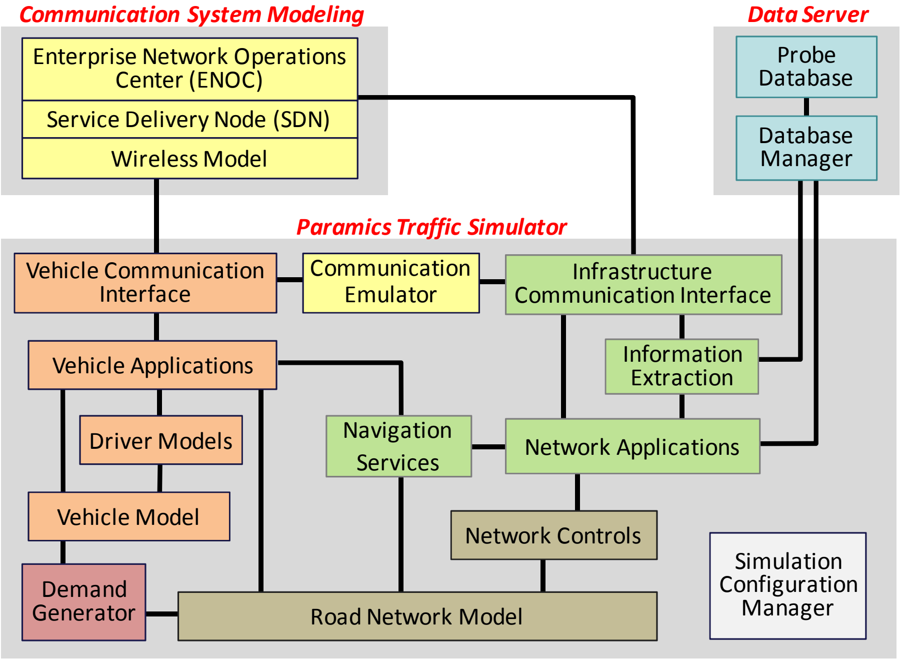


Figure 5-4 – Architecture of IntelliDrive^{SM} Probe Vehicle Data Generator

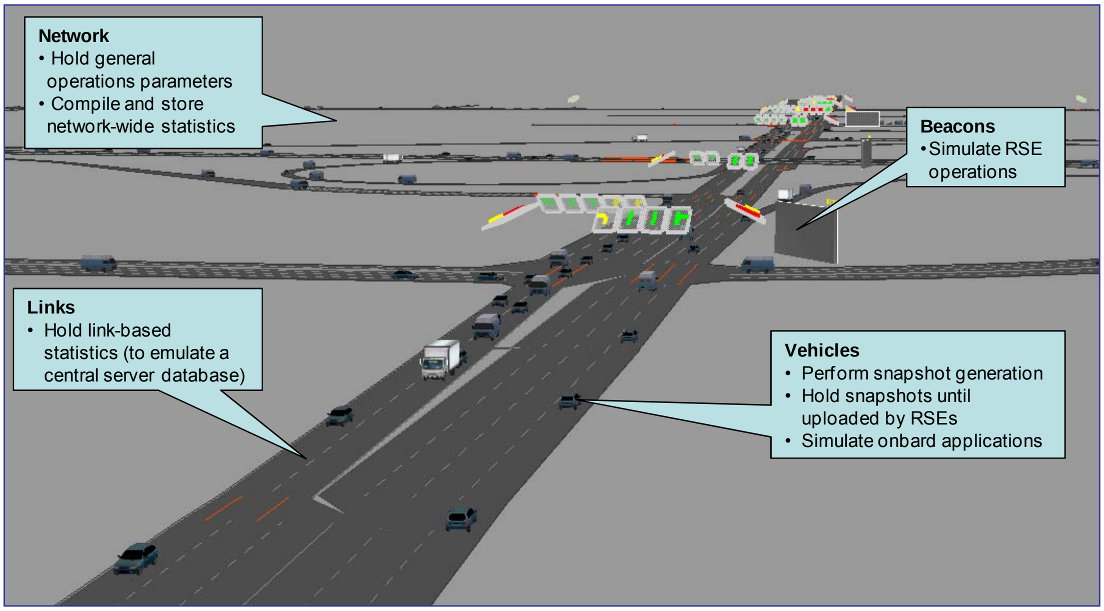


Figure 5-5 – IntelliDrive^{SM} System Modeling Approach

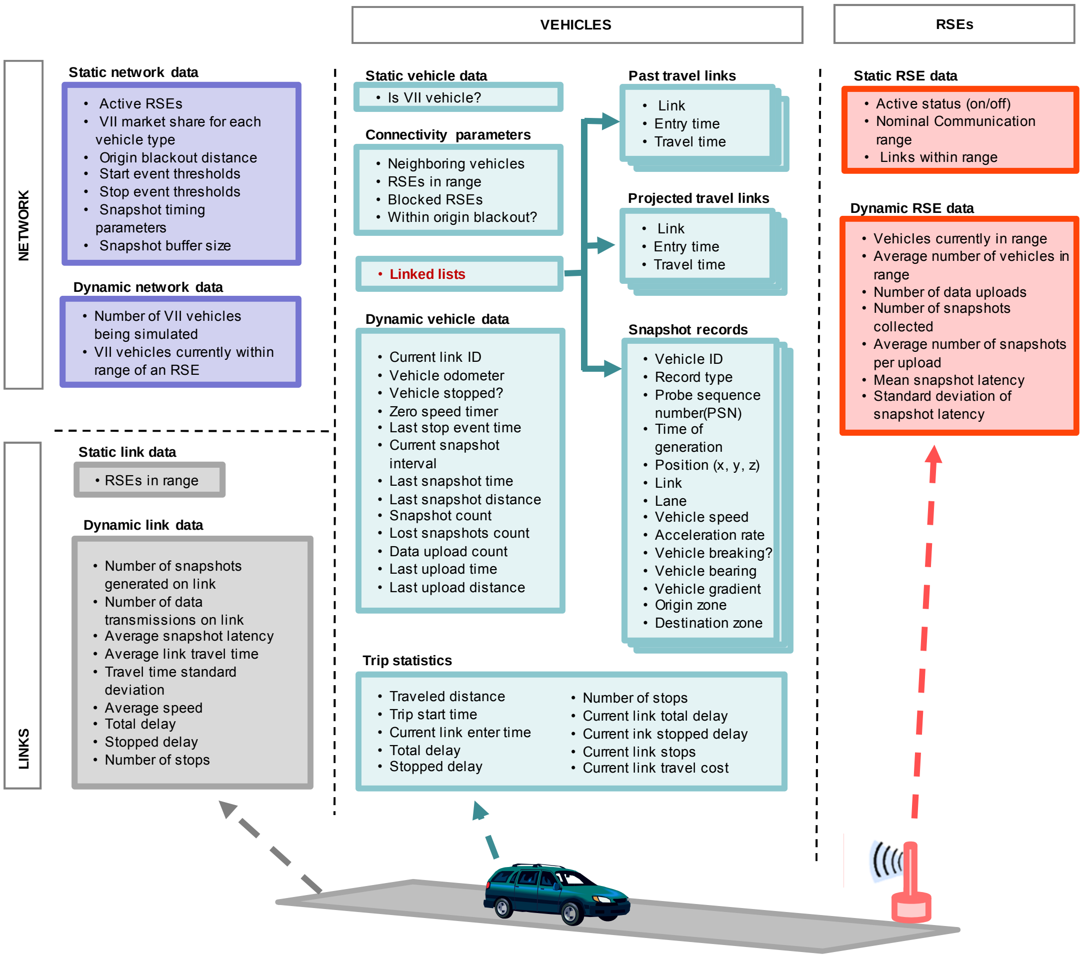


Figure 5-6 – Modeled IntelliDrive^{SM} Data Elements likely host them in real systems. For instance, functions and data that would reside onboard vehicles were coded within Paramics vehicles. Links and nodes were used to emulate functions that would be implemented in link-based and node-based databases. RSE were finally modeled using Variable Message Signs Beacons, while functions hosted at a central application server were modeled within the general road network framework.

The following sections describe in more detail the major modeling elements that were developed to support the simulation and evaluation of IntelliDrive^{SM} systems.

5.4.1. RSE Modeling

To facilitate portability to other Paramics networks, Variable Message Sign Beacon objects were used as RSE emulators. Within Paramics, Beacons are predefined objects representing points along roadways where information can be delivered to drivers. By default, they are graphical representations with no functionalities. Model users must define their use through the development of API functions. The only exception is when Beacons are associated to parking lots. In this case, they are automatically assumed to inform drivers of the number of available parking spaces in the associated lot.

One constraint in the use of Beacons as RSE emulators is that these objects can only be positioned along roadways. However, this is not viewed as a major difficulty for the modeling of IntelliDrive^{SM} systems, as real-world RSEs will likely be installed within 25 ft of the side of a roadway.

Static parameters held by each RSE include a flag indicating whether it is active, a nominal communication range, and a list of links from which communication is possible. Dynamic parameters characterizing system performance, such as the number of vehicles currently within range, the number of data transmissions executed since the start of the current data collection interval, the number of collected snapshots from passing vehicles, and statistics quantifying the latency of collected data.

As illustrates in Figure 5-7, the nominal communication range of each RSE is determined using a simple distance radius criterion. It is currently assumed that all probe vehicles present within the defined radius are able to communicate with the RSE. Future model revisions will attempt to modulate communication capability with signal strength and other communication parameters.

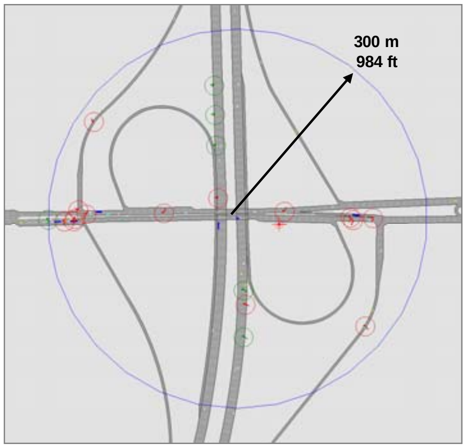


Figure 5-7 – RSE Communication Range Modeling

To allow RSEs to interrogate only vehicles on links from which communication is possible and speed the simulation process, each RSE holds a list of links with which communication is possible. This list is determined prior to the start of a simulation. For each RSE it is determined by calculating the distance from the RSE to each 1-m segment of all links in the network. Any link that has at least one segment within range of the RSE is included in the list, unless indicated otherwise by other criteria.

Snapshot latency is finally determined by compiling the average interval between the moment a snapshot is generated and the moment it is uploaded by the RSE. The primary rationale for compiling data latency is to assess the ability of IntelliDrive^{SM} data collection systems to fulfill the needs of real-time applications, particularly safety applications that may have very little tolerance for small delays in data reception. While RSEs are currently not assumed to impose any further delay on data collection, such as local data processing delay or communication delay with a Service Delivery Node (SDN), plans are currently being made to address these possibilities in future model developments.

5.4.2. Link Parameters

Each link maintains a static list of RSEs that are within communication range. Any RSE for which communication is possible from any portion of the link is included in the list. If a vehicle can communication with more than one RSE from a given location, the closest RSE is by default designated as the one with which communication should be established. This may eventually be revised to reflect signal strength or other communication factors. Despite this simplification, the current modeling is considered adequate for evaluations focusing on snapshot data uses by IntelliDrive^{SM} applications. A more refined modeling would primarily only affect the RSE used to route information to a server and the resulting snapshot latency.

To emulate functionalities that would be provided by a database hosted in a central server, links are further programmed to compile and store various performance statistics. This includes statistics about the number of snapshots generated by vehicles while traveling on the link, the number of data transmissions, the average latency of snapshots generated on the link, and link travel statistics for both IntelliDrive^{SM} and regular vehicles. Travel time statistics for regular vehicles are recorded mainly for comparison and quality control evaluations. The compiled link travel statistics include average travel time, travel time standard deviation, average speed, total delay, stopped delay, and number of stops. These statistics are maintained for both the current user-defined data aggregation interval (typically 5-15 minutes) and the past 12 intervals.

5.4.3. Network Parameters

Parameters stored at the network level primarily include configuration data. Static parameters include a list of active RSEs, the IntelliDrive^{SM} market penetration for each type of vehicle, the distance a vehicle must travel from its origin before snapshot generation is first allowed, parameters defining stop/ start events, and parameters configuring the calculation of intervals between snapshots. Dynamic parameters further include statistics about the number of IntelliDrive^{SM} vehicles currently simulated, and the number of vehicles within RSE range. Similar to link data, dynamic parameters are stored for both the current and past 12 user-defined data aggregation intervals.

5.4.4. Vehicle Parameters

Paramics allows up to 128 vehicle types to be simulated, each with its own weight, length, and acceleration and deceleration characteristics. These characteristics are set when each vehicle is generated. They remain constant until the vehicle reaches its destination. To enable the exploration of market penetration effects, functionalities have been developed to allow the model user to specify the proportion of vehicles within each type that are to be considered as IntelliDrive^{SM} vehicles. This parameter is set by the user in an input file described later in this chapter. Each time a new vehicle is generated, a random process is then used to assign an IntelliDrive^{SM} status (IntelliDrive^{SM} or not) to the new vehicle based on the declared market penetration level for the specified vehicle type.

Replicating what would happen in real-world systems, vehicles hold all the snapshots they generate in a memory buffer until these are transmitted to an RSE. To facilitate the insertion and removal of elements stored within the buffer, as well as remove the need for creating arrays of predefined sizes, a linked list is used to model data storage within the buffer. Each time a new snapshot is added, it is fitted with a pointer to the previous and next element in the list. This approach allows sequential scans of all elements in a list starting from either the top or bottom. A cursor function is also provided to retain the location of the last element accessed within the list.

The dynamic data held by vehicles primarily includes parameters used to manage the generation of snapshots, assess vehicle-specific snapshot generation and transmission activities, and compile trip statistics. Snapshot generation parameters include the following vehicle status flags and timers:

- Is the vehicle stopped?
- Timer indicating how the vehicle has been immobilized (zero speed timer)
- Last stop event time
- Current snapshot interval
- Last snapshot time
- Last snapshot distance
- Last upload time
- Last upload distance

Performance statistics recorded by individual vehicles include parameters quantifying the number of snapshots generated and number of snapshots uploaded from the vehicle during its travel across the network. Trip statistics include parameters commonly used to assess network mobility, such as trip start time, traveled distance, incurred total delay, stopped delay, and number of stops made. These statistics are compiled for both the current link being traveled and the entire trip.

For evaluation purposes, a traveled link buffer is also modeled. This buffer holds information about the successive links a vehicle has traveled. Similar to the snapshot buffer, a linked list is used to hold the data. A new record containing the following information is generated each time a vehicle exits a link:

- Identification of link traveled
- Time of link entry
- Type of link exit (signalized intersection, unsignalized intersection, freeway ramp)
- Turn movement executed at end of link
- Link travel time
- Link travel distance
- Link travel cost
- Incurred total delay
- Incurred stopped delay
- Number of stops made

These records are used to generate optional link entry snapshots. If this option is specified, each time a vehicle comes within range of an RSE, the traveled link buffer is scanned and new snapshots are generated for each link for which a snapshot had not been generated previously.

To support dynamic routing applications, a projected link buffer is finally modeled. Instead of containing information about links that have been traveled on, this buffer contains information about links a vehicle is expected to travel on to reach its destination. This information is determined by using the routing application functions described in Section 5.4.

5.4.5. Snapshot Data

Table 5-1 lists the data currently recorded within individual snapshots. Efforts were made to include all the parameters listed in the SAE J2735 dataset standard that could be produced by the simulation model [SAE International, 2006, 2008]. As shown in Figure 5-8, this results in a good coverage of positioning data. However, very few vehicle status data can be captured, as simulation models typically offer little opportunities to measure such parameters.

While only periodic (type 1), start event (type 3), and stop event (type 4) snapshots are defined in current protocols, the additional snapshot types listed in Table 5-1 were defined to provide a wider range of analysis capabilities. This includes the ability to:

- Continue generating periodic snapshots when a vehicle is stopped (Type 2)
- Generate “link entry” and “decision point entry” event snapshots (types 5, 6, and 7)
- Generate “trip start” and “trip end” event snapshots (types 7 and 8)

A “link entry” snapshot marks the entrance of a vehicle on a link at a node where there is only one possible exit. These are nodes typically used for marking a change in geometry. On the other hand, “decision point entry” snapshot marks the entrance on a link from a node that can be accessed from multiple links or offering multiple exit choices, such intersections or freeway off-ramps. To account for the specific network modeling approach adopted by Paramics, a Type 7 snapshot type is defined to identify vehicles entering a link midblock from a freeway on-ramp.

While also not specified in the SAE J2735 standard, information regarding the link, position along the link, travel lane, intended turn movement, and origin and destination zones were added to the recorded snapshot data to expand the simulation model’s analysis capabilities. These elements represent data that could be obtained with existing systems. For instance, information about the link on which a vehicle is located could be obtained if mapping software is used to locate vehicles on a network based on GPS measurements. While not commonly available from existing mapping software,

Position Data
☒ Time
☒ Date
☒ Latitude
☒ Longitude
☒ Elevation
☒ Heading
☒ Speed

Vehicle Status Data
☐ Air temperature
☐ Vehicle exterior lights
☐ Rain sensor
☐ Sun sensor
☐ Traction control
☐ Stability control
☐ Anti-lock brakes
☐ Vertical acceleration
☒ Brake applied
☐ Steering wheel angle
☒ Longitudinal acceleration
☐ Lateral acceleration
☐ Yaw rate
☐ 100% brake boost applied
☐ Barometric pressure
☐ Tire pressure
☐ Tire pressure monitoring system
☐ Wiper status

Figure 5-8 – Simulated J2735 IntelliDrive^{SM} Data

Table 5-1 – Snapshot Generator Data Items

Data Item	Description
Type of snapshot	Type 1 = Periodic snapshot Type 2 = Periodic snapshot when vehicle is stopped (optional) Type 3 = Stop event Type 4 = Start event Type 5 = Link entry event (optional) Type 6 = Decision point event (optional) – Link entry event at nodes with more than one exist (intersections, freeway off ramps) Type 7 = Freeway on ramp (optional) – Link entry mid-block of a link Type 8 = Trip start (optional) Type 9 = Trip end (optional)
Time snapshot was generated	Time when snapshot was generated, expressed both in hh:mm:ss.dd format and number of seconds from midnight corresponding to the simulation time
Vehicle's odometer reading	Vehicle's internal odometer reading, in m or ft depending on units selected
Position of vehicle when snapshot was generated (X, Y, Z coordinates)	Paramics' X,Y,Z network coordinates, in m or ft depending on units selected
Probe sequence number (PSN)	Tag used to associate short series of snapshots to a unique vehicle
Link on which vehicle was located	Paramics' link designation
Distance from upstream end of link	Distance from upstream end of link, in m or ft depending on units selected
Lane on which vehicle was located	Lane on which vehicle is traveling when snapshot is generate (0 = right curb lane, 1 = second lane, etc.)
Vehicle's intended turn movement at end of link	Vehicle's intended turn movement at end of link, as expressed by the index of the pointer to the next link
Vehicle's instantaneous speed	Vehicle's speed when snapshot is generated, in mph or km/h depending on the units selected
Vehicle's instantaneous acceleration	Vehicle's acceleration rate when snapshot is generated, in ft/s or m/s depending on the units selected
Vehicle's breaking status (breaking or not)	Flag indicating whether the vehicle is braking (value = 1) or not (value = 0) when snapshot is generated
Bearing	Direction of travel of vehicles within network, in degrees
Vertical gradient	Rate of change in elevation where snapshot is generated, expressed as a percentage (for instance 1% = 1 ft rise in elevation over 100 ft)
Vehicle's origin zone	Index of zone where the vehicle originated
Vehicle's intended destination zone	Index of zone where the vehicle intends to travel

information about the lane onto which a vehicle is traveling could become available if GPS systems with sufficient accuracy are used (for instance, differential GPS systems). Finally, information about a vehicle's intended turn movement at an intersection and its travel destination could be obtained from its navigation system if access is granted to the information contained in such a system.

5.4.6. Probe Sequence Numbers (PSNs)

A primary concern in the design of IntelliDrive^{SM} systems has been to ensure the privacy of travelers. This has resulted in a system that generally prevents vehicles from being tracked over long distances, unless explicitly allowed by the driver of a vehicle through opt-in agreements. However, it is generally agreed that tracking over distances similar to what an observer standing on the side of the road could do is acceptable.

To allow tracking over short distances, a tracking number, known as a Probe Sequence Number (PSN), is tagged to periodic and stop/start event snapshots to allow sequences of snapshots to be correlated to a unique vehicle. However, this parameter is not intended for generating long sequences of snapshots. To prevent the formation of long chains, the tags are to be changed periodically, with a mandatory short period between different sequences of PSNs during which no snapshot is recorded. The following details the rules regarding the use of PSNs with IntelliDrive^{SM} probe vehicle data that were implemented within the data generator. These rules correspond to the IntelliDrive^{SM} system recommendations as of September 2009 and the PSN rules that were used in the USDOT POC test program in 2008:

- PSN are only generated if the option to do so is indicated in the model's input parameter file.
- PSN are assigned to both periodic and stop/start event snapshots. Special event snapshots are not assigned a PSN.
- PSN values are randomly generated to prevent vehicle tracking by correlating a series of sequential PSNs.
- PSN values must be changed when:
  - A PSN has been used over a distance of 3280 ft (1000 m) or for 120 s, whichever criterion comes last.
  - A vehicle has traveled 2.49 miles (4000 m) or for 5 minutes without establishing communication with an RSE.
  - A vehicle has completely emptied its memory buffer. Because of the assumption of instantaneous communication, this typically occurs immediately after a vehicle has come within range of an RSE. However, a change is not initiated if the vehicle is already within a PSN changeover gap.
  - An RSE connection is terminated, typically when the vehicle moves out of range. Again, a change is not initiated if the vehicle is already within a PSN changeover gap.
- When a new PSN is generated, no periodic snapshot is recorded during a given changeover interval. This gap is imposed to make it difficult to reconstitute a vehicle's path by correlating data from different groups of snapshots. Stop and start event snapshots are still generated, but assigned no PSN value (a value of "0").
- The duration of a PSN changeover gap is randomly determined using both a distance and a time criterion:

  - The distance criterion randomly assigns the length of the changeover between 164 ft (50 m) and 820 ft (250 m).
  - The time criterion randomly assigns a changeover length between 3 and 13 s.
  - The changeover is terminated whenever the distance or time criterion is met.

- A PSN changeover gap does not reset the timers used for periodic snapshots. It only results in blocking the collection of the snapshots that would be generated during the interval. A short gap may therefore have no impact on snapshot generation if it entirely falls between two scheduled snapshots.

- Any PSN in effect when a vehicle terminates a connection with an RSE is marked as a blocked PSN. This will prevent any new snapshots that may be generated with the same PSN to be uploaded at any other RSE.

As with many other processes, the user is provided with the option to turn on and off rules regarding the use of PSN. These options must be specified in the IntelliDrive^{SM} parameter input file (see Section 5.3.12). Current options include:

- *Enforce PSN rules*: Ability to turn on or off all of the above rules regarding the use of PSNs. If the rules are turned off, all snapshots generated by a vehicle throughout a trip are assigned the same PSN.

- *Hold RSE PSN*: Allows vehicles to retain the same PSN while within range of an RSE. This option effectively cancels the rule imposing a PSN change when a vehicle's memory buffer becomes empty.

- *Single RSE Upload*: Allows turning on or off the rule preventing vehicles from uploading snapshots to an RSE more than once when within communication range.

5.4.7. Snapshot Generation Process

The SAE J2735 Surface Vehicle Standard defines three basic types of snapshots to be generated by IntelliDrive^{SM} vehicles:

- Periodic snapshots taken at predefined intervals
- Stop/start event snapshots taken when a vehicle stops or start moving after a stop
- Special event snapshots recording changes in vehicle status, such as wiper or ABS activation

Currently, only periodic, stop/start event, and brake application snapshots are generated. Because of vehicle modeling limitations in Paramics, most of the special event snapshots defined in the SAE J2735 standard are not modeled.

Periodic and stop/start event snapshots are generated according to the following protocols:

- By default, periodic snapshots are to be generated at intervals based on the speed of a vehicle when the last snapshot was generated. A snapshot would be generated every 20 s for speeds above 60 mph (96 km/h), every 4 s for travel below 20 mph (32 km/h), and at linearly interpolated intervals for speeds in between.

- No periodic snapshot is to be generated when a vehicle is stopped.

- No periodic or stop/start event snapshot is generated for a certain interval following a change in the vehicle's PSN. This block remains in effect for a randomly assigned interval of 3 to 13 s or a randomly assigned distance of 164 ft (50 m) to 820 ft (250 m). The block is removed when both the time and distance criteria have been met. This restriction is imposed to make it difficult to track vehicles across various PSN sequences.

- A stop is only to be recorded after a vehicle has been immobilized for at least 5 s. To avoid recording multiple stops in stop-and-go situations, a stop is only recorded if no other stop has been recorded in the past 15 s.
- Start events are only recorded for vehicles currently assumed as stopped. For these vehicles, a start event is recorded when the speed of the vehicle increases above 10 mph (16 km/h).

The algorithm used for generating snapshots is shown in Figure 5-9. This algorithm was designed to implement the snapshot generation protocols defined above. However, full flexibility is provided to allow model users to define the approach to use for the generation of periodic snapshots. This is done by asking the users to define the following parameters in the IntelliDrive^{SM} parameter input file (see Section 5.4.12):

- Speed thresholds for the shortest and longest intervals for periodic snapshot generation
- Option of using either time or distance for the interval between snapshots
- Duration of the shortest and longest intervals for periodic snapshot generation
- Time interval a vehicle must be immobilized before generating a stop event
- Time interval since last stop event before generating a stop event
- Speed threshold defining a start event
- Whether rules governing the use of PSNs are to be applied

The following approaches can currently be implemented to space periodic snapshots:

- *Speed-based time interval.* This can be implemented by specifying “time” as a snapshot interval criterion in the model’s parameter input file and assigning appropriate values to the shortest and longest intervals associated with the low- and high-speed thresholds (for instance, 4 s at 20 mph and 20 s at 60 mph).
- *Fixed-time interval.* This approach can be implemented by assigning identical values to the shortest and longest intervals associated with the low- and high-speed thresholds (for instance, 4 s at 20 mph and 4 s at 60 mph).
- *Speed-based distance interval.* This can be implemented by specifying “distance” as a snapshot interval criterion and appropriate values to the shortest and longest intervals associated with the low- and high-speed thresholds (for instance, 100 feet at 20 mph and 500 ft at 60 mph).
- *Fixed-time interval.* This approach can be implemented by assigning identical values to the shortest and longest intervals associated with the low- and high-speed thresholds (for instance, 100 ft at 20 mph and 100 ft at 60 mph).

A timed interval is considered by default. If distance spacing is preferred, this option must be specified in the parameter input file. In this case, it should be noted that due to the underlying time-based nature of Paramics simulations, there may some discrepancies between the specified and actual spacing of snapshots. Snapshots will be generated at the first vehicle’s position following the triggering of the distance criterion, which may be a few feet or meters beyond the specified criterion. The magnitude of the discrepancy will depend on the simulation time step used. Typically, the use of shorter time steps will result in smaller discrepancies between the specified and actual spacing of snapshots.

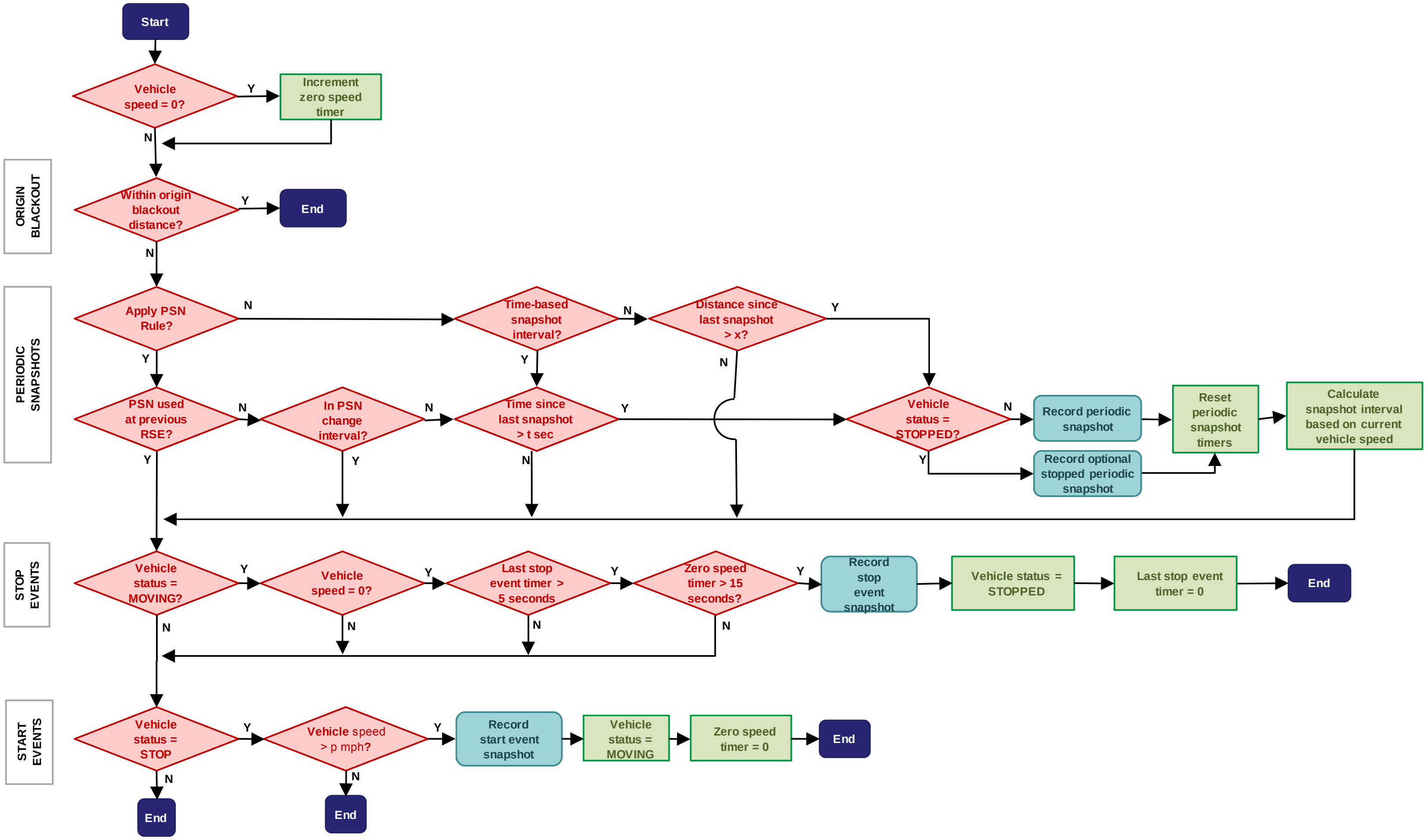


Figure 5-9 – Snapshot Generation Algorithm

While not included in the SAE J2735 standard, an option is provided to allow vehicles to keep recording snapshots while stopped. This is done to enable more detailed stop behavior analyses, particularly where a vehicle may crawl ahead in a queue without reaching the speed triggering the generation of a start event. In such a case, snapshots are generated at the shortest speed-based interval.

Another option provides the ability to record link entry and decision point entry snapshots. In this case, decision points are defined as any node providing vehicles with a choice of exits, such as intersections and freeway ramps. For consistency of reporting, freeway on-ramps are also considered as decision points. This option has been added to allow the calculation of link travel times, for the characterization of network operations or for supporting applications relying on link travel time information.

To alleviate privacy concerns, snapshot generation can be blocked while a vehicle is within a certain distance of its origin. The current recommendation is a blackout distance of 1640 ft (500 m). To implement this block, a function keeps track of the vehicle's odometer. This block is based on actual travel distance and not straight distances between two points. If it is activated, no snapshot is generated until the vehicle has traveled the pre-specified blackout distance.

5.4.8. Snapshot Generation Example

An example of basic snapshot generation is provided in Figures 5-10 and 5-11. Both figures plot the periodic and stop/start event snapshots generated by a single vehicle, and the PSN tagged to each snapshot. One figure plots the snapshots according to time and the other according to the distance traveled.

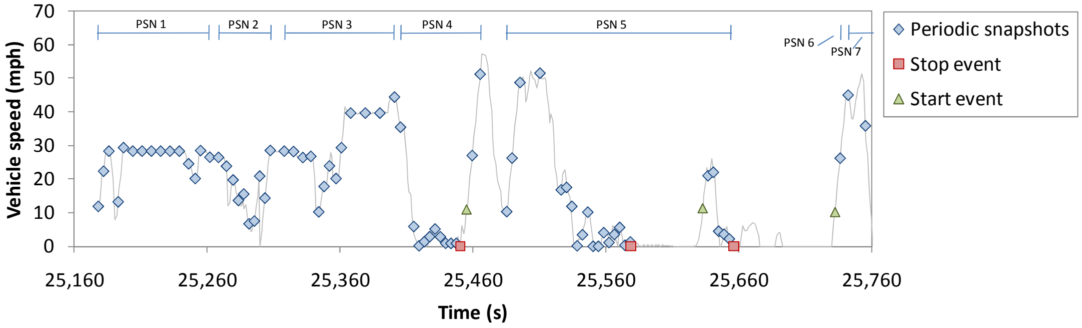


Figure 5-10 –Basic Snapshot Generation Example –Time Profile

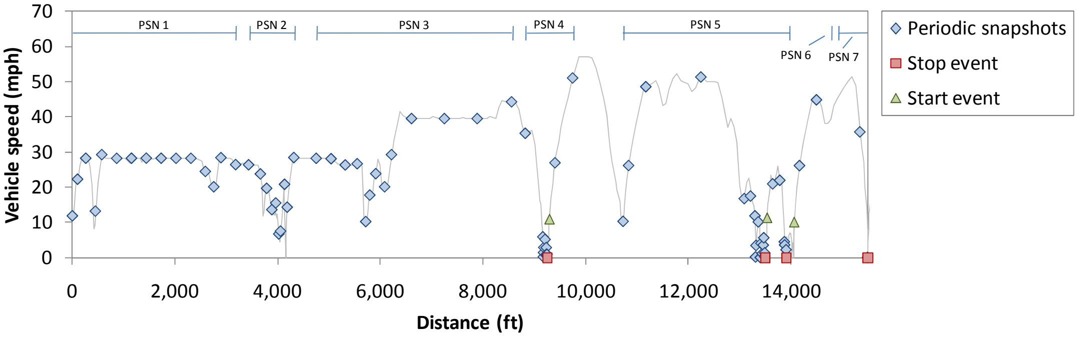


Figure 5-11 – Basic Snapshot Generation Example –Distance Profile

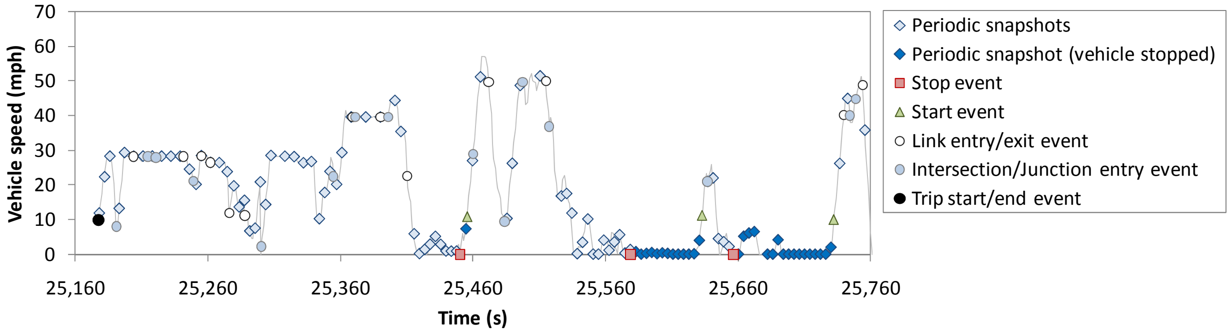


Figure 5-12 – Optional Snapshot Generation Example – Time Profile

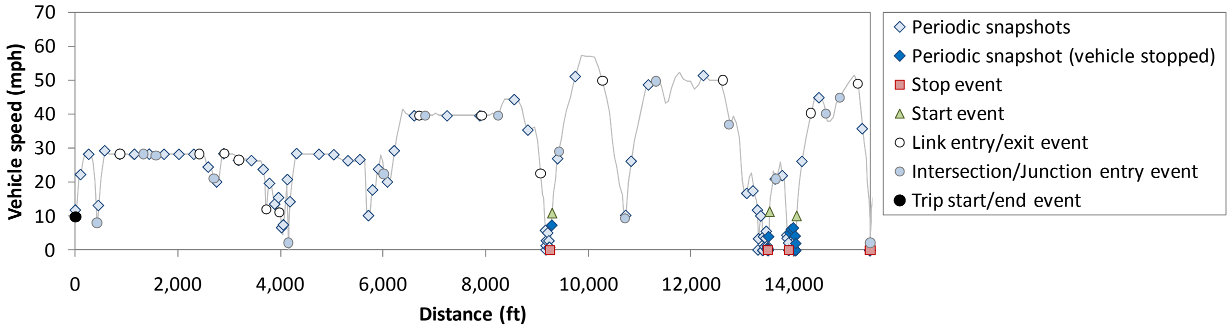


Figure 5-13 – Optional Snapshot Generation Example – Distance Profile

Figure 5-12 and 5-13 further illustrate the optional snapshots that could be generated for the same profiles as Figures 5-10 and 5-11. In addition to the basic periodic and stop/start event snapshots, the figures show:

- Periodic snapshots that could be generated while the vehicle is stopped
- Snapshots marking the moment a vehicle enters each Paramics link
- Snapshots marking the moment when a vehicle enters a node with more than one entry or exit (intersection, freeway ramp junction)
- Snapshots marking the start and end of a trip

5.4.9. Management of Onboard Memory Buffer

Snapshots generated by a vehicle are stored in an onboard memory buffer until they can be sent to a roadside RSE unit. Similar to other simulator parameters, the size of this buffer can be determined by the model user. The current recommendation is to use a buffer holding a minimum of 30 snapshots, with the maximum holding capacity defined by what can be offered with current technologies at a reasonable cost.

Periodic snapshots are inserted into the buffer in the order in which they are generated, with the newest snapshots placed on top of the list to position them first in line for retrieval by RSEs**.** Figure 5-14 illustrates this modeling. Stop/start event snapshots are inserted in a similar fashion, except that they are always stored on top of any existing periodic snapshots to reflect the desire of retrieving them before any periodic snapshot.

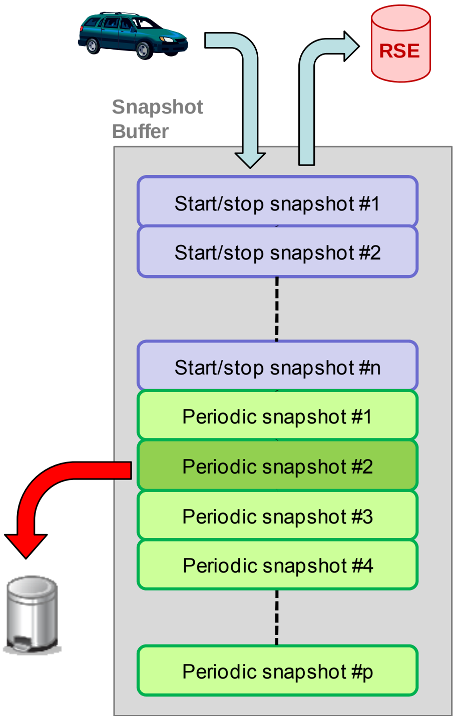


Figure 5-14 – Snapshot Buffer Management

Snapshots are added to the buffer as long as there is space available. When the buffer becomes full, the second oldest available periodic snapshot is removed to make room for new snapshots. The oldest periodic snapshot is kept to retain information about the length of time and distance traveled since the last RSE communication. It is only removed if no other periodic snapshot remains. If the buffer becomes entirely filled with stop/start event snapshots, the oldest stop/start event snapshot is then removed to make room for new stop/start snapshots, but not for new periodic snapshots.

5.4.10. Snapshot Upload Process

Vehicle always establish communication with the RSE that is the closest in distance to their location. When a vehicle comes within range of an RSE, it immediately establishes communication with the device as there is currently no modeling of handshaking or other security validation processes.

Figure 5-15 illustrates a typical sequence of activities that may occur when a vehicle travels across the range of an RSE. Once a connection is established, the vehicle immediately starts uploading the snapshots contained in its memory buffer. Since there is currently no formal modeling of parameters affecting wireless communications, it is assumed that all snapshots stored in the buffer are uploaded in a single transmission, with no delay. All the uploaded snapshots are then sent to a comma-delimited output file that is formatted for easy post-simulation analysis with Microsoft Excel or other data processing software. No data post-processing other that a simple compilation of averages is currently conducted within the simulator itself.

Current snapshot upload protocols call for no new snapshot to be uploaded to an RSE after the memory buffer has been emptied. Any new snapshot generated while within range will only be uploaded at the next RSE. However, this will only occur if a new PSN is assigned to the new snapshots, as snapshots with

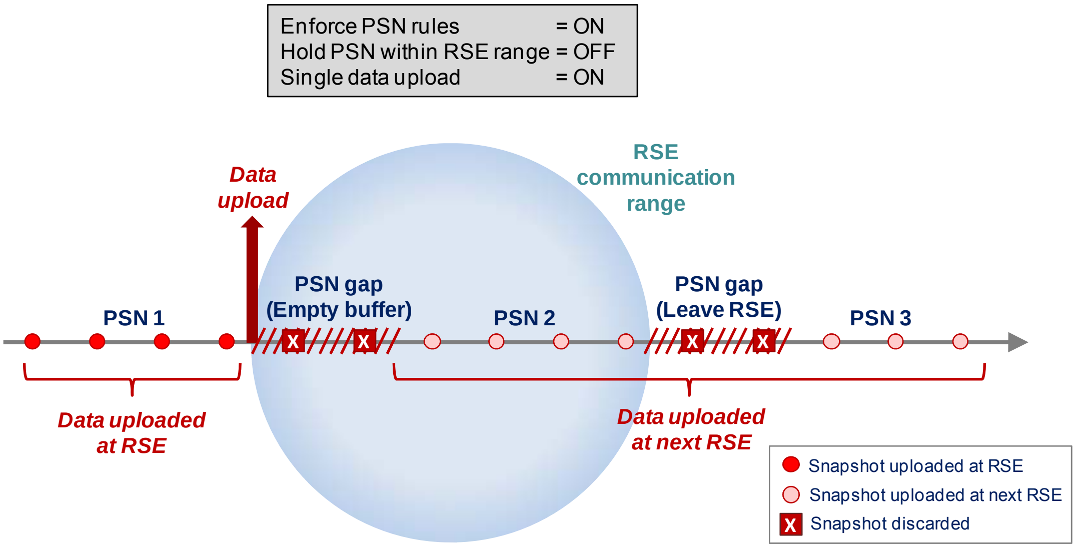


Figure 5-15 – Default Snapshot Upload Process

a specific PSN can only be uploaded at one RSE to prevent the possibility of tracking of vehicles across RSEs. In Figure 5-15, this requirement is satisfied by first requiring vehicles to change their PSN as soon as they have finished uploading their data. The requirement is further enforced by requesting another PSN change after the termination of an RSE connection. This occurs either when the vehicle moving out of range or due to an early termination triggered by technical elements.

The setup of Figure 5-15 represents the default snapshot handling protocol modeled within RSEs. Similar to other simulation processes, options are provided in the parameter input file (see Section 5.3.12) to allow alternative RSE operations. As illustrated in Figure 5-16, various snapshot upload protocols can be created by toggling on or off the following three options:

- *Single RSE Upload*: Allows turning on or off the rule preventing vehicles from uploading snapshots to an RSE more than once when within communication range.
- *Enforce PSN rules*: Ability to turn on or off all the rules regarding the use of PSN.
- *Hold RSE PSN*: Allows vehicles to retain the same PSN while within range of an RSE. This option cancels the rule imposing a PSN change when a vehicle's memory buffer becomes empty.

The above modeling represents only a first solution. While simplistic, this modeling is sufficient to enable evaluation of a range of snapshot generation protocols. It also enables the evaluation of applications using snapshot data if an accurate modeling of data latency is not required. Future model expansions will seek to develop a modeling of the snapshot upload process attempting to reflect more closely actual system operations. Potential refinements include a more accurate simulation of probe data messaging protocols, replacing the instantaneous communication assumption by more realistic data transmission rates, considerations of signal strength, consideration for the direction toward which a vehicle is moving, or any other criteria used to determine the RSE with which a vehicle establishes communication. Notably, an effort currently under way, funded by the National Science Foundation, is exploring possibilities of providing more realistic wireless communication simulations by linking Paramics with the ns-2 wireless communication simulator.

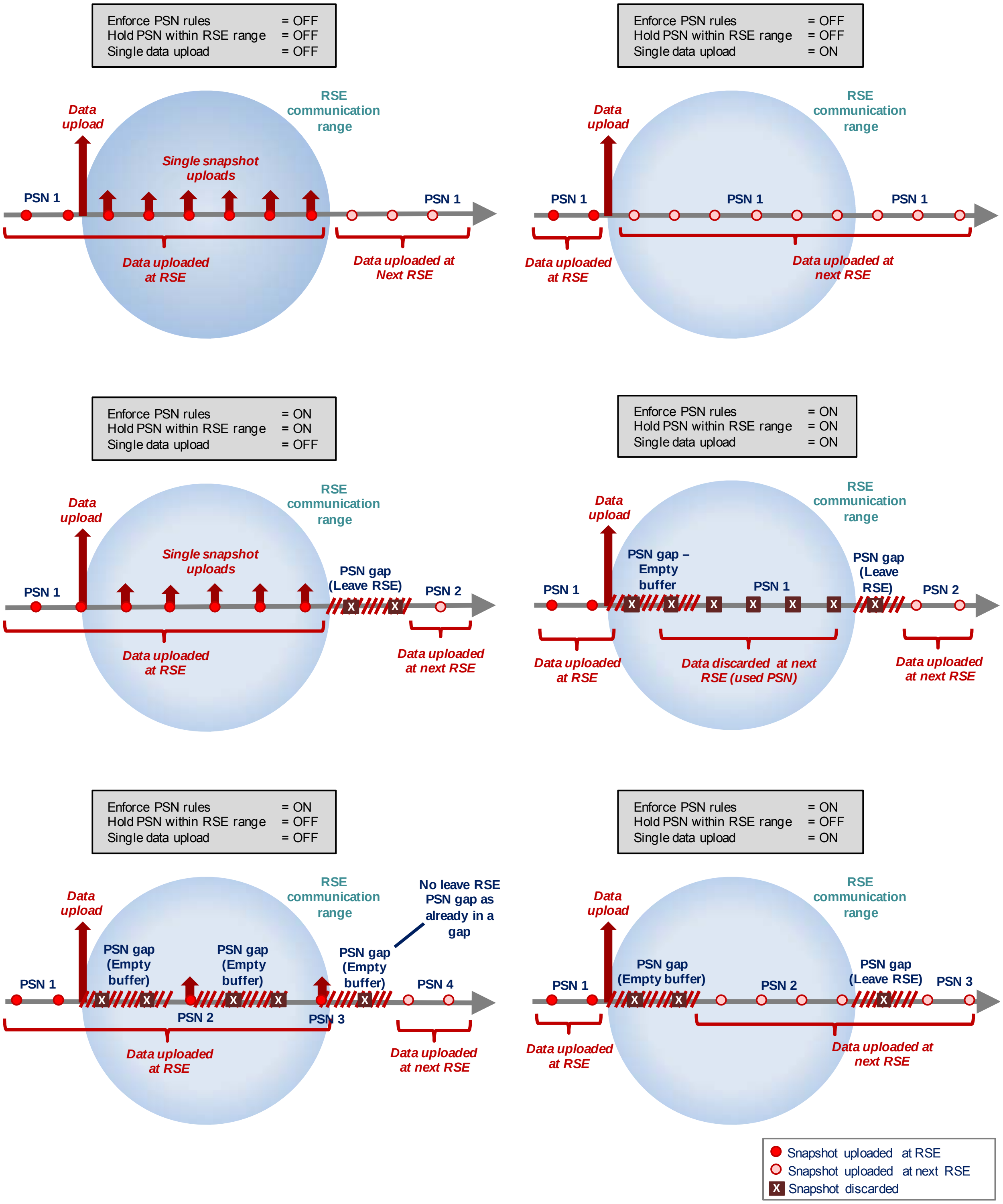


Figure 5-16 – Alternative Snapshot Upload Processes

5.4.11. Snapshot RSE Header Data

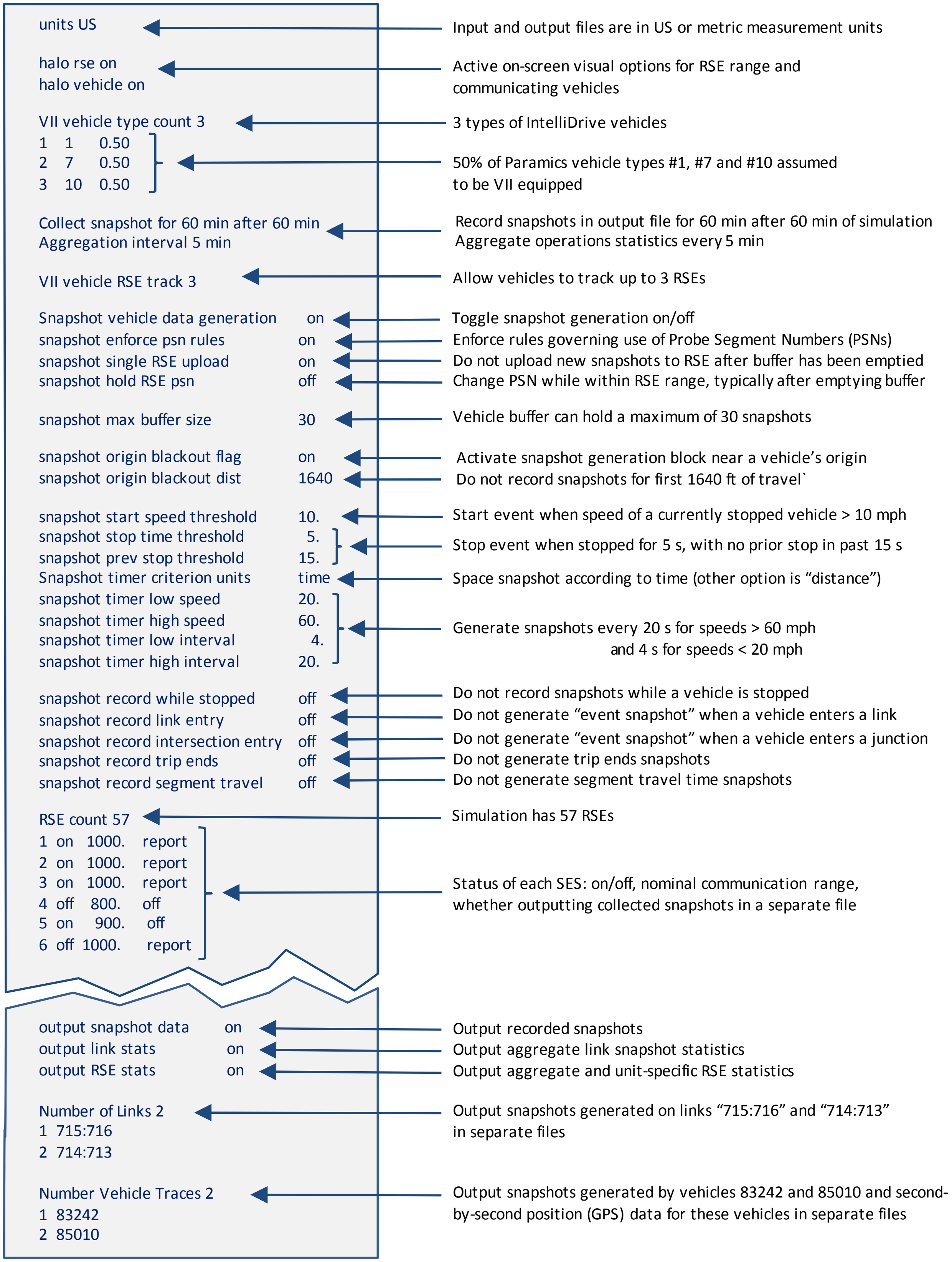
Each time a snapshot is uploaded to an RSE additional data is appended to the front of the snapshot to record the time of the upload and identify the RSE uploading the snapshot. This additional information, shown in Table 5-2, represents some of the message header data that would be transmitted in real-world systems by an RSE when forwarding snapshot data to a SDN. This information is recorded to allow analysis of snapshot collection activities at individual RSEs.

Table 5-2 – Snapshot Generator RSE Header Data

Data Item	Description
Upload time	Time when snapshot was uploaded by the RSE, both in hh:mm:ss.dd format and number of seconds from midnight corresponding to the simulation time
RSE index	Paramic's index number of RSE where snapshot has been uploaded (value between 1 and number of defined RSEs)
RSE name	Name of RSE where snapshot has been uploaded

5.4.12. Input Parameter File

To facilitate the simulation of alternate scenarios without having to recompile the application code, an input file following the conventions used in other Paramics files has been developed. An example modeling current snapshot generation and collection protocols is shown in Figure 5-17. Parameters are read from this file by a program seeking recognition of specific sequences of keywords, which allows for a very flexible placement of input commands.



```
units US

halo rse on
halo vehicle on

VII vehicle type count 3
1  1    0.50
2  7    0.50
3  10   0.50

Collect snapshot for 60 min after 60 min
Aggregation interval 5 min

VII vehicle RSE track 3

Snapshot vehicle data generation        on
snapshot enforce psn rules             on
snapshot single RSE upload             on
snapshot hold RSE psn                  off

snapshot max buffer size               30

snapshot origin blackout flag          on
snapshot origin blackout dist          1640

snapshot start speed threshold         10.
snapshot stop time threshold            5.
snapshot prev stop threshold           15.
Snapshot timer criterion units         time
snapshot timer low speed               20.
snapshot timer high speed              60.
snapshot timer low interval             4.
snapshot timer high interval           20.

snapshot record while stopped          off
snapshot record link entry             off
snapshot record intersection entry     off
snapshot record trip ends              off
snapshot record segment travel         off

RSE count 57
1  on   1000.   report
2  on   1000.   report
3  on   1000.   report
4  off   800.   off
5  on    900.   off
6  off  1000.   report

output snapshot data     on
output link stats        on
output RSE stats         on

Number of Links 2
1  715:716
2  714:713

Number Vehicle Traces 2
1  83242
2  85010
```

Input and output files are in US or metric measurement units

Active on-screen visual options for RSE range and communicating vehicles

3 types of IntelliDrive vehicles

50% of Paramics vehicle types #1, #7 and #10 assumed to be VII equipped

Record snapshots in output file for 60 min after 60 min of simulation
Aggregate operations statistics every 5 min

Allow vehicles to track up to 3 RSEs

Toggle snapshot generation on/off
Enforce rules governing use of Probe Segment Numbers (PSNs)
Do not upload new snapshots to RSE after buffer has been emptied
Change PSN while within RSE range, typically after emptying buffer

Vehicle buffer can hold a maximum of 30 snapshots

Activate snapshot generation block near a vehicle's origin
Do not record snapshots for first 1640 ft of travel`

Start event when speed of a currently stopped vehicle > 10 mph
Stop event when stopped for 5 s, with no prior stop in past 15 s
Space snapshot according to time (other option is "distance")

Generate snapshots every 20 s for speeds > 60 mph
and 4 s for speeds < 20 mph

Do not record snapshots while a vehicle is stopped
Do not generate "event snapshot" when a vehicle enters a link
Do not generate "event snapshot" when a vehicle enters a junction
Do not generate trip ends snapshots
Do not generate segment travel time snapshots

Simulation has 57 RSEs

Status of each SES: on/off, nominal communication range, whether outputting collected snapshots in a separate file

Output recorded snapshots
Output aggregate link snapshot statistics
Output aggregate and unit-specific RSE statistics

Output snapshots generated on links "715:716" and "714:713" in separate files

Output snapshots generated by vehicles 83242 and 85010 and second-by-second position (GPS) data for these vehicles in separate files

Figure 5-17 – Modeling of Snapshot Generation and Upload in IntelliDrive^{SM} Input File

5.4.13. Output Files

For convenience, data generated from a simulation are outputted in a series of comma-delimited files that can easily be opened in Microsoft Excel. Table 5-3 lists the main output files currently generated.

Table 5-3 – Snapshot Generator Output Data Files

File name	Description
GPSstats.csv	File containing the second-by-second records of position and speed for the vehicles for which a trace is requested.
Veh_snapshots_vehID.csv	Snapshots generated by vehicles for which a trace is requested. For each file, the "vehID" string is replaced by the Paramics identification number of the vehicles for which data is stored in the file.
Link_snapshots_linkID.csv	Snapshots generated on links for which a link-specific output is requested. For each file, the "LinkID" string is replaced by the name of the link for which data is stored in the file.
RSE_snapshots_RSEID.csv	File containing all the snapshots collected by RSE n.
Snapshots.csv	File containing all snapshots generated during a simulation.
Linkstats.csv	File containing link performance statistics (flow count, average speed, standard deviation, snapshot count, data upload count, etc.) for each link for each data aggregation interval.
Linkstatsum.csv	File containing average performance statistics (flow count, average speed, standard deviation, snapshot count, data upload count, etc.) for all links for each data aggregation interval.
Segments_stats.csv	File containing link performance statistics (flow count, average speed, standard deviation, snapshot count, data upload count, etc.) for groups of links between decision points (intersections, on-ramps and off-ramps). Information is only available for links that have been traveled by vehicles
RSEstats.csv	File containing a summary of activities (number of data uploads, number of snapshots uploaded) for each RSE for each data aggregation interval.
RSEstatsum.csv	File containing a summary of activities (number of data uploads, number of snapshots uploaded) for all RSEs for each data aggregation interval.

5.5. *Application Supporting Functionalities*

This section describes various applications that have been developed and implemented within the Paramics IntelliDrive^{SM} simulator. These applications include:

- Dynamic vehicle routing
- Incident re-routing
- Link flow projections

5.5.1. Dynamic Routing

In a basic Paramics simulation, vehicles are routed from a given origin to a given destination according to route trees that are built by considering the costs of traveling on individual links and restrictions associated with these links. While these route trees can be updated periodically, such as every five minutes, there are limitations in how this updating process can efficiently model dynamic routing applications. The main limiting factor is the fact that simulated vehicles are by default only instructed to retain information about the current link they are traveling on and the next two links. This limited knowledge often results in vehicles making route choices that appear ideal at a local level but not so when considering the intended destination. While the route trees can be periodically updated based on the most recent observed travel times, such as every 5 minutes, there are no mechanisms to target path updates in individual vehicles at specific times.

Vehicles with a navigation system have typically a more extensive knowledge of their projected path than what is currently modeled in Paramics. In most cases, the path to reach a specific destination is known in its entirety. Furthermore, this path is usually automatically recalculated the moment a vehicle makes a "wrong turn" or if there are significant changes in reported traffic conditions along the projected route (for instance, after receipt of a message indicating the occurrence of an incident).

This section describes the functionalities that were programmed to allow vehicles within Paramics to request new projected travel paths and to store these projected paths within their onboard memory. The following sections successively describe the route search algorithm, the functions used for estimating travel cost, the process by which routes can be updated, and some validation results.

5.5.1.1. *Travel Cost Estimation Function*

Paramics estimates travel costs along roadway links using a weighted combination of travel time, travel distance, and out-of-pocket costs. The function used to estimate these travel costs can be written as follows:

$$Travel\ Cost = \sum_{link\ i} f_{cost\ i} \times (\alpha\ TT_i + \beta\ Dist_i + \gamma\ Toll_i)$$

where: *Travel Cost* = Network travel cost
TT_i = Travel time on link *i* (seconds)
$Dist_i$ = Travel distance on link *i* (meters)
$Toll_i$ = Toll to travel on link *i*
α, β, γ = Network-wide weight cost element parameters
$f_{cost\ i}$ = Cost multiplication factor for link *i*

In the above equation, the parameters α, β and γ are uniformly applied to all vehicles in a network. They specify the relative importance that travelers put on each cost element. Default values assume $\alpha = 1$, $\beta = 0$, and $\gamma = 0$. This translates into vehicle routing solely based on travel time.

Link cost factors, $f_{cost\ l}$, are further used to provide higher or lower weights to the travel costs associated with specific links. For instance, a link factor greater than 1.0 can be used to increase the perceived cost of traveling on a link with an active work zone to emulate the desire of travelers to avoid such links if alternatives exist. Conversely, factors lower than 1.0 could be used to reduce the perceived cost of traveling on specific links. Such factors can be used, for example, to take into consideration that many drivers prefer to travel on freeways.

Since travel time, travel distance, and out-of-pocket (toll) expenses represent the basic cost elements used by a majority of routing applications, the dynamic routing application implemented within Paramics retains by default the use of the same cost function and same cost weights.

5.5.1.2. Route Search Algorithm

Projected paths are determined by seeking a sequence of links offering a minimum-cost path from a given origin node to a specified destination node. The algorithm that has been implemented to perform this search is based on the traditional Disktra's algorithm:

- Starting from a vehicle's current location, the algorithm first calculates the cost of travel to the node at the end of the link on which the vehicle is located.
- From the identified node, the algorithm calculates the cost of travel to all neighboring nodes. At each node that has been reached, the minimum cost path between the trip origin zone and the node being considered is stored within the node's data structure.
- The node with the lowest travel cost is then selected as the next node from which travel is to be considered.
- The path with the lowest cost is always retained. This can result in a change of path if the newly generated path has a lower travel cost than the current one.
- The above process is repeated until the intended destination node is reached or until all nodes have been visited at least once.
- If all nodes are visited before the destination is reached, an invalid path search is then declared, and no path is returned by the algorithm. Such cases may occur due to some complex network geometry requiring drivers to visit some nodes multiple times from different directions.

At the end of a search, the produced path is stored within the vehicle that has requested its generation as a list of projected travel links. For each link along a given path, the following information is retained:

- Link traveled
- Link projected turn movement (next link to take)
- Link projected entry time
- Link projected travel time
- Link projected travel distance
- Link projected travel cost
- Link cost factor
- Link distance factor

In addition to individual link data, the following overall trip statistics are also produced:

- Number of links along projected path
- Projected total trip time
- Projected trip distance
- Projected trip cost
- Flag indicating whether the intended destination has been successfully reached

5.5.1.3. Traffic Condition Update Mechanisms

Within Paramics, routing decisions are based on the latest available estimates of link travel times and prevailing toll rates. The degree to which this information represents current conditions is determined by the frequency of information feedback defined in the network configuration file. If no information feedback is defined, all routing decisions are based on traffic conditions that were in effect at the beginning of a simulation. If a 5-minute feedback loop is defined, then all link travel times will be reassessed every 5 minutes based on the observed travel times of vehicles that have completed travel across each link during the previous interval. To reduce undesired fluctuations, a smoothing process is applied to this adjustment, where observed travel times in the previous interval are weighted in the corresponding average travel times that were in effect during the prior intervals. The result of this adjustment will thus depend on strength of the smoothing factors defined by the user.

An option is further provided to replace the link travel times returned by Paramics by times read from a user-supplied table. Current modeling allows the user to provide travel times for each link for up to 24 intervals. If an interval is defined as being 5-minutes long, this allows the provision of time-dependent travel times for a period of two hours. When a vehicle is being routed, the travel time for a specific link that is read from the table is the one that corresponds to the interval during which the vehicle is projected to enter the link. This option allows routing decisions to be made based on projected travel times. Instead of routing vehicles based on current traffic conditions, as is typically done by Paramics, vehicles could be routed according to the conditions they can expect to encounter on each link.

For many networks, information about historical link travel times could be developed based on data from traffic surveillance systems. If such data is not available, model users are provided with the option to have Paramics automatically generate the “historical” link travel time data. To perform this task, the user can run a simulation with the option to print observed link travel times in an output file. Following a simple change of file extension (from “.out” to “.dat”), the resulting output files could then be used as input files for other simulations using the same network.

In the file defining link travel times, data can be provided for each link exit movement. For instance, at an intersection where vehicles could turn left, go straight or turn right, travel time data can be provided for each of the three movements. If movement-specific data is not available, the same travel times could then be entered for each movement. This is to allow evaluations of applications considering specific movements.

5.5.1.4. Route Update Triggers

To allow projected paths to be adjusted to changes in network traffic conditions or unexpected turn decisions, the following events act as triggers for the regeneration of projected paths:

- Vehicle entering a different link than the one stored within its projected path

- Vehicle entering a link more than *n* second before or after the expected link entry time (user-defined parameter)
- Execution of a link travel cost feedback loop by Paramics. This event results in vehicles reassigning their projected path the next time they transfer from one link to the next. Any change in projected path then takes effect at the downstream end of the link just entered.

The user is provided with the option to turn off both the link entry time adjustment and path regeneration following a link travel time feedback loop by Paramics.

To reduce the computational burden, constraints have also been defined to reduce the number of path regenerations. Currently, path regeneration can be blocked when a vehicle:

- Has had a path generated within the past *n* seconds (user-definable parameter)
- Is within *n* feet of its destination (user-definable parameter)
- Is currently on a link connected to its destination zone

A repeat mechanism has also been built to allow a vehicle to bypass some of the above constraints in cases in which the search algorithm fails to determine a valid path. In such a case, a flag is turned on to indicate that the vehicle attempting to obtain a path was unable to do so. This flag will allow the vehicle to ignore time and distance constraints between path regeneration until a valid path is obtained. When this occurs, the flag is then turned off to resume normal path search activities.

Finally, an option has been built to allow a specific path to be imposed on a vehicle. Each time a vehicle enters a link, the option will assess whether the next and second next intended links returned by the Paramics default routing algorithm corresponds to the first and second next links in the vehicle's stored path. If a difference exists, vehicles then have the option to either follow the routing decision determined by Paramics or follow the path stored in their memory. Which approach is taken will entirely depend on how the user sets up the routing application.

5.5.1.5. Vehicle Route Summaries

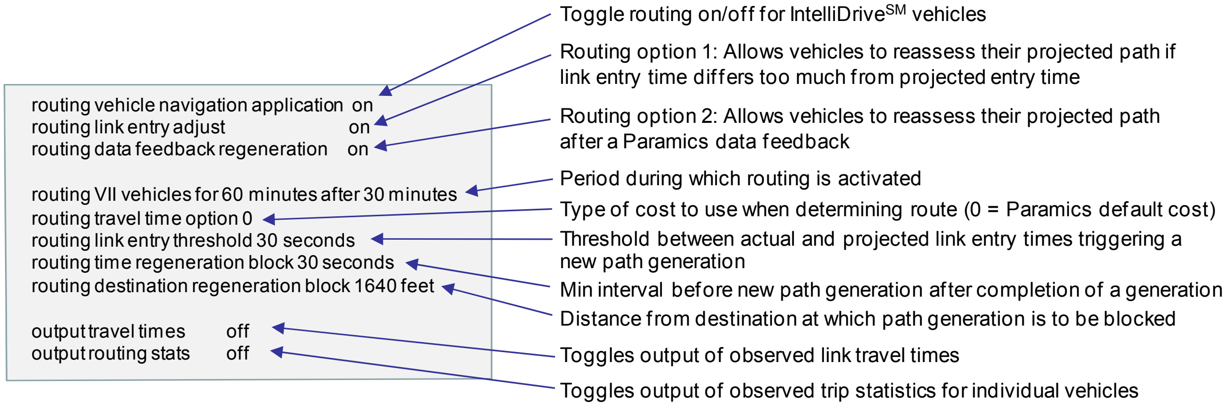
If requested, a trip summary can be produced for each vehicle reaching its destination. This summary contains the following information:

- Vehicle identification number
- Vehicle type
- Number of passenger car units (PCUs) associated with the vehicle type
- Is the vehicle a truck?
- Is the vehicle a bus?
- Origin zone
- Destination zone
- Trip start time (seconds)
- Trip end time (seconds)
- Is the vehicle an IntelliDrive^{SM} vehicle?
- Is vehicle navigation on?
- Trip cost estimated when vehicle was generated
- Estimated number of links to travel through when vehicle was generated
- Actual number of links traveled through

- Trip distance (feet or meters)
- Trip time (seconds)
- Average trip speed (mph or km/h)
- Total incurred delay
- Total incurred stopped delay
- Total number of stops incurred
- Trip final cost

5.5.1.6. Application Modeling in IntelliDrive^{SM} Input File

Modifications were made to the input file used to model IntelliDrive^{SM} systems to allow the user to specify various options regarding the dynamic routing algorithm. Figure 5-18 provides an example of the additional input commands.



```
routing vehicle navigation application  on
routing link entry adjust               on
routing data feedback regeneration      on

routing VII vehicles for 60 minutes after 30 minutes
routing travel time option 0
routing link entry threshold 30 seconds
routing time regeneration block 30 seconds
routing destination regeneration block 1640 feet

output travel times      off
output routing stats     off
```

Toggle routing on/off for IntelliDrive^{SM} vehicles

Routing option 1: Allows vehicles to reassess their projected path if link entry time differs too much from projected entry time

Routing option 2: Allows vehicles to reassess their projected path after a Paramics data feedback

Period during which routing is activated

Type of cost to use when determining route (0 = Paramics default cost)

Threshold between actual and projected link entry times triggering a new path generation

Min interval before new path generation after completion of a generation

Distance from destination at which path generation is to be blocked

Toggles output of observed link travel times

Toggles output of observed trip statistics for individual vehicles

Figure 5-18 – Dynamic Routing Options in IntelliDrive^{SM} Input File

5.5.1.7. Search Algorithm Validation

Validation of the search algorithm has been conducted by comparing vehicle behavior under identical cost weight assumptions in scenarios using the default Paramics routing and scenarios using the developed search algorithm. Simulation results have indicated that the developed routing algorithm generally produces identical travel paths as Paramics' internal routing functions. Differences were observed in a very small number of cases (less than 3% for the test network of Figure 5-1). In most cases, these differences could be attributed to network geometrical constructs that make it difficult to process correctly a specific sequence of nodes that a driver would take to cross an intersection. Particularly difficult intersections to process are those with "Michigan Left-Turns." There, vehicles have to turn right and use a median U-turn to make a left turn.

5.5.2. Incident Rerouting

Paramics allows users to simulate incidents that disrupt network operations, for example, a vehicle breakdown on a traffic lane or vehicles stopping on a traffic lane to drop off or pick up passengers near a bus terminal or other point of interest. Incidents are defined by coding in an input file labeled "incidents" the location of the incident, its duration, the speed at which vehicles pass the blockage on adjacent lanes, and, to simulate rubbernecking, the speed of vehicles traveling on the opposing lane.

Under normal Paramics operations, vehicles would only adjust their routing decision in response to an incident if an information feedback loop is used. These loops are used to update at regular intervals the cost of traveling on individual links. These cost updates are executed by factoring in actual link travel times from vehicles that have completed travel on each link since the execution of the last feedback loop. Following an incident, queue buildup on links leading to the incident would result in increasingly longer travel times. As these increases in travel times are factored in the average link travel cost, alternate routes would then be produced if these changes lead to the identification of new shorter paths to a vehicle's intended destination.

The rate at which Paramics updates link travel costs depends on the frequency of the feedback loop set up by the model users. If a 5-minute frequency is used, a 5-minute delay could then occur before the congestion created by an incident starts to affect routing decisions. In such a case, the response may be further dampened by the use of moving averages and other smoothing parameters. This may result in a system that reacts too slowly to an incident.

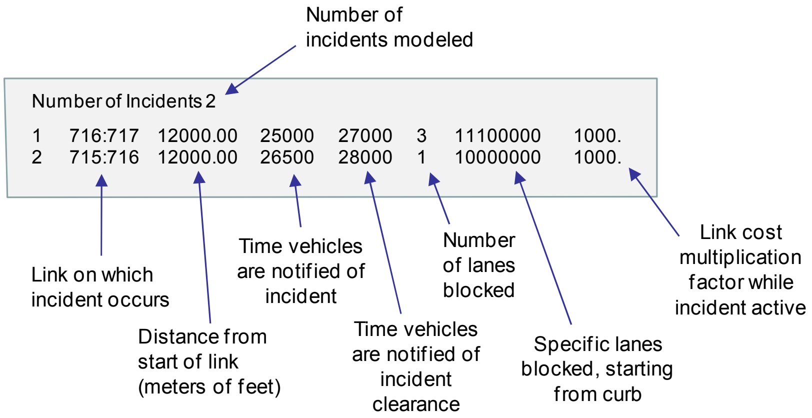
To model the ability of IntelliDrive^{SM} vehicles to respond to incident notification messages, functionalities have been added to the dynamic routing application described in Section 5.5.1 to factor in the presence of incidents on specific links within the network when routing decisions are made. These new functionalities require the provision of additional data in the "DSRCSetup.dat" parameter input file, modifications to the function used to estimate link travel costs, and new mechanisms for triggering the generation of new projected paths.

5.5.2.1. Incident Modeling in IntelliDrive^{SM} Parameter Input File

The incident rerouting application assumes that the IntelliDrive^{SM} vehicles are provided with a message warning them about the presence of an incident on a specific link. This message provides information characterizing the duration and magnitude of one or more incidents as described in the IntelliDrive^{SM} input parameter file.

Figure 5-19 presents the format of the information that must be provided. This information includes:

- The name of the link on which the incident is located
- The location of the incident on the link
- The times at which vehicles are notified of the incident and its clearance



```
Number of Incidents 2

1    716:717   12000.00   25000   27000   3   11100000     1000.
2    715:716   12000.00   26500   28000   1   10000000     1000.
```

Figure 5-19 – Incident Rerouting Parameters in IntelliDrive^{SM} Input File

- The number of lanes blocked by the incident
- The identification of the specific lanes being blocked
- A travel cost multiplication factor that is to be applied to link costs when the incident is active

Depending on the scenario considered, the defined incident start and end times may not correspond to the actual incident start and end times. Since Paramics is left in charge of simulating the incident, the actual start time and duration of an incident will correspond to the parameters defined in the Paramics incident input file ("incidents.dat"). The incident start time provided in the IntelliDrive^{SM} input file can be the actual time at which the incident occurs or the moment when vehicles are notified of the incident, after it has been identified and verified. Similarly, the incident end time can the moment the incident is cleared or the moment vehicles are actually notified of its clearance.

5.5.2.2. *Adjusted Travel Cost Function*

Following notification of an incident, the normal response would be to try to seek an alternative route around the incident. To model this response, an incident cost factor has been added to the function used to estimate link travel cost. The resulting function takes the following form:

$$Travel\ Cost = \sum_{link\ i} f_{cost\ i} \times f_{incident\ i} \times (\alpha\, TT_i + \beta\, Dist_i + \gamma\, Toll_i)$$

with:

$$f_{incident\ i} = \begin{cases} user-defined\ value & if\ T \geq I_{start}\ and\ T < I_{end} \\ 1.000 & otherwise \end{cases}$$

where: *Travel Cost* = Network travel cost
T = Simulation time (seconds)
TT_i = Travel time on link *i* (seconds)
$Dist_i$ = Travel distance on link *i* (meters)
$Toll_i$ = Toll to travel on link *i*
α, β, γ = Network-wide weight parameters
$f_{cost\ i}$ = Cost multiplication factor for link *i*
$f_{incident\ i}$ = Incident cost multiplication factor for link *i*
I_{start} = Start time of incident (seconds)
I_{end} = End time of incident (seconds)

The multiplication factor is only applied when an incident is assumed to be affecting traffic. Both the parameters defining start time (I_{start}) and end time (I_{end}) are user-defined. Any vehicle intending to travel on the link affected by the incident between the defined start and end times will then have its travel cost on the affected link adjusted by the supplied factor. Use of a multiplication factor of 1.0 would result in the incident being effectively ignored. Factors greater than 1.0 would result in proportionally higher additional costs for traveling along the link. To prevent a vehicle from traveling on the link, a very large factor, such as 1000 or 10,000 could be used to generate a large cost increase that would make any other potential route more attractive.

5.5.2.3. *Route Recalculation Trigger Mechanisms*

Route recalculation is set to affect only IntelliDrive^{SM} vehicles. When the simulation reaches the defined incident start time (I_{start}), a flag is activated to instruct all IntelliDrive^{SM} vehicles to reevaluate their projected route at the first possible occasion. Any vehicle projected to enter the link with the incident between I_{start} and I_{end} will then be instructed to recalculate its intended route using the supplied incident cost multiplication factor. Depending on the current location and intended destination of a vehicle, this route recalculation may result in the vehicle following an alternate path around the incident or still attempting to go through the link with the incident if no viable alternative is found. When the simulation reaches the incident end time (I_{end}), vehicles are again instructed to reassess their projected route at the first possible occasion. This second reassessment may result in vehicles returning to their original paths or continuing to travel on their alternate paths.

Route reassessment happens when a vehicle transfers from one link to another. This modeling was adopted for computational efficiency. Since short links are often used to model road networks in Paramics, this approach typically results in delays of only a few seconds between the start of an incident and the moment vehicles start responding to it. This delay can be the time needed for receiving the incident notification message or for a navigation system to generate a new route. The only vehicles for which this approach may negatively restrict routing options are those that are traveling on the link immediately upstream of the last potential reroute decision point when the incident message is received. Because routing is reassessed after the vehicle has transferred to the downstream link, these vehicles will effectively be prevented from seeking an alternate route. However, because of the use of short links, such a treatment should only affect a very small number of vehicles.

Paramics incident definition

```
incident definitions

type 1 "lane closure" 0x00ff00ff
                    wait time 00:15:00 in lane 1
                    passing speed 30 mph opposing speed 40 mph

type 2 "lane closure" 0x00ff00ff
                    wait time 00:15:00 in lane 2
                    passing speed 30 mph opposing speed 40 mph

Incident locations
link 715:716 at 07:00:00 at 800 ft type 1
link 716:717 at 07:00:00 at 30 ft type 2
```

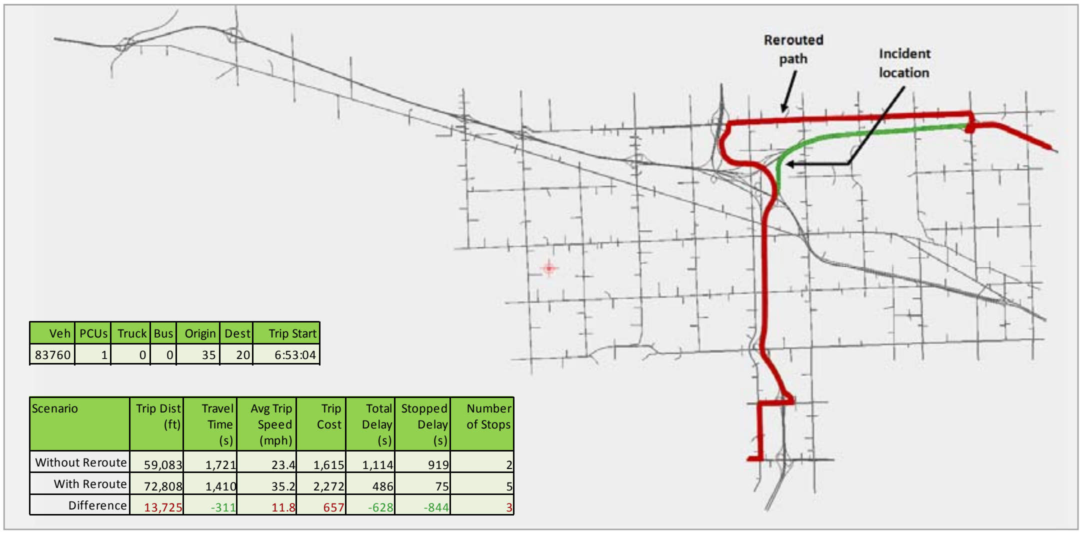
Incident blocking all available lanes (2 lanes) of freeway ramp from 7:00 to 7:15

*(Models a disabled vehicle at downstream end of Lane 1 on link 715:716
and a disabled vehicle at upstream end of Lane 2 on link 716:715)*

IntelliDrive incident messaging definition

```
Number of Incidents 1
1  716:717   4000.   25260   26220   2   11000000   10000.
```

- *Incident occurrence on link 716:717, 4000 ft from start of link*
- *Message sent at 7:01 (25260 s)*
- *Incident end message sent at 7:17 (26220 s)*
- *Incident blocking 2 lanes from curb (all ramp lanes)*
- *Impact factor of 10,000 to be used while incident is in effect*



Veh	PCUs	Truck	Bus	Origin	Dest	Trip Start
83760	1	0	0	35	20	6:53:04

Scenario	Trip Dist (ft)	Travel Time (s)	Avg Trip Speed (mph)	Trip Cost	Total Delay (s)	Stopped Delay (s)	Number of Stops
Without Reroute	59,083	1,721	23.4	1,615	1,114	919	2
With Reroute	72,808	1,410	35.2	2,272	486	75	5
Difference	13,725	-311	11.8	657	-628	-844	3

Figure 5-20 – Incident Rerouting Example

5.5.2.4. Application Example

An example of incident rerouting is shown in Figure 5-20. The example models an incident that completely blocks the ramp from I-96/I-275 to I-696 eastbound from 7:00 to 7:15. While the incident starts at 7:00, it is assumed that IntelliDrive^{SM} vehicles receive notification of its occurrence at 7:01. Similarly, after the incident has been cleared, two minutes elapse before vehicles are notified that the ramp is again fully open. To entice vehicles to seek alternate routes while the incident is active, the affected ramp is finally assigned an incident cost factor of 10,000. The figure shows the path taken by a vehicle around the incident. The original path is shown in green and has the vehicle traveling along the freeway. The rerouted path is shown in red and has the vehicle taking a nearby arterial up to the next interchange to bypass the incident. While the reroute results in a path that is longer by 2.6 mi, it results in an overall travel time saving of more than 5 min compared to a situation in which the vehicle would have had to wait in a queue for the incident to be cleared.

5.5.3. Link Flow Projections

An application has been programmed to allow Paramics to keep track of projected link flows on individual links. This application uses the expected link entry time attached to an individual link record within a vehicle's projected path to compile future demand for each link. As it requires knowledge of the projected path of a vehicle, this application can only be used if the routing application described in Section 5.5.1 has been activated for IntelliDrive^{SM} vehicles.

To account for potential time-based fluctuations, the projected demand for each link is compiled in intervals. The duration of these intervals is to be defined by the user. If the user specifies the use of 5-minute intervals, projected link entry flows will then be compiled for each successive 5-minute interval.

In addition to dividing flow projections in intervals, updates are made when the following events occur:

- Each time a new route is generated upon the release of a vehicle from an origin zone
- When an existing route is updated
- When a vehicle transfers from one link to the next

In the first case, the projected link entry times of the newly released vehicle are used to increment the number of vehicles expected to enter each link along its path within the time interval corresponding to each link's entry time. In the second case, projected flows on individual links within a specific interval are adjusted to account for changes in the time at which a vehicle is projected to enter the link. This adjustment only has an impact if it results in a vehicle entering a link in a different time interval. Adjustments are also made to account for path changes. For instance, projected flows would be decreased on links that are removed from the projected path of a vehicle and incremented on links that are part of any new projected route. In the last case, the addition and subtraction to projected flows are carried out to account for vehicles entering and leaving links.

Flow projections are made both for individual link exit movements (for instance, right-turning, through and left-turning vehicles) and for entire link traffic as a whole. This enables evaluations of applications focusing on all the vehicles traveling on a link or vehicles making specific turn decisions.

Paramics does not explicitly label turn movements as "right-turn," "through," or "left-turn" movements. Turn movements are defined within Paramics by a link exit index number. This index number varies between 0 and the number of links that can be accessed from the current link. Each link that can be accessed is assigned a specific index number that does not necessarily correspond to a specific movement. The movement associated with each index can be uniquely defined by outputting the pair of links associated with the movement, in the order in which vehicles travel the links.

6. Evaluation of IntelliDrive^{SM} Probe Vehicle Data Collection Processes

This chapter focuses on evaluations aiming to determine the general quality and characteristics of probe vehicle data that may be collected through an IntelliDrive^{SM} system relying solely on the use of roadside communication units (RSEs) to retrieved data from individual vehicles. The importance of such an evaluation lies in the potential effects that insufficient or inaccurate data may have on the operation of specific applications. Specific issues that are evaluated in this chapter include:

- Data sampling rate
- Ability to collect data from every link in a network
- Potential for data bias due to snapshot generation protocols
- Potential data losses due to full memory buffer
- Impacts of privacy rules on quantity of data collected
- Ability to effectively track vehicles over short distances and across intersections
- Data latency

6.1. Data Sampling Rate

One of the main touted benefits of IntelliDrive^{SM} systems is the ability to collect data from every link on which a probe vehicle travels. From a theoretical standpoint, this will eventually allow data to be collected from every road or street in a network once all vehicles would be equipped with wireless communicators. While it may be possible to collect data from every link, a more practical issue is whether enough data can be collected to support intended uses. Since traffic flow is subject to stochastic variations, using information provided by a few snapshots will not be sufficient in many cases to provide reliable estimates of traffic conditions and support operational decisions.

While some applications may require only a few data points, others may require significantly more. For instance, a link with stable traffic conditions may only require 4 or 5 speed samples to assess the average link speed at a given confidence level for a specified tolerable error. For moderately variable conditions, more than 20 samples may be needed to reach the same level of confidence for the given tolerable error (Oppenlander, 1976; Quiroga and Bullock, 1998a, 1998b). Specific confidence levels tolerable errors will also vary based on the application. Confidence levels suggested in NCHRP Report 398 (Lomax *et al.,* 1997) for the collection of travel data to quantity congestion vary between 80% and 90% for planning activities, and between 90% and 95% for operational analyses. Confidence level for Highway Pavement Monitoring System data vary within the same range. Tolerable errors typically vary between 5% and 20%, with 5% often used for design and operational analysis and 10% for planning and programming studies.

The quantity of data collected by probe vehicles will greatly depend on the design parameters used for snapshot generation. To illustrate this effect, the virtual probe vehicle data generator described in Chapter 5 is used to estimate the quantity of data that could be collected from individual roadway links in a network under various snapshots generation protocols. For this evaluation, the test network of Figure 6-1 is used as a case study. As indicated previously, this network models the 57 RSEs that were used in 2008 for the USDOT VII POC test program in Novi, Michigan.

The simulation setup assumes that all RSEs within the network operate with an effective communication range of 1600 ft (500 m), which corresponds to the range that was observed to produce fewer communication problems during the POC tests. Data collection protocols are further generally configured to match those used during the POC tests. To remove effects due to changes in traffic patterns, a constant traffic demand is simulated between all origin and destination zones. This demand leads to the generation of approximately 70,000 vehicles per hour. All these vehicles are further assumed to have the capability to generate snapshots and communicate with RSEs, as well as to hold a standard 30-snapshot buffer. Two types of data generation protocols are finally considered: protocols generating snapshots according to a fixed interval and protocols generating snapshots based on the speed of the vehicle.

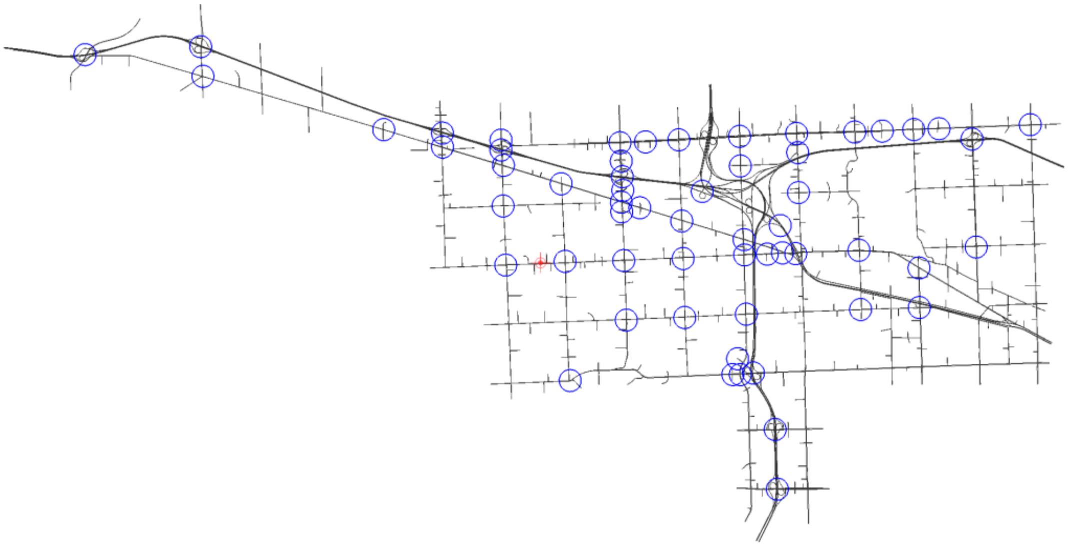


Figure 6-1 – Evaluation Model of POC Test Network with 500-m Communication Range

Table 6-1 – Effects of Design Parameters on Snapshots Generated and Collected

20 mph Speed interval (s)	60 mph Speed interval (s)	Number of snapshots uploaded per RSE (snaps/RSE/min)	Number of snapshots generated per vehicle (snaps/veh)	Number of snapshots discarded per vehicle due to PSN rules (snaps/veh)	Number of snapshots deleted per vehicles due to a full buffer (snaps/veh)	Number of snapshots lost per vehicle due incapacity to connect with an RSE (snaps/veh)	Number of snapshots uploaded to RSE per vehicle (snaps/veh)
Fixed time intervals							
1	1	156,208	430.6	47.7	227.7	27.2	128.0
2	2	125,172	217.3	23.9	66.3	24.4	102.7
3	3	99,597	146.2	15.9	27.0	21.4	81.9
4	4	81,411	110.7	12.0	13.1	18.6	67.0
5	5	68,513	89.3	9.6	7.0	16.2	56.5
10	10	37,795	46.6	4.9	0.7	9.8	31.2
15	15	26,374	32.3	3.3	0.1	7.1	21.8
20	20	20,517	25.2	2.6	0.0	5.7	16.9
25	25	17,048	20.9	2.1	0.0	4.7	14.1
30	30	17,048	20.9	2.1	0.0	4.7	14.1
Speed-based time intervals							
4	5	76,530	104.5	11.1	12.3	18.0	63.1
4	10	52,398	69.5	6.7	5.3	14.1	43.4
4	15	42,285	55.6	5.1	3.3	12.1	35.1
4	20	36,377	47.6	4.2	2.4	10.8	30.2
4	25	32,320	42.2	3.6	1.8	9.9	26.9
4	30	29,334	38.2	3.2	1.4	9.2	24.4

* Scenario: 100% market penetration / 500 m communication range / 30-snapshot buffer / PSN rules active
* Data representing average of twelve 5-minute periods

Table 6-1 compiles the simulation results. To account for stochastic effects, the table presents average quantities of snapshots generated and collected over twelve successive 5-min intervals. As can be observed, altering the snapshot generation protocol significantly affects data collection. Calling for snapshots to be taken at intervals varying between 4 and 20 s based on the speed of the probe vehicle leads to the generation of an average of 47.6 periodic and stop/start event snapshots per vehicle. However, because of the use of a small 30-snapshot buffer, which also represents a current recommendation, 2.4 snapshots are discarded on average per vehicle to make room for new ones in full buffers. An additional 4.2 snapshots per vehicle are also discarded by the application of rules governing the use of PSNs. Overall, only 30.2 snapshots are effectively retrieved from each vehicle, resulting in an average upload rate of 36,377 snapshots per minute per RSE. This rate is less than the one that would be obtained by simply subtracting the number of snapshots discarded from the number of snapshots generated since many vehicles are not able to come within range of a new RSE before reaching their destination. This effect results in all the snapshots remaining in their buffer at the time they leave the network (turn their engine off) to be effectively lost.

Using a fixed 4-s snapshot interval protocol increases the generation rate by 132% when compared to the default speed-based variable protocol. This increase results in each vehicle generating on average 110.7 periodic and stop/start event snapshots. However, due to the increased data storage needs, more snapshots are also discarded due to the 30-snapshot buffer becoming full more frequently. On average, 13.1 snapshots are discarded per vehicle for this reason. Further considering the data discarded due to privacy rules and the snapshots lost when vehicles reach their destination, the fixed 4-s interval protocol produces an effective upload rate of 67.0 snapshots per vehicle. This yields an average upload rate of 81,411 snapshots per RSE per minute, which represents a 125% increase over the default speed-based variable protocol.

6.2. Network Coverage

Data collection rates are function of RSE placements. To illustrate this effect, the test network shown in Figure 6-1 is again used as a case study. In this case, simulations were executed to determine the number of links from which at least 1 snapshot, 30 snapshots and 60 snapshots could be obtained on average over a 5-min period under a constant, typical AM-peak morning traffic demand with market penetrations varying between 1 and 100%.

The simulation results are shown in Table 6-2. The ability to collect at least one snapshot represents in this case a boundary scenario that is used to assess the impacts of higher data collection needs. Under the assumed demand pattern, the current RSE placement would allow on average at least one snapshot to be obtained every 5 min from nearly 90% of the links within the test network on which probe vehicles travel in a full market penetration situation. Links with no vehicles traveling on them are not considered to avoid biasing the assessment. The 10% remaining links are primarily links located at the boundary of the network. While probe vehicles travel on them, these vehicles do not come within range of an RSE before reaching their destination. As a result, they have no opportunity to upload the snapshots they generate on the link. This results in a complete loss of data for these links.

If the data collection requirement is increased to at least 30 snapshots, sufficient data is then only obtained from approximately 64% of the network links. If the requirement is further increased to 60 snapshots, sufficient data is then collected from less than 50% of the links. The significance of these results does not lie in the exact percentage of links covered but in the demonstration that the performance of applications relying on individual link data will be affected by the number and location of RSEs. Adding RSEs would obviously improve network coverage by allowing the capture of data from more vehicles. Similar effects could also be obtained by strategically changing the location of the existing set of RSEs to ensure the widest possible network coverage.

Table 6-2 – Effect of Market Penetration Level on Network Coverage

Market Penetration (%)	Links with at least 1 Snapshot (%)	Links with at least 30 Snapshots (%)	Links with at least 60 Snapshots (%)
1	73.1	0.7	0.1
3	81.2	2.6	0.9
5	83.3	5.7	1.9
10	85.3	14.3	6.0
20	86.9	27.6	14.5
30	87.3	37.5	19.7
40	87.7	44.3	27.7
50	87.8	49.3	33.0
60	88.1	52.3	37.7
70	88.3	56.6	40.9
80	88.4	59.2	44.2
90	88.5	61.4	47.2
100	88.6	64.1	49.4

* Scenario: 100% market penetration / 500 m communication range / 30-snapshot buffer
* Data representing average of twelve 5-min periods

The number and location of RSEs used in actual deployments will likely depend on funds available for installation and maintenance and specific network surveillance needs. If funds only allow installations along major roadways, such as freeways and major urban arterials, it could then only be expected that adequate data collection will be possible for the roads targeted by the positioned RSEs. However, data may also be obtained from streets feeding traffic to the roads under surveillance and lesser roads in the immediate surroundings of RSEs, as opportunities would exist to capture snapshots generated by vehicles traveling on these streets, whether or not they end up traveling on the roads that are the focus of the surveillance. Data collection from roads and streets further would also be possible depending on local traffic patterns.

6.3. Potential Data Biases

Another potential effect of altering the protocol used for generating snapshots is a potential bias on the types of traffic conditions characterized. To illustrate this bias, Figure 6-2 compares the snapshots generated along an arterial link between two intersections. In this example, the downstream intersection is controlled by a traffic signal while the upstream intersection only has a stop sign on the cross street. For each case, two graphs are shown. The top graph plots the speed recorded by each snapshot according to its location along the link while the bottom graph bins the recorded speeds in 5-mph groups. In each of the bottom graphs, the listed average speed is obtained by averaging the speeds contained in all the captured snapshots. Since all three scenarios consider the same underlying traffic demand, the traffic conditions on all simulated links are therefore identical in all three cases.

When considering the time that each vehicle actually takes to travel across the link, an average travel speed of 19.4 mph is obtained. However, as can be observed by comparing the speed distributions compiled in the three bottom graphs of Figure 6-2, improper snapshot generation protocols can create significant biases in the collected data:

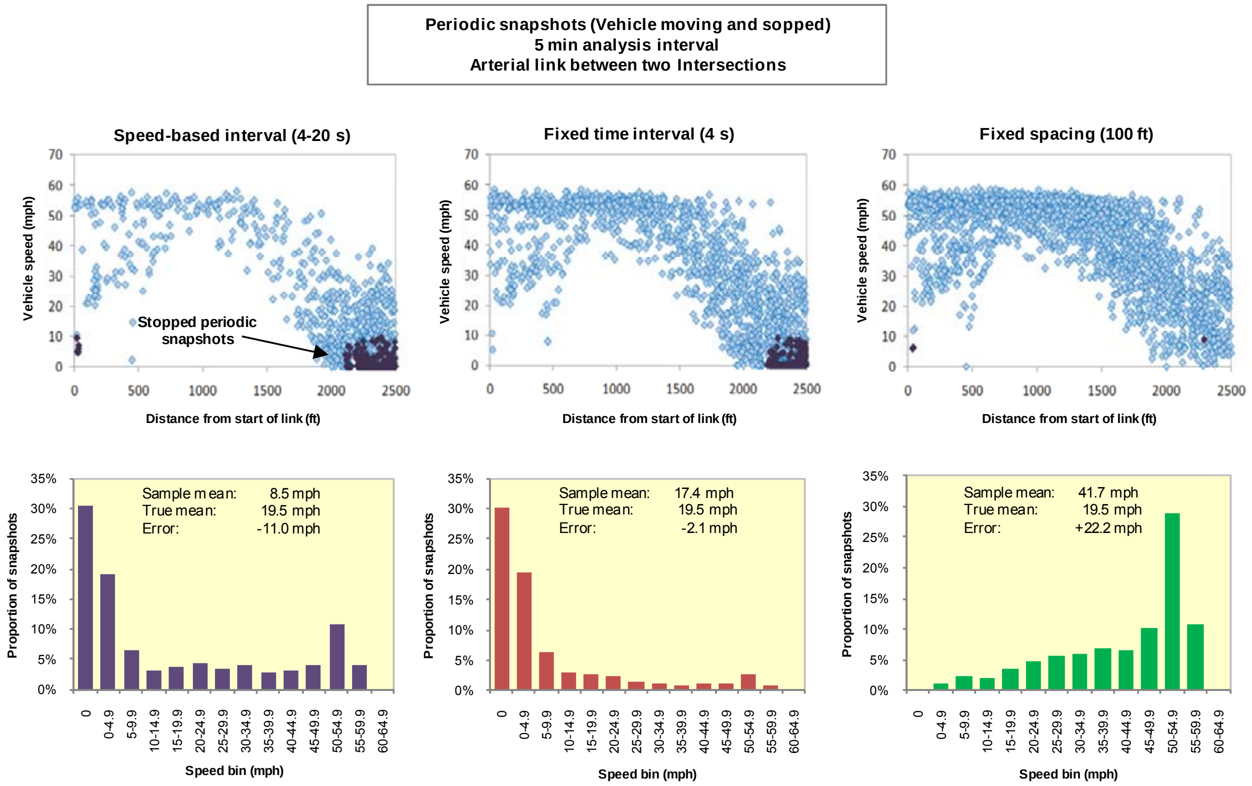


Figure 6-2 –Distribution of Snapshots by Speed under Various Generation Protocols

- Under the current protocol varying the interval between snapshots between 4 and 20 s based on the speed of the vehicle, snapshots are generated at closer intervals when traveling at slower speeds. This results in more snapshots characterizing low-speed conditions than high-speed conditions. The bias can be significant if there is a large difference between the intervals used at high and low speed. In Figure 6-2, the average speed of all recorded snapshots is 8.5 mph, which is significantly lower than the true average speed of 19.4 mph.
- With a fixed 4-s interval, there is a more representative distribution of snapshots across all traffic conditions. However, a slight bias towards low speeds still exists, as vehicles traveling at lower speed still generate more snapshots per unit distance than faster vehicles. This results in an average speed across all snapshots of 17.4 mph, which is much closer to the true average speed of 19.4 mph.
- Using a fixed spacing based on distance traveled would theoretically provide a more accurate sampling of traffic conditions along a link. However, such a protocol would not provide a representation of congested conditions as stopped vehicles would not generate any snapshots until they start to move again. This explains the 41.7 mph average speed across all snapshots.

Based on the above assessment, there is no ideal protocol as each of the protocols investigated results in some form of bias. An ideal approach may be to combine protocols, such as using distance-based sampling when vehicles are moving and time-based sampling when vehicles are stopped. However, if the solution field is restricted to the three simple protocols defined above, it would then be recommended to use a short, fixed-time snapshot interval as such a protocol is thought to provide the least bias over all possible traffic conditions.

6.4. Data Losses due to Insufficient Buffer Size

Current snapshot generation protocols only require that vehicles hold a 30-snapshot onboard memory buffer to store all the snapshots generated while outside the range of an RSE. If the buffer becomes full, old snapshots are to be discarded to make room for new ones. Section 5.4.9 outlined the rules determining which snapshots are to be deleted depending on the content of the buffer. Such deletions can result in potentially significant data losses if a buffer frequently reaches its maximum capacity.

The impacts of an insufficient buffer size can be observed in the simulation data of Table 6-1. The data shown in the table assume that all vehicles can only store 30 snapshots in their onboard memory buffer. Generating snapshots at intervals varying between 4 and 20 s based on the speed of a vehicle, as currently recommended, results in the discarding of 2.4 snapshots per vehicle on average due to a full buffer. This represents about 5% of the total snapshots generated. Under a fixed 4-s interval protocol, an average of 13.1 snapshots would then be discarded, which would represent about 12% of all generated snapshots.

As shown in Figure 6-3, tests with various buffer sizes indicate that a buffer capable of storing at least 80 snapshots would result in relatively minor losses over the test network of Figure 6-1 when generating snapshots at intervals varying between 4 and 20 s based on the speed of the vehicle. A buffer capable of holding 100 snapshots would further allow retaining virtually all the snapshots generated. With a fixed 4-s interval protocol, a 150-snapshot buffer would result in negligible losses while a 250-snapshot buffer would eliminate virtually all losses. These results are consistent with the recommendation made by the POC test evaluators that a 300-snapshot buffer should be used instead of a 30-snapshot buffer to reduce data collection losses.

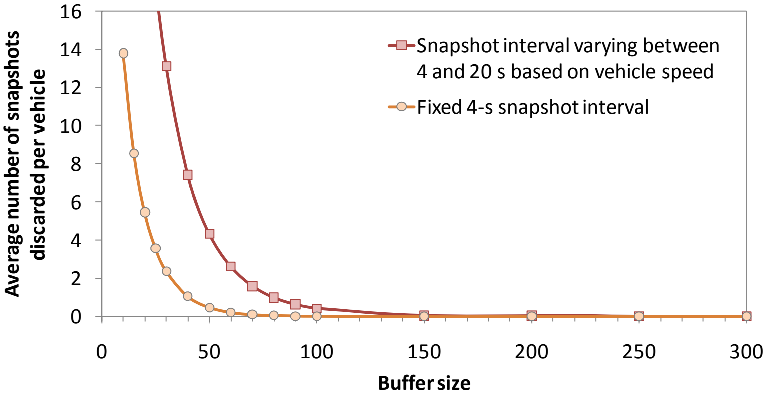


Figure 6-3 – Number of Snapshots Discarded as a Function of Buffer Size under Standard Snapshot Generation Protocol

The assessments of Table 6-1 and Figure 6-3 are based on scenarios considering only the generation of periodic and stop/start event snapshots. While allowing additional types of snapshots to be generated would increase buffer size requirements, explorations with scenarios including the generation of additional types of snapshots indicate that a 300-snapshot buffer could still be adequate to accommodate the extra storage needs. Figure 6-4 illustrates the impact on the number of snapshots deleted due to a full buffer of allowing vehicles to generate snapshots while stopped, when exiting a link and when starting or ending a trip. While there is a significant increase in the number of data lost with small buffer, a 300-snapshot buffer still appears adequate.

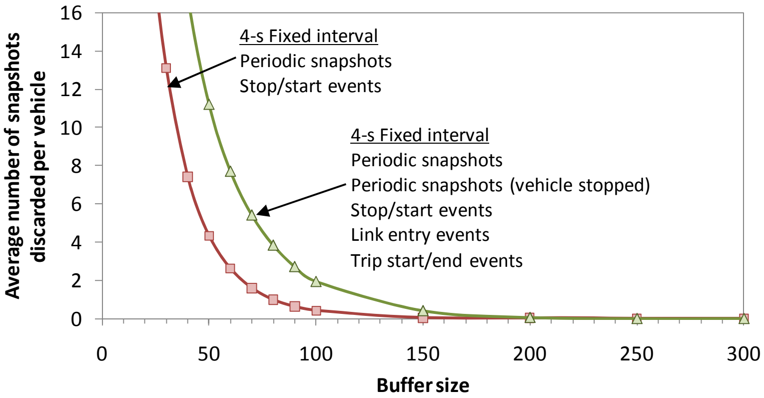


Figure 6-4 – Number of Snapshots Discarded as a Function of Buffer Size under Standard and Expanded Snapshot Generation Protocols

In addition to the number of snapshots lost, full memory buffers will have different impacts on the number of periodic, stop/start and special events snapshots that may be lost. Based on current data handling protocols, snapshots are discarded from a full buffer to make space for new snapshots in the following order:

- When more than one periodic snapshot is in the buffer, the second oldest available periodic snapshot is removed to make room for the new snapshot. The oldest snapshot is kept to retain information about the length of time and traveled distance since the last RSE communication.
- If only one periodic snapshot remains, this snapshot is removed.
- If there is no periodic snapshot in the buffer, the oldest stop/start event snapshot is removed to make room for new stop/start snapshots. No removal is made to allow new periodic snapshots to be added to the buffer.
- If there is no periodic or stop/start event snapshot, the oldest special event snapshot is then removed. No removal is made to enable the addition of new periodic or stop/start snapshots.

Based on the above rules, periodic snapshots would generally suffer the greatest losses from the occurrence of full memory buffers. Stop/start event snapshots would only be discarded in cases in which there remain no periodic snapshot to delete. This may occur if a vehicle travels for a long time or stops frequently between two RSEs, or if it generates a large number of stop/start or special event snapshots.

While the use of a 30-snapshot buffer may have been promoted for cost efficiency reasons, the use of such a small buffer must be weighed against potential data losses, particularly in situations in which it may be desired to collect periodic snapshots at a high frequency. Allowing too much data to be lost due to insufficient memory capacity may also be viewed as inefficient system operations. This assessment points to the need to use larger memory buffers and further supports the recommendation from the POC evaluators that a 300-snapshot buffer should be used instead of a 30-snapshot buffer to reduce the frequency with which a vehicle's memory buffer may become full.

6.5. Impacts of Privacy Rules

As was indicated in Section 2.5, the following rules are imposed on the snapshot generation process to ensure the privacy of travelers:

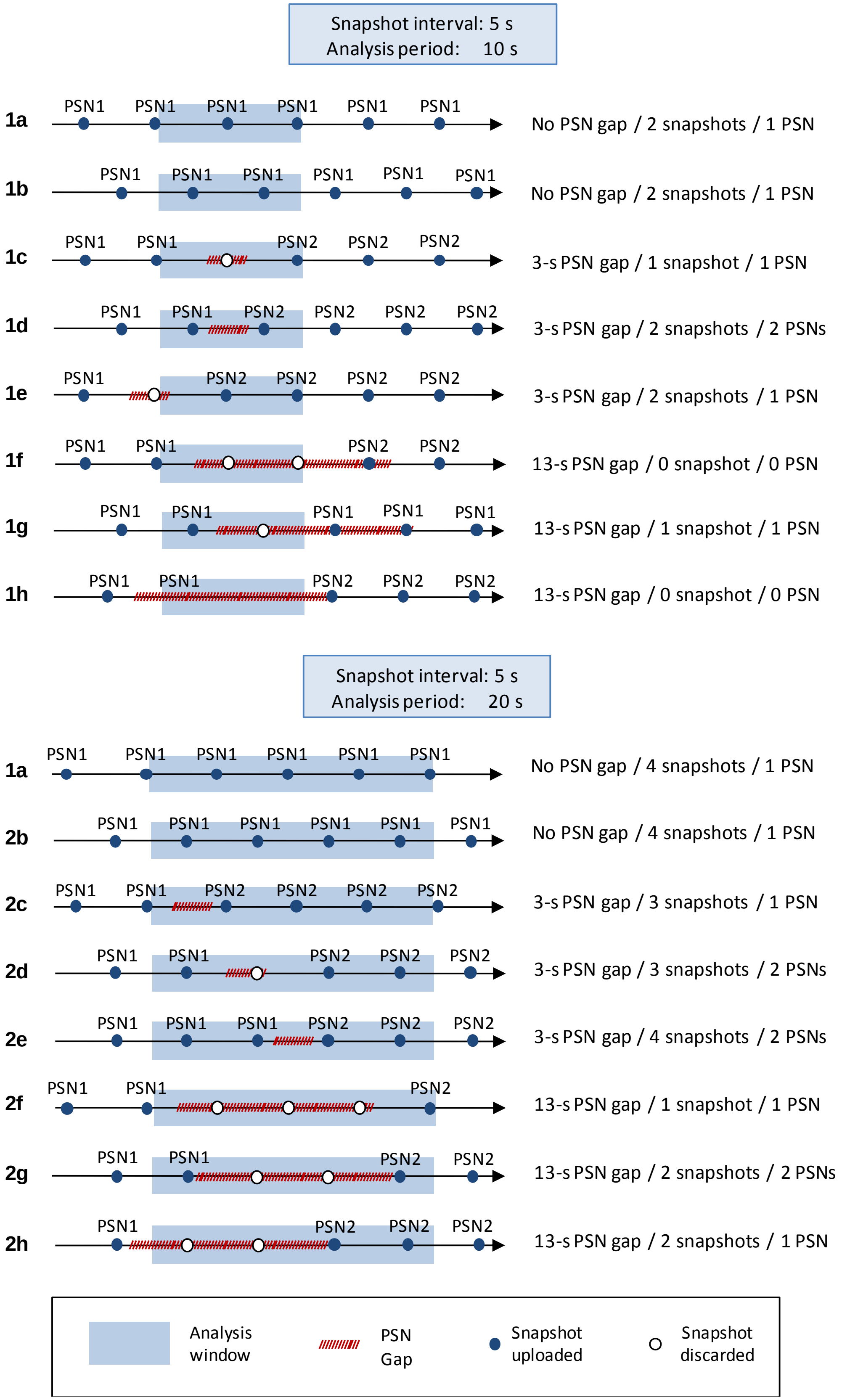


Figure 6-5 – Effect of PSN Switch Rule on Snapshot Generation

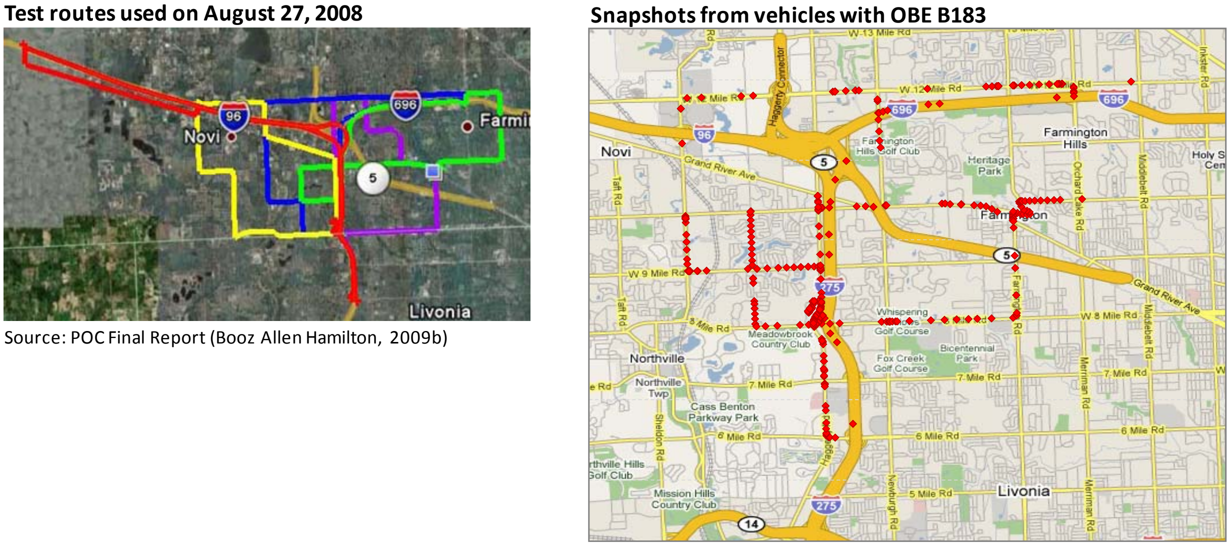
- The PSN assigned to snapshots must be changed when a vehicle has traveled 3280 ft (1000 m), or when 120 s has elapsed since the last change, whichever occurs last.
- Following a change of PSN, all periodic snapshots generated during a randomly determined interval of 3 to 13 s, or 164 to 820 ft (50 to 250 m), whichever occurs first, are discarded.
- After a snapshot with a specific PSN has been uploaded to an RSE, other snapshots generated with the same PSN cannot be uploaded at other RSEs. This effectively results in all snapshots generated with the same PSN to be effectively discarded.
- To reduce the probability of generating snapshots with a PSN that has already been used by snapshots uploaded to an RSE, vehicles are required to change their PSN immediately after having emptied their memory buffer, as well as upon termination of a connection with an RSE.

Figure 6-5 illustrates some of the effects that these rules may have on the number of snapshots that may be collected from a vehicle. For simplicity, all scenarios consider a fixed 5-s interval between snapshots. Scenarios on the top half of the figure illustrate the snapshots that would be generated in a 10-s analysis window, while the scenarios in the bottom half consider a 20-s window. In each scenario, the snapshots generated are represented by the circles along the timeline. The snapshots that would be retained are identified by a filled circle, while those that would discarded due to a PSN changeover gap are represented by a hollow circle.

In scenarios 1a and 1b, two snapshots would be collected within a 10-s analysis window under the assumed 5-s generation rate if all the rules regarding the use of PSNs were ignored. Scenarios 1c, 1d and 1e illustrate what may happen when a 3-s minimum gap is imposed following a change of PSN. Scenarios 1f, 1g and 1h further illustrate what may happen with a maximum gap of 13 s. Depending on when the PSN change occurs and the duration of the changeover gap, either zero, one or two snapshots may be retrieved from the passing vehicle in a 10-s window. These snapshots could further feature identical or different PSNs. The same effects can be observed in scenarios 2a through 2h, which illustrate a similar analysis for a 20-s data collection window. In this case, four snapshots would normally be generated within a 20-s interval with fixed 5-s spacing. Depending on when a PSN changeover would occur and on the length of the subsequent changeover gap, between one and four snapshots featuring either the same or two different PSNs may be retrieved from the passing vehicle.

Figure 6-6 provides another example of the potential effects of PSN rules on data collection. The figure illustrates the snapshots that were generated by a single test vehicle during the USDOT VII POC test program during a three-hour period on August 27, 2008. Such an analysis was made possible by the fact that all probe vehicle messages generated during the tests were tagged with a message serial number containing the identification number of the OBE transmitting the data. All the snapshots produced by a specific vehicle could therefore be identified by simply retrieving messages featuring the same OBE identification number. Due to the PSN rules, the test vehicle shown in the figure was observed to generate 452 snapshots using 199 unique PSN values over a three-hour period. This results in each PSN being tagged on an average to only 2.3 snapshots.

While gaps of up to 13 s in the illustrated path of Figure 6-6 could be directly linked to the discarding of snapshots during mandatory PSN changeover gaps, the occurrence of longer gaps can be explained by other effects:



Test routes used on August 27, 2008

Snapshots from vehicles with OBE B183

Source: POC Final Report (Booz Allen Hamilton, 2009b)

Figure 6-6 – Snapshots Generated by a Single POC Test Vehicle over a Three-Hour Period

- **Full memory buffer.** Vehicles used in the POC tests had a relatively small 30-snapshot buffer. Because of this small buffer, the test vehicle may have on occasion completely filled up its buffer with snapshots while traveling between RSEs relatively far apart. In such cases, the oldest snapshots contained in the buffer would have been deleted to make room for new ones, thus creating holes in the data sequences.
- **Unexpected RSE connection termination.** Occasionally, RSE connections were unexpectedly lost due to technical reasons. When such terminations occurred, the probe vehicles were instructed to dump all the snapshots remaining in their memory buffer, thus creating additional holes in the data sequences. Data dumps were ordered because RSEs were unable to determine if a specific vehicle was able to re-establish connection with them. Estimates from the POC evaluations indicate that up to 10% of all snapshots could have been lost due to such effects [VII Consortium, 2009c].

Another effect of the privacy rules can be found in the simulation results of Table 6-1. The fifth column indicates the number of snapshots that have been discarded due to the imposition of PSN changeover gaps. In the absence of gaps, all the snapshots listed in the column would have been retained. In this case, the simulation data indicates that between 8 and 11% of all the snapshots generated were discarded due the imposition of temporary blocks on snapshot recording.

Comparing the above simulation results with the POC test evaluations is not straightforward due to potential differences in how the evaluations are made:

- As indicated above, RSE connections within the POC tests were on occasion unexpectedly terminated due to technical issues. This resulted in the dumping of all unset snapshots from the memory buffer. Within UMTRI's probe data simulator, unexpected communication terminations do not occur and data transfer occurs instantly. Vehicles are therefore always able to upload all the data contained in their buffer. In this context, assessed data loss within the simulator should convert into higher losses in actual systems.
- In the POC evaluations, losses are assessed against the number of snapshots present in a vehicle's memory buffer when communication with an RSE is established. This ignores the

snapshots discarded during a PSN change. In the probe data generator, data losses are assessed against the total number of snapshots that could have been generated if all privacy rules were removed. This results in a higher number of discarded or lost snapshots than what would have been assessed with the POC approach.

The POC and simulation evaluations indicate that current privacy rules may result in approximately 10% data losses, even with all system components are operating as intended. The following summarizes the general impacts that rules surrounding the use of PSNs may have on the generation, collection and uses of probe vehicle snapshots:

- Potential reduction in the number of snapshots collected from probe vehicles due to the imposition of gaps in snapshot generation. This may affect the accuracy of traffic condition assessments on links where a non-negligible portion of snapshots may be lost.
- Since PSN are meant to be the only element allowing snapshots to be associated to specific vehicles, the use of multiple PSNs by a given vehicle may lead to incorrectly assuming that snapshots generated by the vehicle come instead from different ones. This may have impacts on applications attempting to use probe data to count vehicles.
- Inability to estimate the true origin and true destination of a vehicle, as vehicles are prevented from using the same PSN for more than 3280 ft (1000 m) or 120 s.
- Potential increase in the minimum amount of snapshots to collect, and thus minimum market penetration required, for applications to reach an effective operating level or start yielding benefits.

A potential solution to reduce data losses without significantly affecting privacy needs is suggested in the USDOT POC evaluation report. This solution first consists in allowing vehicles to try to reconnect with an RSE following the unexpected termination of a connection. This reconnection would be tried before ordering the deletion of any data remaining in a vehicle's memory buffer. To prevent the RSEs from rejecting the snapshots that are still to be uploaded because they share a PSN with previously uploaded data, the RSEs should also be allowed to recognize the new connection as coming from a vehicle that was previously uploading data to them.

6.6. Short-Distance Vehicle Tracking

While long-distance tracking is intentionally restricted to protect the privacy of travelers, tracking over short distances is allowed to enable various evaluations, such as analyzing lane-changing behavior or determining turn movement proportions at decision points.

As outlined in Section 2.5, the primary mechanism for tracking vehicles is through the tagging of a short-lived PSN to periodic snapshots. Current rules trigger a PSN change after a vehicle has traveled 3280 ft (1000 m) or 120 s, whichever occurs last. Since both criteria must be met, the rules theoretically allow individual vehicles to be tracked over a minimum distance of 0.6 mi (1000 m), which is somewhat similar to what an observer standing on the side of the road can already do. The maximum tracking distance will depend on the distance that can be traveled in a two-minute interval. As shown in Table 6-3, the rules would for instance allow tracking a vehicle traveling at 50 mph for 1.67 mi if nothing else triggers a PSN change. For a vehicle traveling at 70 mph, tracking could be done over a distance 2.33 mi.

Table 6-3 – Traveled Distance over 120 s at Constant Speed

Speed (mph)	Speed (ft/s)	Distance over 120 seconds (ft)	Distance over 120 seconds (mi)
5	7.33	880	0.17
10	14.67	1760	0.33
15	22.00	2640	0.50
20	29.33	3520	0.67
25	36.67	4400	0.83
30	44.00	5280	1.00
35	51.33	6160	1.17
40	58.67	7040	1.33
45	66.00	7920	1.50
50	73.33	8800	1.67
55	80.67	9680	1.83
60	88.00	10560	2.00
65	95.33	11440	2.17
70	102.67	12320	2.33
75	110.00	13200	2.50
80	117.33	14080	2.67
85	124.67	14960	2.83
90	132.00	15840	3.00

Current protocols further require vehicles to change their PSN after they have emptied their memory buffer, which typically occurs after a communication has been established with an RSE and when they leave the range of the RSE. This can results in more frequent PSN changes than what is required by the time and distance criteria presented above and can significantly reduce the capability to track vehicles of usable distances.

To assess short-term tracking capability, all the periodic snapshots from the USDOT POC test program collected between August 20 and 28, 2008 were compiled. This period correspond to main application testing phase. The 64,444 snapshots that were collected during this period were tagged with 22,777 unique PSNs, yielding an average of 2.83 snapshots per PSN. If a maximum interval of 20 s is considered between consecutive snapshots, as defined in the default generation protocol, the above statistics yield an average tracking time of 56 s, which is much shorter than the 120 s tracking time allowed by the defined privacy rules. This shorter tracking capability can be linked to rules requiring vehicles to change their PSN after emptying their buffer or leaving the range of an RSE. Unexpected communication losses, which were observed to occur somewhat frequently and which triggered mandatory purges of the vehicle's memory buffer, may have also contributed to the situation. A few RSEs were also not operational, which may have resulted in some vehicles filling their memory buffer and discarding snapshots more frequently than expected.

Figure 6-7 provides an alternate analysis of snapshot groupings from the POC tests. The figure illustrates how many PSNs were assigned to one snapshot, two snapshots, three snapshots, etc., under current default snapshot generation protocols. As can be observed, only 79% of snapshots were assigned a PSN that was used by at least another snapshot. While two snapshots sharing a PSN technically allow some vehicle tracking, this may not be sufficient for practical uses. If we consider larger groupings, 59% of snapshots were assigned a PSN that was used by at least 4 snapshots. 32% of snapshots were further assigned a PSN that used by at least 10 snapshots, while 21% were assigned a PSN used by 20 or more snapshots. The last grouping notably only contains 0.5% of all PSNs. It also holds and significant number snapshots generated by stopped vehicles.

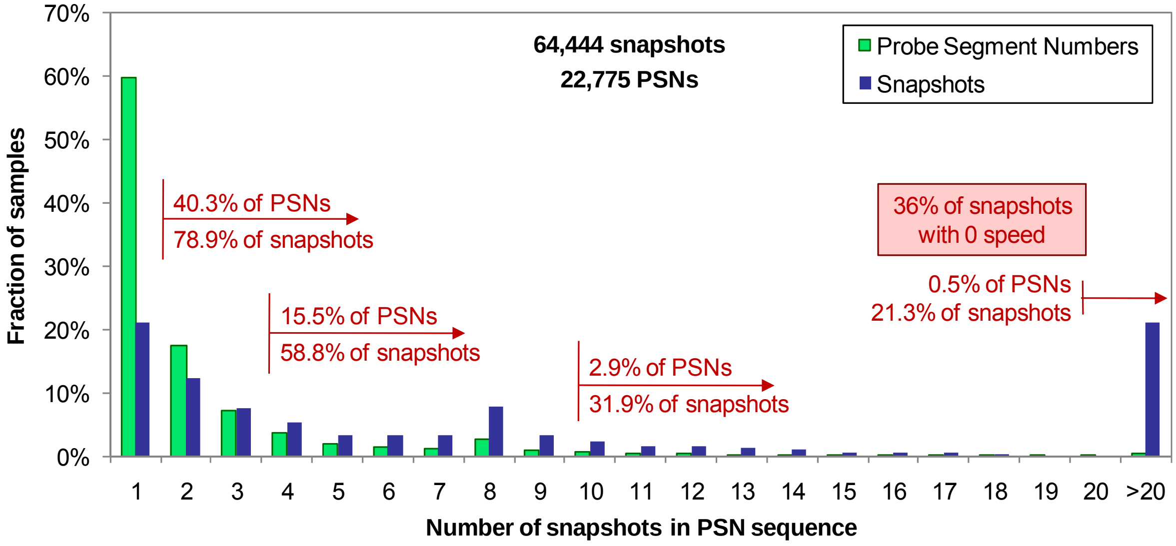


Figure 6-7 – Distribution of PSN Snapshot Groupings in POC Test Data

The above data indicate a relatively small ability to track large numbers of vehicles over usable distances. To validate this assessment, UMTRI's probe vehicle data simulator was used to assess the impacts of alternative data generation protocols on PSN groupings. The simulation results are shown in Table 6-4. These results are for scenarios in which all vehicles generate snapshots. For the default speed-based data generation protocol, the simulations indicate that 58.3% of all PSNs would be assigned to at least two snapshots when discarding all periodic snapshots generated by stopped vehicles. 31.5% of PSNs would further be assigned to groups of 4 or more snapshots, 11.0% to groups of at least 10 snapshots, and 1.2%t to groups of 20 or more snapshots. When comparing these results with the data of Figure 6-7, it can be observed that the simulation results are generally consistent with the POC data.

While some difference exists between the field and simulation data, these can be explained by various factors. For instance, the POC tests only involved a few vehicles traveling along a limited number of routes while the simulation data consider snapshots generated by thousand of vehicles traveling along a wide range or paths. The POC data include potential data losses from the use of a relatively small 30-snapshot buffer while the simulations used a 900-snapshot buffer to eliminate such losses. The POC data further incorporate the effects of data losses from unexpected terminations of RSE connections, which do not occur in the simulations.

Table 6-4 – Impacts of Alternate Generation Protocols on PSN Snapshot Groupings

Data generation protocol	Number of snapshots in PSN group							PSN groups crossing an intersection
	2+	4+	6+	8+	10+	15+	20+	
USDOT proof-of-concept test data								
Periodic snapshots only	40.3	15.5	9.7	6.7	2.9	0.9	0.5	Not estimated
Speed-based interval (4-20s)								
Periodic snapshots only	58.3	31.5	21.7	15.0	10.9	4.2	1.2	27.5%
Periodic + stopped periodic snapshots	55.8	30.9	22.5	17.0	13.9	8.0	3.8	30.7%
Fixed time interval (4s)								
Periodic snapshots only	85.9	72.9	56.1	39.3	29.0	16.5	9.3	49.0%
Periodic + stopped periodic snapshots	85.0	72.3	55.7	39.4	29.7	18.5	11.9	48.7%

* 100% market penetration / 500-m RSE range / 900-snapshot buffer
* Data representing an average of twelve 5-min sampling intervals

According to the data of Table 6-4, allowing vehicles to generate snapshot more frequently at high speeds appears to impact tractability significantly. Under current data generation protocols, a vehicle traveling at 65 mph (105 km/h) would generate a snapshot every 20 s, which translates into a snapshot approximately every 1900 ft (580 m). Since vehicles are required to change their PSN after emptying their buffer and exiting the range of an RSE, networks with closely spaced RSEs, such as the once considered, would frequently force vehicles to change their PSN before a second or third one could be generated. Forcing vehicles to change their PSN every 3280 ft (1000 m) or 120 s further constrains operations. In this case, using a short, fixed 4-s interval significantly increases the probability that multiple snapshots can be generated with the same PSN, as exemplified by the 85% proportion of PSNs assigned to two or more snapshots under this alternate protocol.

The data further indicate that allowing vehicles to retain the periodic snapshots generated while they are stopped does not significantly improve tractability. While there are some increases in the proportion of PSN groupInsts containing 10 or more snapshots under both the default speed-based and alternate fixed 4-s interval protocols, the differences are relatively small.

6.7. Vehicle Tracking across Intersections

The data on the last column of Table 6-4 focus on the ability to track vehicles across intersections. For each scenario, the data indicate the proportion of PSN groupings containing two or more snapshots in which at least one snapshot was generated on a link leading to an intersection and another one on a link leading away from the intersection. Such sequences of snapshots are important as they allow determining whether a vehicle turned left, went straight or turned right. This information could then be used to compile turn percentages and conduct various directional flow analyses.

The simulation results indicate significant limitations in the ability to track vehicles across intersections when implementing currently recommended snapshot generation and retrieval protocols. Under the default variable speed-based snapshot interval protocol, only 27.5% of all the PSN groupings that were produced over the POC test network were found to extend across an intersection. This represents an ability to track successfully about one vehicle out of every four.

Allowing vehicles to generate snapshots more frequently improves tractability but can still results in high proportion of unusable data. For instance, while the use of a fixed 4-s snapshot interval protocol increases the proportion of PSN groupings crossing an intersection over the simulated POC network, the increase still only results in an ability to track one out of every two vehicles. Further allowing vehicles to keep generating snapshots while stopped to reduce the interval between the last snapshot on an approach link and the first snapshot on an exit link does not significantly improve data usability. As shown in Table 6-4, this option results relatively marginal changes in the proportion of PSN groupings crossing an intersection.

The low tracking capability outlined by the simulation results can be explained by interactions between the various rules forcing indicating when vehicles must change their PSN. While some vehicles may reach the distance or time triggers forcing a PSN change around an intersection, other changes may be caused by vehicles initiating or terminating connection with an RSE near an intersection. A particularly compounding factor is the imposition of a mandatory gap in data collection following each PSN change. Because of this gap, tracking capability is not only lost for vehicles initiating a PSN change within an intersection but also for vehicles potentially initiating changes 164 to 820 ft (50 to 250 m) from the intersection. Reducing the size of the gap should result in a higher proportion of usable data.

6.8. Probe Vehicle Data Latency

An important characteristic affecting the usability of collected probe vehicle data is data latency. Data latency can be broadly defined as the amount of time that elapses between the moment a piece of information is generated and the moment it is received at an application server. The older the received data is, the less useful it is for real-time applications. This section reviews some of the various elements that can impacts data latency:

- Latency from time required to reach a wireless communication zone
- Latency from wireless communication effects
- Effect of full memory buffer

6.8.1. Latency from Time Required to Reach a Wireless Communication Zone

In RSE-based data collection systems, the largest contributor to data latency is likely to be the time needed by a vehicle to reach the range of an RSE. As an example, Figure 6-8 illustrates simulation results evaluating the average latency of the snapshots that could be retrieved by each RSE within the USDOT POC network. The simulation results are for a scenario simulating a typical AM peak morning traffic across the network and assuming that all vehicles are capable of collecting and transmitting snapshots. Each vehicle was further assumed to implement existing snapshot generation and vehicle-RSE protocols. This resulted in snapshots being generated at intervals varying from 4 to 20 s based on the speed of each vehicle, and in vehicles communicating only once with each RSE. Rules governing the use of PSNs were also applied. To avoid biasing the evaluation results, all vehicles were finally assumed to have the capability to store 900 snapshots. This prevented the deletion of older snapshots to make room for newer ones when a vehicle's memory buffer would become full.

As shown in Figure 6-8, the existing snapshot generation and vehicle-RSE protocols result in snapshots being sent to an RSE on average 61 s after their generation. Particularly noteworthy is the variation of average latency across RSEs. While data collected at some RSEs have latency as low as 10 s, data collected through other RSEs exhibit latency as high as 165 s. These simulation results notably

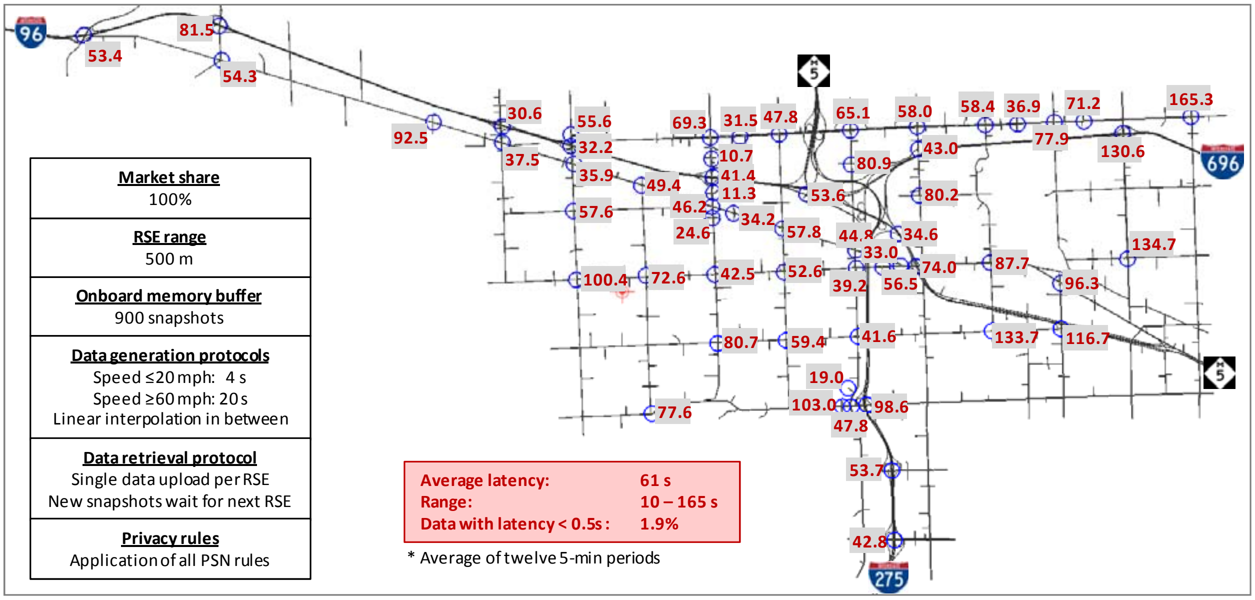


Figure 6-8 – Time from Snapshot Generation to RSE Upload with Single Upload Capability

correspond to the latencies that were observed during the USDOT POC tests over the same road network with the same RSE configuration.

An element strongly affecting data latency with RSE-based data collection systems is the density of RSEs. For instance, shorter latencies would be expected from areas with dense RSE coverage, as vehicles would not have to drive long distances to go from one RSE to the next. This effect can be observed in Figure 6-8, where average data latencies are generally shorter at RSEs in the middle of the network than at its edge. Expected latencies in rural environments can be particularly long. In this case, RSE may be installed significantly apart, such as every 50 miles. Vehicles may then have to travel for 30, 45 or 60 minutes before coming within range of an RSE. While such long delays in collecting probe vehicle snapshots may not affect offline analyses, they may significantly affect the usability of the data for real-time applications. Delays of only a few minutes may also significantly affect the ability to monitor traffic conditions and to respond effectively to dynamic changes in traffic conditions.

A potential solution to reduce latency is to allow vehicles to keep sending new snapshots to an RSE while within its range. This is not currently allowed. Following the establishment of a new connection with an RSE, vehicles are allowed to upload to the RSE all the snapshots that have been cumulating in their onboard memory buffer since the last RSE encounter. However, once this upload is terminated, vehicles must then wait to reach another RSE to upload any new snapshot generated while still within range of the first RSE. This can artificially increases data latency by several tens of seconds, if not minutes.

Figure 6-9 illustrates what would happen if vehicles were allowed to transmit immediately the snapshots generated while within range of an RSE. As can be observed, this simple change has significant impacts on latency. The average time needed across the network for a snapshot to be uploaded at an RSE reduces from 65 s to 30 s. The longest average latency at an individual RSE further reduces from 165 s to 92 s. Some RSEs even exhibit no latency (0 s), indicating that they now primarily collect snapshots generated within their range. While some RSEs experience a latency increase, this is explained by the fact that many of the more recent snapshots they used to collect under the previous scenario are now being retrieved by surrounding RSEs.

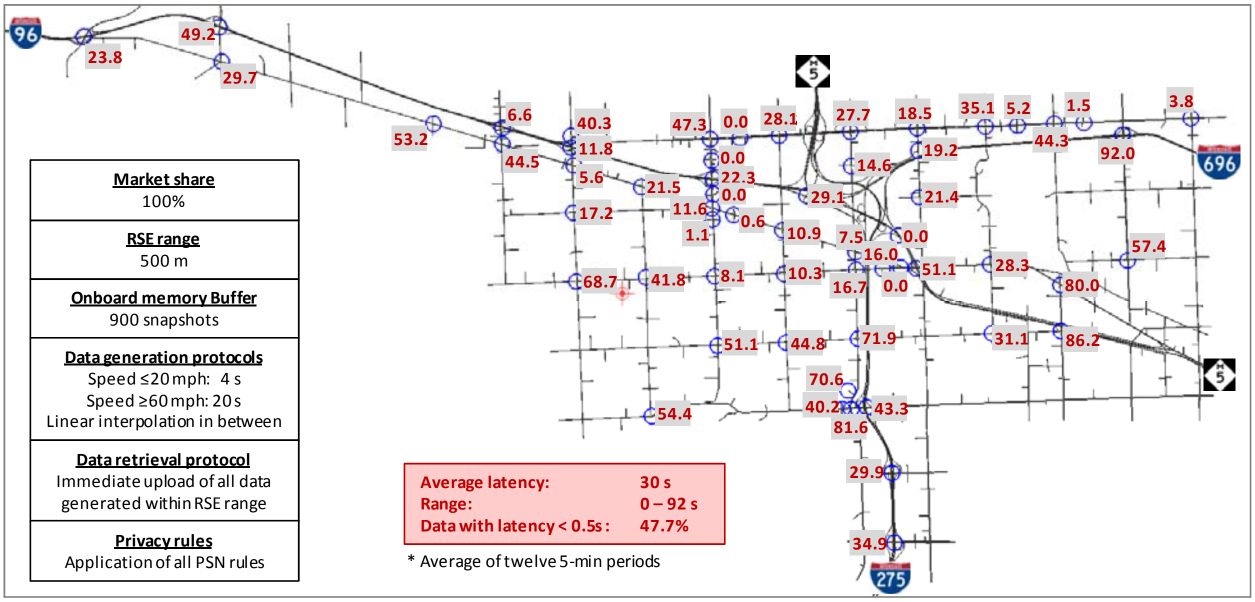


Figure 6-9 – Time from Snapshot Generation to RSE Upload with Multiple Upload Capability

Figure 6-10 compares the distributions of data latencies from the scenarios of Figure 6-8 and Figure 6-9. As can be observed, simply allowing vehicles to upload to an RSE all the snapshots generated while within its range allows approximately 45% of all snapshots to be collected sooner than under the current single-upload protocol. For the simulated scenario, this simple change notably results in almost half of the generated snapshots being collected immediately after their generation, as evidenced by the high proportion of snapshots with 0-s latency.

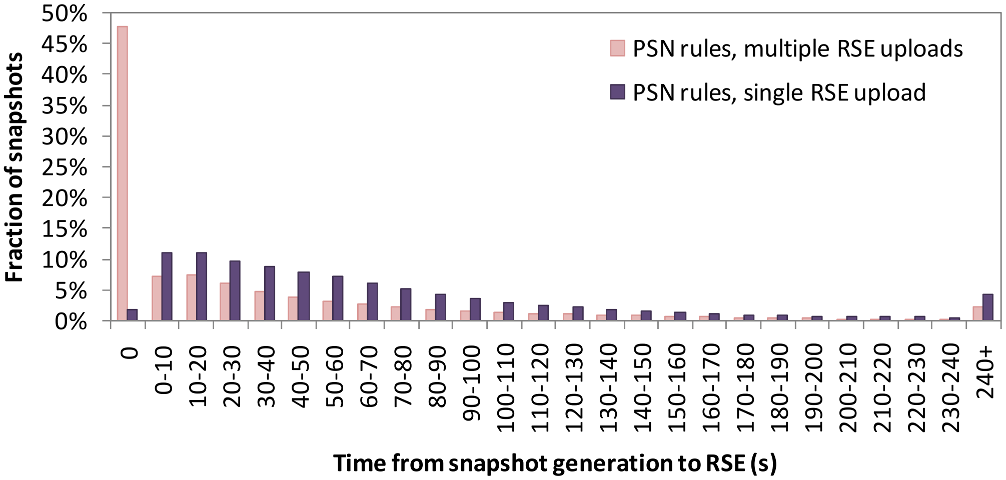


Figure 6-10 – Distribution of Snapshot Latency with Single and Multiple RSE Upload Capabilities

Another potential solution to reduce data latency is to allow probe vehicle data to be transmitted via cellular phone communication. This could be particularly advantageous in areas where low RSE coverage results in significant travel times between RSEs, such as in rural areas. Ubiquitous cellular phone coverage will allow in many areas data to be collected much sooner than through RSEs. However, some data latency may still be expected, as data transmission through cellular phone modems is not instantaneous. Delays in data collection may also occur for vehicles traveling in rural areas with poor cellular phone coverage.

The above examples point to a need to consider latency carefully when compiling data streaming from various RSEs. With traditional monitoring systems, data from point detectors typically stream in with the same latency. This simplifies data compilations. With probe vehicle data, data from various RSEs may characterize traffic conditions that were observed at slightly different times. The latency from each RSE may also potentially vary within a day and from day-to-day due to changes in the movements of vehicles between RSEs and the time required to reach successive RSEs. Because of these variations, it may not be possible to compare directly data streaming in from probe vehicles when they are received at an application server. The data will need to be binned according to the time each snapshot generated, not the time it is received. This further creates a need to wait for the data with the largest latency to come in before being able to produce network-wide evaluations. This could have particularly important effects on network management applications relying on real-time information.

6.8.2. Latency from Wireless Communication Effects

In addition to the time needed to reach an RSE or area with wireless communication, some delays in receiving collected snapshots may be imposed by the wireless transmissions. For instance, evaluations from the USDOT VII POC test program have already indicated that a delay of 0.5 to 1.5 s can be expected when transferring data from a vehicle OBE to an application server through RSEs. The evaluations also indicate that this delay may vary based on the technologies used to provide communication between a vehicle and an RSE, and between an RSE and application server.

A potentially impacting factor that has not been evaluated during the test program is the potential impacts on data delivery of congestion within the underlying communication network. All evaluations were made using a relatively small number of vehicles that were only required to transmit basic probe vehicle data. Real system deployments will eventually create situations in which hundreds or thousands of vehicles may need to communicate simultaneously with the same RSE or same cellular phone tower. These vehicles may also be running multiple applications, each with its own set of data communication needs. This may result in significant data communication loads that could potentially slow data transmission and propagation. While deemed important and noted, this effect has also not been evaluated in this project, as the probe data simulator used to conduct the evaluations did not yet provide a capability for realistically simulating data propagation across wireless networks.

6.8.3. Latency Effects Due to Data Priority

In addition to wireless communication effects, data transmission can be affected by the level of priority of the data being broadcast. In envisioned IntelliDrive^{SM} systems, probe vehicle data will be broadcast in parallel with data generated by other applications. If all data share the same priority level, data packets will typically be transmitted following the order in which they are sent to the transmitter, i.e., in a first-in first out fashion. However, data with higher priority levels may be allowed to bypass the transmission queue. This could result in transmission delays for lower priority data, particularly if there are high volumes of high priority data being transmitted.

Probe vehicle data will likely be assigned a medium priority level, if not lower level. Data supporting vehicle safety applications will likely be assigned a higher priority level. In vehicles running probe vehicle data collection and safety applications, the safety data will likely be transmitted before the probe data if a single data transmission channel is used. While such a process is likely to result in additional latency for probe vehicle data, the magnitude of the added transmission delays will be dependent on the combination of active data-generating applications onboard each vehicle. This makes assessing the potential effects of data latency relatively difficult in early system development stages.

6.8.4. Effects of a Full Memory Buffer on Latency

Another factor potentially affecting latency is the frequency with which vehicles may fill their memory buffer. When this occurs, older data is removed to make room for new snapshots. Regardless of the rules used to determine which snapshot should be deleted, the replacement of old snapshots with newer ones reduces the overall age of the data contained in the buffer and results in lower apparent latencies when uploading the data at an RSE.

The above effect can be seen in Figure 6-11. The figure illustrates the results of simulations that were executed over the POC test network model of Figure 6-1 while assuming that all vehicles in the network generate snapshots and could only store 30 snapshots in their onboard memory buffer. For each snapshot spacing protocol considered, the figure shows the average number of snapshots discarded due to a full buffer and the average latency of the data collected by RSEs across the network. The left portion provide simulation results for scenarios considering snapshots generated at fixed intervals, while the right side considers snapshots generated at variable intervals based on the speed of the vehicle.

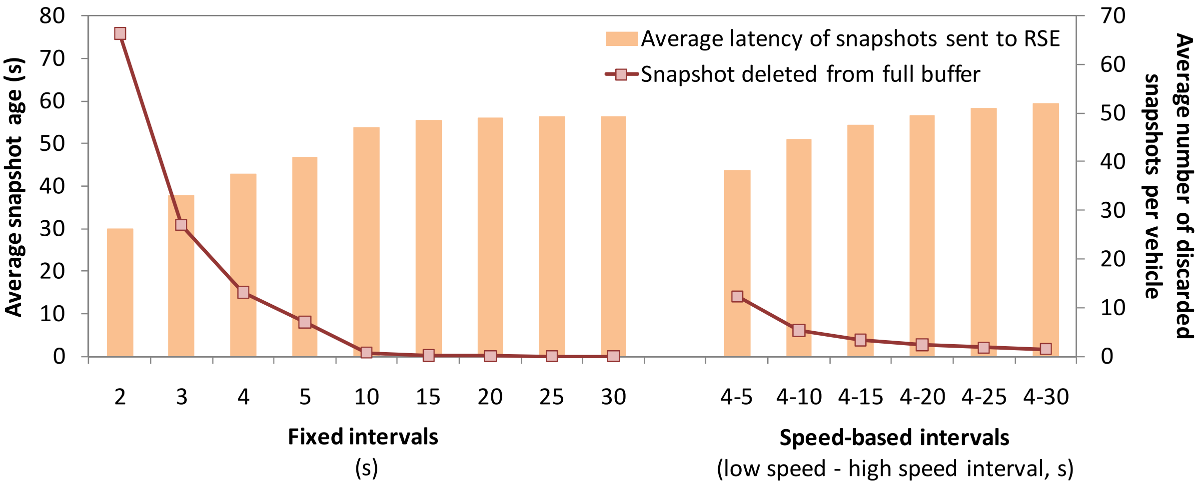


Figure 6-11 – Impact of a Full Buffer on Latency of Data Sent to an RSE

The simulation results clearly indicate that snapshot deletion from full buffers has a non-negligible impact on the latency of collected data. For the scenarios generating data at fixed intervals, reducing the interval between snapshots increases the number of snapshots stored in the memory buffer between RSEs and leads to more frequent snapshot deletions. In this case, the increase in the number of snapshot deletions leads to an apparent reduction in data latency from 56.2 to 18.4 s. For the speed-based interval scenarios, the apparent latency drops from 59.3 to 43.6 s. Since these changes are obtained at the expense of data losses, they do not represent real system efficiency gains.

To reduce the above effects, probe vehicles should be provided with sufficient memory capacity to store all the snapshots they are expected to generate. To limit snapshot deletions, the POC evaluations recommend using a buffer capable of holding 300 snapshots instead of the currently 30-snapshot minimum size. A similar conclusion is reached when analyzing the simulation results of Figure 6-3 and Figure 6-4 presented earlier in this chapter.

6.9. Summary of Findings

The primary results of the evaluations conducted in this chapter include:

- Significant data losses could occur if vehicles are allowed to operate with a small memory buffer, such as the 30-snapshot buffer currently recommended in general system design standards. Both simulation tests and POC evaluations indicate that a 300-snapshot buffer may be required to reduce the risk of completely filling onboard memory buffers and losing data.
- Simply collecting snapshots every 4 s instead of at intervals varying between 4 and 20 s based on the speed of the vehicle could more than double the amount of data collected when holding all other system parameters fixed.
- All snapshot generation protocols have a potential sampling bias, particularly on roads on which traffic speeds are not constant. Allowing the interval between snapshots to vary between 4 and 20 s based on the speed of the vehicle can result in an over-representation of low-speed traffic conditions. Generating snapshots at fixed intervals provide a more representative sampling of traffic conditions but still produces a slight bias towards low speeds as slower vehicles still generate more snapshots per unit distance than faster vehicles. Finally, while using a fixed

spacing based on distance traveled would theoretically provide a more representative sampling, it would also prevent collecting data while stopped. While there is no ideal sampling approach, the best option appears to generate snapshots at fixed time intervals.

- The requirement that vehicles stop recording snapshots for a short interval following a change of identification number can result in a loss of approximately 10% of all generated snapshots.
- Rules imposed to safeguard the privacy of travelers forcing frequent PSN changes significantly limiting the ability to track vehicle movements over usable distances. While current system designs forces PSNs to be changed after a vehicle has traveled 3280 ft (1000 m) or 120 s, whichever occurs first, PSN must also be changed when a memory buffer is emptied and a when a vehicle exits the range of an RSE. Simulation results indicate that these frequent changes result in practice in much shorter tracking capabilities than the touted 3280 ft or 120 s.
- Rules forcing frequent PSN changes have a significant limiting effect on the ability to track vehicles across intersections. This affects the ability to use snapshots to conduct movement-specific analyses at decision points. Simulation results indicate an ability to use less than 30% of all collected data for tracking movements across intersections under the current speed-based snapshot spacing protocols. Generating snapshots every 4 s increases this proportion to about 50%.
- The largest potential source of latency in RSE-based systems is likely to be the time needed for probe vehicles to reach an RSE, particularly if vehicles are restricted to communicate only once with an RSE. Other elements that may affect latency include wireless communication effects, data priority level, and data losses due to full onboard memory buffers.
- Restricting vehicles to communicate only once with an RSE can significantly increase data latency. A simulation study indicated for instance an ability to reduce average data latency from 61 to 30 s across the POC test network by simply allowing vehicles to communicate more than once with an RSE.
- Because of local effects, data collected by each RSE may exhibit different latencies. This creates additional complexity when attempting to compile data from various RSEs.

7. General Probe Vehicle Data Processing Needs

Raw probe vehicle data collected from individual vehicles will require some processing before it is ready to be used in applications. A flow chart illustrating typical data processing steps required to convert raw probe vehicle data into usable data is shown in Figure 7-1. While the exact number and nature of required data processing steps may vary based on the application considered, six basic steps can be defined:

- Data validation
- Time classification
- Roadway link association
- Snapshot association for short-term vehicle tracking
- Fusion with data from other sources
- Conversion of snapshot data into performance measures

7.1. Data Validation

The first process after receiving raw data from RSEs is to assess the validity of the data. The goal is to remove any erroneous data that may result from technical problems with the sensing and measuring instruments located onboard vehicles. Examples of erroneous data may be negative or unrealistic speeds, such as vehicles assessed to go at 100 mph on a residential street, unrealistic elevations for the area where the data is collected, invalid latitude or longitude coordinates, etc. As part of the validation process, decisions will need to be made about whether the values assigned to individual data fields should be kept and marked as invalid or simply deleted. Decisions will also have to be made regarding which circumstances snapshots with invalid data should be kept or deleted.

7.2. Time Binning

Probe vehicle data will need to be classified according to the time that each snapshot was generated. In traditional surveillance systems, data usually stream sequentially into an application server. This allows information pertaining to specific periods to be determined by simply compiling the data received within each period. With probe vehicle data collection systems, the sequence according to which data will stream into an application server will depend on when and where vehicles connect with individual RSEs. This is likely to result in data streaming in a non-sequential fashion. For instance, a snapshot characterizing traffic conditions observed on a link 30 s ago may be followed by a snapshot characterizing traffic conditions observed by another vehicle on the same link 50 s ago. To characterize traffic and network conditions adequately, a received snapshot should not be binned according to the time of its reception at an application server but rather according to the time stamp indicating when it was generated.

Whether to use 1-min, 5-min, 15-min, 1-hour or larger data aggregation time bins will depend on the assessed data needs. Since all snapshots will be time stamped, it may be possible to store all the data in a single database. However, this approach is not recommended, as it would require conducting data searches in large databases. The recommended approach is to store the collected information in databases that would closely reflect MDOT operational needs and facilitate future data uses.

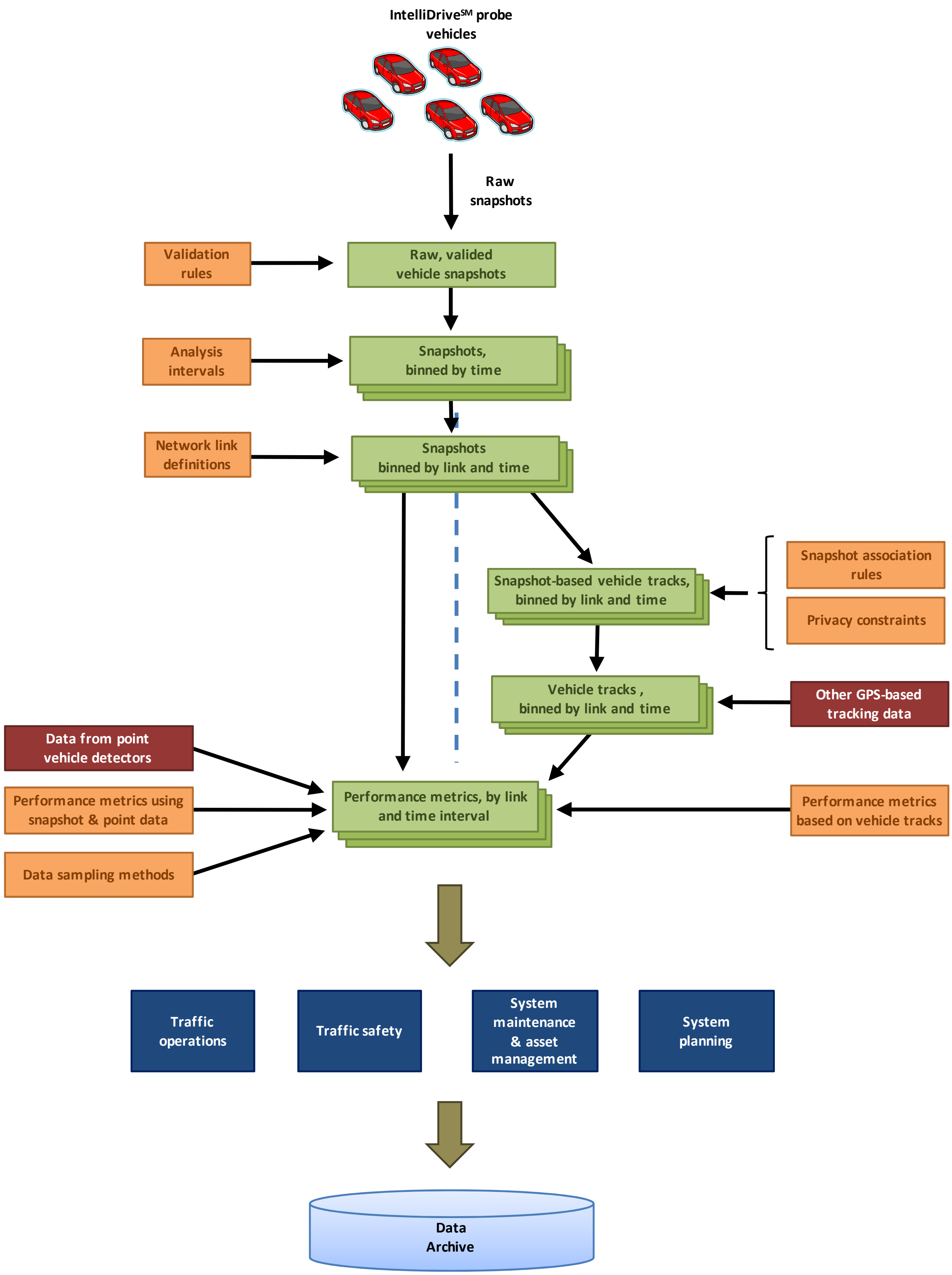


Figure 7-1 – Basic IntelliDrive^{SM} Probe Vehicle Data Processes

7.3. Roadway Link Association

Following data validation, collected snapshots should be associated to specific links. This step is required as most applications of interest to departments of transportation are based on an ability to assess infrastructure or traffic conditions along specific links. Since position data is recorded within individual snapshots in the form of a latitude and longitude, mapping software will be required to associate snapshots to specific links. To ensure data usability across as many applications as possible, a common link referencing system should be used, such as the Michigan Geographic Framework. This framework serves as the digital base map for State of Michigan government agencies. It is also used as the geographic reference for many data processes within MDOT.

The result of this data processing step is a database containing sets of snapshots categorized according to the links on which they were generated. Such a database would allow collected snapshots to be used in analyses targeting specific types of roadway segments, such as freeways, urban arterials, or local roads. Link groupings could also be defined to allow the analysis of data associated with specific intersections or corridors.

7.4. Identification of Short-Term Vehicle Tracks

Some applications, such as the determination of turn movements at intersections or lane changes on freeways, may rely on short-term vehicle tracking. While current snapshot generation standards prevent vehicles from being tracked over long distances, mechanisms are provided to allow short-lived identification numbers to be assigned to sequences of snapshots. Because snapshots may stream to a data server across various messages, data mining processes attempting to retrieve matching snapshots across multiple messages or within a database will need to be developed. Processes will also need to be developed to determine the time interval to which each vehicle trace is associated, particularly for traces that may start in one analysis interval and end in another one.

7.5. Fusion of Data from Alternative Sources

Probe vehicle data is likely to be used in parallel with data provided by other surveillance and sensing systems, such as data from loop detectors. In many situations, probe vehicle data may be used to supplement data collected through other surveillance systems, or validate performance measures determined from alternate sources. The opposite is also possible, where other data sources may be used in support of probe vehicle data. In both cases, methods will need to be developed to determine how to best merge data from sources that may have different measurement approaches and accuracies.

7.6. Data Sampling Methods

Appropriate sampling methods will need to be defined to use collected probe vehicle data effectively. For instance, data exhibiting high variability may require the processing of much larger data samples to produce statistically valid averages than data exhibiting much less variance. In such a situation, data sampling methods may be used to determine minimum sampling requirements to meet certain confidence level with a given tolerable error. These methods may also be used to determine minimum market penetration levels beyond which sufficient data may be provided to support given applications.

Data sampling methods may also be used to improve the efficiency of data processing. While an ideal objective is to use all data streaming into an application server to determine performance metrics of interest, such an approach may impose a significant computational burden on the data processing. As the quantity of collected data increases with growth in the proportion of probe vehicles, a point may be reached where there is not sufficient time to process all the data being collected within a desirable interval. In such a situation, data sampling methods could be used to restrict the data processing only to the quantity of data needed to produce statistically valid metrics.

7.7. Calculation of Performance Measures

The primary goal of collecting probe vehicle data is to use the information to assess various performance measures. These measures can be used to assess the number of vehicles traveling on a given link at a given time, directional flow movements at an intersection, the average time needed to travel across a link, or whether there are indications of slippery road conditions. The specific needs of each agency will determine which performance measures need to be compiled. The type of information provided by probe vehicles will also affect what can be determined from the data.

Table 7-1 summarizes the data needs of various applications of interest to departments of transportation. For each application, the table provides potential data sources, the parameters of interest to the application, and the basic data that can be used to derive the various parameters of interests. The analysis does not only consider data that can be provided by probe vehicles. It considers all potential sources of data, whether associated with traditional traffic detection methods or emerging technologies. Table 7-2 provides further information about the individual performance metrics, indicating notably what types of data are required to estimate each of the performance measures mentioned in Table 7-1.

A particularly noteworthy observation from the data of Tables 7-1 and 7-2 is that many performance metrics can be estimated from a relatively small set of basic parameters that include:

- Travel times
- Speed profiles
- Traffic volumes
- Queue location
- Turning movements at intersections

Not surprisingly, these basic parameters correspond to the performance metrics that current traffic surveillance systems generally attempt to measure. Point detectors are for instance used to obtain traffic volumes and speed measurements at specific locations. This information is then used to calculate average travel times along roadway segments. Point detectors are also placed at strategic locations at intersections to detect when queues of vehicles reach a certain length or to monitor the demand for turning movements on exclusive turning lanes.

One of the primary envisioned benefits of IntelliDrive^{SM} systems is the ability to convert ordinary vehicles into probe vehicles. It is expected that this ability will allow collecting information about traffic conditions from every link vehicles will travel. While the type of data collected will depend on the instruments installed onboard each vehicle, at a minimum vehicles will be able to report on a periodic basis data provided by an onboard GPS positioning system, i.e., their position, speed and heading on a second-by-second or other interval schedule. From a theoretical standpoint, it will then be possible to process this data to obtain link-specific vehicle counts, speed profiles, travel time estimates, queuing statistics, and information about turning movements.

However, the actual extent to which each of the above basic parameters could be derived from probe vehicle data will depend on the protocols used to generate the snapshots, notably those determining the interval between successive snapshots, as well as data collection safeguards imposed to protect driver privacy. These issues are explored in the next chapter of the report, which investigates how various basic flow performance measures can be determined from probe vehicle traffic snapshots generated according to currently recommended protocols.

7.8. Data Archival

The last processing step consists in appropriately archiving all collected data. This step should not be overlooked, particularly is data is to be later used to support various off-line analyses and management needs. Data archiving involves not only storing the collected raw data into a database, but also storing any relevant information derived from the data. Efforts should also be made to store metadata characterizing the context in which the data was collected. For instance, metadata for probe vehicle data may include links to information characterizing the weather and traffic conditions on the day or period the data were collected. Information may also be stored to characterize the various processes that were applied to the data.

Table 7-1 – Application Data Needs

Application	Description	Data Sources	Performance metrics of interest	Basic data
Traffic monitoring				
Monitoring of network operations	Monitoring of traffic flow on freeway and arterials	• Point traffic detectors • GPS tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles • Weather stations	• Average annual daily traffic (AADT) • Commercial annual daily traffic (CAADT) • Vehicle throughput • Vehicle-miles traveled (VMT) • Commercial vehicle-miles traveled (CVMT) • Volume-to-capacity ratio (V/C) • Lost capacity • Flow density • Average speed • Speed profiles • Average link travel time • Travel time congestion index • Total delay • Stopped delay • Average delay per vehicle • Average stopped delay per vehicle • Spatial extent of congestion • Temporal extent of congestion • Traffic demand indicator • Buffer index • Planning time index	• Vehicle counts • Link travel times • Spot speeds • Vehicle passenger occupancy • Vehicle tracking data
Detection of unusual traffic demand patterns	Identification of traffic flow patterns differing from expected conditions	• Point traffic detectors • GPS tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles	• Flow rate • Vehicle throughput • Volume-to-capacity ratio • Traffic density • Average speed • Average link travel time • Travel time congestion index • Total delay • Stopped delay • Average total delay per vehicle • Average stopped delay per vehicle • Spatial extent of congestion • Traffic demand indicator • Number of reported incidents • Number of reported control device failures	• Vehicle counts • Link travel times • Spot speed measurements • Trip vehicle tracking data • Incident reports • Traffic control device failure reports
Monitoring of weather impacts on traffic	Monitoring of weather conditions and detection of impact on road conditions and traffic flows	• Point traffic detectors • GPS tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles • Weather stations	• Flow rate • Vehicle throughput • Weather event VMT ratio • Volume-to-capacity ratio • Traffic density • Average speed • Speed profiles • Average link travel time • Travel time congestion index • Total delay • Average total delay per vehicle • Weather event delay ratio • Spatial extent of congestion • Number of reported incidents • Extent of network affected by snow or ice • Extent of network affected by rain • Extent of network affected by fog • Number of incidents due to weather	• Vehicle counts • Spot speed measurements • Link travel times • Vehicle tracking data • Weather data (temperature, precipitation, etc.) • Vehicle status reports (wipers, headlights, etc.) • Vehicle safety system activations (ABS, traction) • Incident reports
Monitoring of traffic conditions around work zones	Monitoring of impacts of work zones on traffic flows	• Point traffic detectors • GPS tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles • Work zone traffic management plans	• Volume through work zone • Average speed across work zone • Travel time across work zone • Total delay • Stopped delay • Average total delay per vehicle • Average stopped delay per vehicle • Average vehicle delay within work zone • Average vehicle delay on work zone approach • Temporal extent of congestion • Spatial extent of congestion • Lane-hours lost due to work zone • Lane-miles lost due to work zone	• Vehicle counts • Spot speed measurements • Link travel times

Table 7-1 – Application Data Needs (cont'd)

Application	Description	Data sources	Performance metrics of interest	Basic data
Incident detection	Detection of unusual traffic patterns that may be caused by incident	• Point traffic detectors • GPS tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles	• Lane occupancy • Flow rate • Average speed	• Vehicle counts • Spot speed measurements • Lane occupancy measurements • Incident reports
Weather Impacts	Collection of data from vehicles and air monitoring stations for assessing air quality	• Roadside weather stations • Regional weather data • Instrumented probe vehicles	• Link average speed • Link speed profile • Fuel consumption per VMT • Vehicle emissions per VMT	• Link vehicle counts • Spot speed measurements • Vehicle tracking data • Vehicle fleet characteristics
Traffic management				
Level-of-service (LOS) analysis – Highways / Freeways / Arterials	Evaluation of operating conditions on individual roadway segments	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Traffic volume • Flow throughput • Flow density • Average travel speed • Average total delay per vehicle • Queue length	• Vehicle counts • Vehicle classification • Spot speed measurements • Link travel times • Vehicle tracking data
Level-of-service (LOS) analysis - Intersections	Evaluation of traffic operating conditions at signalized and unsignalized intersections; detection of potential signal failures	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Traffic volumes • Turning percentages • Saturation flow rate • Total delay per approach • Stopped delay per approach • Average total delay per vehicle per approach • Average stopped delay per vehicle per approach • Queue length • Proportion of cycle failures • Signal phase and timing (SPAT) data	• Vehicle counts • Vehicle classification • Spot speed measurements • Link travel times • Vehicle tracking data
Traffic signal optimization	Determination of signal timings to use at individual intersections (fixed or real time)	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Traffic volumes • Turning percentages • Saturation flow rate • Total delay per approach • Stopped delay per approach • Average total delay per vehicle per approach • Average stopped delay per vehicle per approach • Queue length • Driver reaction time	• Vehicle counts • Vehicle presence detection (point detectors) • Spot speed measurements • Link travel times • Vehicle tracking data
Operation of Freeway Ramp Meters	Determination of rate at which vehicles are allowed to enter a freeway	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Traffic volumes • Queue length • Average stopped delay per vehicle • Driver reaction time • Headway between vehicles on freeway	• Vehicle counts • Vehicle presence detection (point detectors) • Spot speed measurements • Link travel times • Vehicle tracking data
Incident management	Detection of incidents; implementation of incident response plan; monitoring of incident duration and traffic impacts	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Flow throughput • Speed profiles • Average link travel time • Total delay due to incident • Stopped delay due to incident • Average total delay per vehicle • Average stopped delay per vehicle • Queue length • Incident duration • Blockage duration • Incident notification time • First responder time • Total response time • Incident clearance time • On-scene time • Incident linger time • Incident influence time • Lane-hour loss due to incident	• Vehicle counts • Spot speed measurements • Link travel times • Vehicle tracking data • Incident activity reports

Table 7-1 – Application Data Needs (cont'd)

Application	Description	Data sources	Performance metrics of interest	Basic data
Corridor management	Optimization of traffic patterns along freeway/arterial corridors by adjusting traffic signal timing plans, ramp meters, and VMS messages as required based on observed flow performance	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Directional traffic volumes • Flow throughput • Average link travel time • Total delay • Total stopped delay • Average total delay per vehicle • Average stopped delay per vehicle • Level-of-service (LOS) • Queue length • Headway between vehicles (freeway segments, for ramp meters) • Signal phase and timing (SPAT) data	• Vehicle counts • Vehicle classification • Vehicle presence detection (point detectors) • Spot speed measurements • Link travel times • Vehicle tracking data
Special event planning and management	Planning and scheduling of special actions necessary to minimize impact on traffic of special events; real-time control of traffic devices to accommodate observed traffic patterns	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Directional traffic flows • Flow throughput • Average link travel time • Total delay • Average total delay per vehicle • Queue length • Headway between vehicles (freeway segments, for ramp meters) • Signal phase and timing (SPAT) data	• Vehicle counts • Vehicle presence detection (point detectors) • Spot speed measurements • Link travel times • Vehicle tracking data
Evacuation planning and management	Emergency evacuation policies, practices and procedures designed to maximize quick evacuations where needed	• Point traffic detectors • GPS tracking data • Bluetooth detector tracking • Cellular phone tracking • Instrumented probe vehicles	• Directional traffic flows • Flow throughput • Average link travel time • Total delay • Average total delay per vehicle • Queue length • Headway between vehicles (freeway segments, for ramp meters) • Signal phase and timing (SPAT) data	• Vehicle counts • Vehicle presence detection (point detectors) • Spot speed measurements • Link travel times • Vehicle tracking data
Commercial vehicles				
Hazardous cargo Monitoring	Monitoring and tracking of hazardous material movements	• AVI tags • Driver logs • Truck licensing and registration databases • Instrumented probe vehicles	• Current location of truck carrying hazardous material • Path followed by truck	• Vehicle detection at specific locations • Vehicle tracking data • Vehicle operator data
Electronic weight inspection	Weigh-in-motion roadside equipment to monitor vehicles for excessive axle loading	• Driver logs • Truck licensing and registration databases • Instrumented probe vehicles	• Vehicle axle weight data • Driver identification data • Fleet operator data	• Vehicle operator data • Vehicle status reports
General safety inspection	Monitoring of heavy truck safety conditions by inspections using non-intrusive wireless technologies	• Driver logs • Truck licensing and registration databases • Instrumented probe vehicles	• Vehicle axle weight data • Vehicle safety system status reports • Driver identification data • Fleet operator data	• Vehicle operator data • Vehicle status reports
Transportation system safety statistics				
Monitoring of incidents	Collection of statistics regarding incidents occurring on roadway network	• Incident reports • Instrumented probe vehicles	• Number of crashes • Number of fatal crashes • Number of crashes with injuries • Number of secondary crashes • Overall crash rate • Fatal crash rate • Injury crash rate • Secondary crash rate	• Incident report data • Incident message generated by IntelliDrive^{SM} vehicles

Table 7-1 – Application Data Needs (cont'd)

Application	Description	Data sources	Performance metrics of interest	Basic data
Transportation planning				
Determination of traffic flow patterns	Collection of origin-destination data for transportation planning purposes, congestion management, and traffic control applications	• Travel surveys • GSP tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles	• Origin-destination flows • Average annual daily traffic (AADT) for individual road sections • Commercial average annual daily traffic (CAADT) for individual road sections • Average travel time between origin-destination pairs • Link travel times • Turn percentages at intersection, junctions, road splits	• Vehicle counts • Vehicle classification • Link travel times • Spot speed measurements • Link/trip vehicle tracking data • Vehicle passenger occupancy
Transportation system modeling	Development of network models for simulation and analyses using collected and archived traffic data to evaluate network system performance	• Point traffic detectors • GSP tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles	• Origin-destination flow rates • Intersection/junction turn percentages • Link saturation flow rate • Link travel time • Average link vehicle speeds • Speed profiles • Queue statistics • Driver behavior parameters • Traffic control device operational parameters • Roadway geometric features	• Vehicle counts • Vehicle classification • Link/trip vehicle tracking data • Spot speed measurements • Link travel times • Vehicle passenger occupancy • Link/trip vehicle tracking data
Asset management				
Pavement Pothole/crack detection and mapping	Monitoring and reporting road surface condition problems	• Visual road inspections • Pothole reports from travelers • Instrumented probe vehicles	• Location of potholes • Pothole depth (severity)	• Visual observation of potholes • Vehicle onboard sensors (accelerometers, GPS) • Pothole reports by travelers
General pavement condition assessment	Determination of general quality of pavement	• Measurements from specially equipped Instrumented probe vehicles	• Distress Index (DI) • PASER ride-quality rating • Present Serviceability Rating (PSR) • Present Serviceability Index (PSI) • International Roughness Index (IRS) • Remaining Service Life (RLS)	• Pavement slope variance • Rut depth • Density of patching and cracking • Cumulative suspension motion • Ratings from visual inspections
Bridge deck monitoring	Monitoring of loading, stresses imposed by passing trucks.	• Load/tension sensors on bridge structure • Instrumented probe vehicles • Point traffic detectors • AVI tags	• Truck volume • Individual truck speeds • Truck weight • Static/dynamic loads put on bridge	• Vehicle counts • Spot speed measurements • Vehicle status data (weight, number of axles, etc.) • Data from onboard vehicle accelerometers • Data from sensors installed on bridge deck
Scheduling and Monitoring of salt and snow plow activities	Scheduling and monitoring of salt and snow plow activities during inclement winter weather	• Point traffic detectors • Commercial telemetry systems • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles • Weather stations	• Time between 2 inches of snow accumulation • Lane-miles pretreated with chemical snow/ice control • Lane-miles pretreated with chemical snow/ice control that experienced snow or ice conditions • Links with reported slippery conditions	• Salt/snow plow vehicle tracking • Spot speed measurements • Link travel times • Vehicle safety system activation reports (ABS brakes, traction system, etc.) • Incident reports
DOT Vehicle tracking and work-order management	Tracking maintenance equipment to manage logistics and schedule uses	• Commercial telemetry systems • Instrumented probe vehicles	• Vehicle information (type, equipment) • Vehicle location • Driver / crew data • Activity reports	• Vehicle tracking • Activity reports
Sign inventory	Monitoring of roadside signage condition and placement	• Vehicles equipped with a special array of sensors • Manual inspections	• Inventory control number • Sign location along road • Sign placement relative to edge of road • Sign condition • Signal retro-reflectivity level • Maintenance action executed	• Sign description data • Positioning data • Retro-reflectivity measurements • Measurements from other devices

Table 7-1 – Application Data Needs (cont'd)

Application	Description	Data sources	Performance metrics of interest	Basic data
Traveler information systems				
Management of Changeable Message Signs	Messages given to driving public through roadside changeable message signs regarding traffic flow and other driving situations.	• Point traffic detectors • GSP tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles • Weather stations	• Flow rate • Vehicle throughput • Volume-to-capacity ratio • Traffic density • Average speed • Travel time • Travel time congestion index • Total delay • Average total delay per vehicle • Spatial extent of congestion • Traffic demand indicator • Number of reported incidents • Number of reported traffic control device failures	• Vehicle counts • Link travel times • Spot speed measurements • Trip vehicle tracking data • Incident reports • Traffic control device failure reports
Traffic flow information to websites	Aggregated traffic flow information provided to web servers to continuously inform drivers of traffic flow situation	• Point traffic detectors • GSP tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles • Weather stations	• Flow rate • Vehicle throughput • Volume-to-capacity ratio • Traffic density • Average speed • Travel time • Travel time congestion index • Total delay • Average total delay per vehicle • Spatial extent of congestion • Traffic demand indicator • Number of reported incidents • Number of reported traffic control device failures	• Vehicle counts • Link travel times • Spot speed measurements • Trip vehicle tracking data • Incident reports • Traffic control device failure reports
Identification of potential roadway design deficiencies	Identification of road sections with geometric features negatively affecting traffic flow behavior	• Point traffic detectors • GSP tracking data • Bluetooth device tracking • Cellular phone tracking • Instrumented probe vehicles	• Locations with higher than expected crash rates • Locations with frequent hard braking • Locations with unstable traffic flow	• Vehicle event data (brake activation, etc.) • Vehicle tracking data • Incident reports

Table 7-2 – Performance Metrics Basic Data Needs

Performance metric	Definition	Units	Geographic scale	Time scale	Basic measurement data
Traffic demand assessment					
Average daily traffic (ADT)	Total volume of vehicle traffic for a year divided by 365 days	Vehicles/day	• Road section	• Annually	• Vehicle counts
Vehicle-miles traveled (VMT)	Product of the number of vehicles traveling over a length of road by the length of the section of road	Vehicles-miles	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts
Commercial average daily traffic (CADT)	Total volume of commercial traffic for a year divided by 365 days	Vehicles/day	• Road section	• Annually	• Vehicle counts • Vehicle classification
Commercial vehicle-miles traveled (VMT)	Product of the number of commercial vehicles traveling over a length of road by the length of the section of road	Vehicles-miles	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts • Vehicle classification
Average hourly flow	Average number of vehicles expected to travel on a road section during an hour	Vehicles/hour	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts
Origin-destination flows	Number of vehicles traveling between a specific origin zone to a specific destination zone	Vehicles/hour	• Network	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle tracking data • Travel survey data • Vehicle counts (for estimating synthetic origin-destination flow rates)
Directional traffic flows	Proportion of vehicles going in each direction at an intersection, junction of split	Vehicles/hour per direction Percentage of flow in each direction	• Intersection/junction	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts • Vehicle tracking data
Volume-to-capacity ratio	Ratio of traffic volume to the capacity of the roadway segment	None	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts • Capacity estimate
Traffic demand indicator	Ratio of actual traffic volume to average volume	None	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts
Traffic flow characteristics / Quality of service					
Vehicle Throughput	Number of vehicles traversing a section of road in a given interval	Vehicles/unit of time Persons/unit of time	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts • Vehicle passenger occupancy (if estimating on a person basis)
Saturation Flow	Maximum flow rate that can be sustained across a specific point in the absence of traffic control devices	Vehicles/hour	• Road section • Intersection approach	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Weather event	• Vehicle counts
Average speed	Average speed of traffic	Miles/hour	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements
Average vehicle headway	Average interval between the moment a vehicle passes a specific point and the moment the next vehicle passes the same point	Seconds	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Time-based Vehicle counts

Table 7-2 – Performance Metrics Basic Data Needs (cont'd)

Performance metric	Definition	Units	Geographic scale	Time scale	Basic measurement data
Average travel time	Average time consumed by vehicles traveling a fixed distance	Minutes	• Roadway section • Specific points along a representative trip • Separate evaluation for different lane uses (general lanes, HOV, etc.)	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Section travel times
Travel congestion time index	Ratio of actual travel time to ideal travel time under free-flow conditions	None	• Road section • Specific points along a representative trip • Separate evaluation for different lane uses (general lanes, HOV, etc.)	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Speed measurements • Section travel times
Total delay	Excess travel time beyond what would occur under ideal conditions	Vehicle-hours Persons-hours	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Section travel times • Vehicle passenger occupancy (if estimating on a person basis)
Average total vehicle delay	Total delay divided by the number of vehicles traveling the section of roadway	Vehicle-hour/vehicle Minute/vehicle Seconds/vehicle	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Section travel time • Vehicle counts
Level-of-Service (LOS)	Rating of the ease of travel across a section of road	A to F scale based on delay (intersections) or flow density (highways and freeways)	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Section travel times • Spot speed measurements • Vehicle counts
Spatial extent of congestion	Portion of road with speed below a certain threshold	Percent	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements
Temporal extent of congestion	Portion of day with speed below a certain threshold	Percent	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements
Flow density	Number of vehicles occupying a length of road	Vehicles/lane/mile	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicles counts along a roadway section
Lane occupancy	Proportion of time a specific point along a lane is occupied by a vehicle.	Percent	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Portion of time a vehicle covers a point detector
Lost capacity	Difference between measured volumes under congested conditions compared to the maximum capacity	Vehicles/hour	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts • Section capacity estimate

Table 7-2 – Performance Metrics Basic Data Needs (cont'd)

Performance metric	Definition	Units	Geographic scale	Time scale	Basic measurement data
Reliability measures					
95th percentile travel time	Travel time observed on some of the busiest travel periods	Minutes	• Roadway section • Specific points along a representative trip • Separate evaluation for different lane uses (general lanes, HOV, etc.)	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Section travel times •
Buffer index	Difference between 95th percentile travel time and average travel time	Percent	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Section travel time
Planning time index	Measure of how much time a traveler should allow to ensure on-time arrival; typically represented as ratio of 95th percentile travel time to ideal or free-flow travel time	None	• Road section • Network area	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Section travel time
Work zones monitoring					
Lane-hours lost due to work zone	Number of whole or partial freeway lanes blocked by the work zone, multiplied by the number of hours the lanes are blocked	Lane-hours	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Work zone traffic management plan data • Vehicle tracking across work zones
Lane-miles lost due to work zone	Number of whole or partial freeway lanes blocked by the work zone, multiplied by the length of the work zone	Lane-miles	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Work zone traffic management plan data • Vehicle tracking across work zones
Speed across work zone	Average traffic speed across work zone	Miles/hour	• Road section •	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements
Travel time across work zone	Average time taken by vehicles to travel across work zone	Minutes	• Road section •	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Travel time measurements between start and end of work zone
Spatial extent of congestion upstream of work zone	Length of road upstream of work zones with speed below a certain threshold	Miles	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Travel time measurements between upstream point and start of work zone
Temporal extent of congestion due to work zone	Portion of day with congestion due to work zone	Miles	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Travel time measurements between upstream point and start of work zone
Delay approaching work zone	Delay incurred by vehicles while approaching the work zone	Minutes	• Road section	• Hourly • Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Travel time measurements between upstream point and start of work zone
Delay within work zone	Delay incurred by vehicles within the work zone	Minutes	• Road section	• Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Travel time measurements between start and end of work zone

Table 7-2 – Performance Metrics Basic Data Needs (cont'd)

Performance metric	Definition	Units	Geographic scale	Time scale	Basic measurement data
Total work zone delay	Summation of delay incurred approaching work zone and delay incurred within work zone	Minutes	• Road section	• Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Spot speed measurements • Travel time measurements between selected upstream point and end of work zone
Average work zone delay	Ratio of total work zone delay by the number of vehicles going through the work zone	Minutes/vehicle	• Road section	• Time-of-day period (Peak, off-peak, midday, evening) • Daily	• Vehicle counts • Spot speed measurements • Travel time measurements between selected upstream point and end of work zone
Weather impacts					
Extent of network affected by snow or ice	Centerline mileage under the influence of uncleared snow or ice	Centerline-miles	• Road section • Network area	• Hourly • Daily	• Air temperature data • Precipitation data • Spot speed measurements • Vehicle system activation reports (ABS, traction, wipers, etc.) • Pavement temperature sensor data
Extent of network affected by rain	Centerline mileage under the influence of rain	Centerline-miles	• Road section • Network area	• Hourly • Daily	• Air temperature data • Precipitation data • Spot speed measurements • Vehicle system activation reports (ABS, traction, wipers, etc.)
Extent of network affected by fog	Centerline mileage under the influence of fog	Centerline-miles	• Road section • Network area	• Hourly • Daily	• Air temperature data • Spot speed measurements • Vehicle system activation reports (brakes, wipers, fog lights, etc.)
Total Weather delay	Traffic delay attributable to inclement weather	Vehicle-hours	• Road section • Network area	• Hourly • Daily • Weather event	• Spot speed measurements • Observed travel time between specific points • Free-flow travel time between specific points
Weather event delay ratio	Ratio of delay observed during weather event compared to the average delay observed during a normal day	None	• Road section • Network area	• Hourly • Weather event	• Spot speed measurements • Observed travel time between specific points • Free-flow travel time between specific points
Weather event vehicle-miles traveled (VMT) ratio	Ratio of VMT during weather event compared to the average VMT during a normal day	None	• Road section • Network area	• Hourly • Weather event	• Vehicle counts
Number of incidents due to weather event	Number of incidents that can directly be attributed to the weather event	Number of incidents	• Road section • Network area	• Hourly • Weather event	• Incident reports
Traffic signal operations					
Lost time	Amount of green time effectively lost due to driver reacting to the start of green or onset of yellow signal	Second/signal phase	• Approach link • Intersection	• Typically fixed value	• Vehicle tracking data • Traffic signal parameters
Number of stops	Number of times a vehicles came to a stop	Number of stops	• Approach link • Intersection	• Hourly • Time-of-day period (Peak, off-peak, midday, evening)	• Vehicle tracking data • Queue measurements
Total stopped delay	Amount of time a vehicle is immobilized or traveling below a certain speed (e.g., 5 mph).	Vehicle-hours Persons-hours	• Approach link • Intersection	• Hourly • Time-of-day period (Peak, off-peak, midday, evening)	• Vehicle tracking data • Vehicle passenger occupancy (if estimating on a person basis)
Average stopped vehicle delay	Total stopped delay divided by the number of vehicles traveling the section of roadway	Seconds/vehicle	• Approach link • Intersection	• Hourly • Time-of-day period (Peak, off-peak, midday, evening)	• Vehicle tracking data • Vehicle counts

Table 7-2 – Performance Metrics Basic Data Needs (cont'd)

Performance metric	Definition	Units	Geographic scale	Time scale	Basic measurement data
Average stop duration	Total stopped delay divided by the number of stops made on the section of roadway	Seconds/vehicle	• Approach link • Intersection	• Hourly • Time-of-day period (Peak, off-peak, midday, evening)	• Vehicle tracking data • Vehicle counts • Queue measurements
Control delay	Total delay directly attributable to the traffic signal operation	Vehicle-hours	• Approach link • Intersection • Metered freeway on-ramp	• Hourly • Time-of-day period (Peak, off-peak, midday, evening)	• Link travel times • Vehicle tracking data • Queue measurements
Queue reach	Maximum extent of queue forming upstream of a stop line	Vehicles	• Approach link	• Hourly • Time-of-day period (Peak, off-peak, midday, evening)	• Queue measurements • Vehicle tracking data • Spot speed measurements
Proportion of cycle failures	Proportion of signal cycles during which all queued vehicles at the beginning of the cycle were not cleared	Percent	• Approach link • Intersection	• Hourly • Time-of-day period (Peak, off-peak, midday, evening)	• Vehicle counts • Queue measurements
Traffic safety					
Number of crashes	Number of crashes for which a police report form is generated	Number	• Road section • Network area	• Annually	• Incident activity reports
Number of fatal crashes	Number of crashes with at least one fatality	Number	• Road section • Network area	• Annually	• Incident activity reports
Number of crashes with injury	Number of crashes in which persons are injured	Number	• Road section • Network area	• Annually	• Incident activity reports
Number of secondary crashes	Number of crashes occurring in the presence of an earlier crash	Number	• Road section • Network area	• Annually	• Incident activity reports
Crash rate	Number of crashes divided by the number of vehicle-miles traveled on the road section or area	Number of crash per 100 million vehicle-miles traveled	• Road section • Network area	• Annually	• Incident activity reports • Vehicle counts
Fatal crash rate	Number of crashes with at least one fatality divided by the number of vehicle-miles traveled on the road section or area	Number of crash per 100 million vehicle-miles traveled	• Road section • Network area	• Annually	• Incident activity reports • Vehicle counts
Injury crash rate	Number of crashes in which persons are injured divided by the number of vehicle-miles traveled on the road section or area	Number of crash per 100 million vehicle-miles traveled	• Road section • Network area	• Annually	• Incident activity reports • Vehicle counts
Secondary crash rate	Number of crashes occurring in the presence of an earlier crash divided by the number of vehicle-miles traveled on the road section or area	Number of crash per 100 million vehicle-miles traveled	• Road section • Network area	• Annually	• Incident activity reports • Vehicle counts
Incident management					
Incident notification time	Time from the moment an incident was first detected to when the last agency needed to response to the incident was notified	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
First responder response time	Time between the moment an incident is first detected and the on-scene arrival of the first responder	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
Total response time	Time between the moment an incident is first detected and the on-scene arrival of the last responder	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports

Table 7-2 – Performance Metrics Basic Data Needs (cont'd)

Performance metric	Definition	Units	Geographic scale	Time scale	Basic measurement data
Incident duration	Time elapsed from the notification of an incident to the moment the last responder has left the incident scene	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
Blockage duration	Time elapsed from the notification of an incident to when all evidence of the incident have been removed from the travel lanes	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
Incident clearance time	Time between the moment the first responder arrives on the scene of an incident and the blockage of a traffic lane is removed	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
On-scene time	Time between the moment the first responder arrives and the moment the last responder leaves the incident scene	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
Incident linger time	Time between the moment the blockage of a traffic time is removed and the moment the last responder leaves the incident scene	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
Incident influence time	Time between when an incident was first detected and the last responder leaves the incident scene	Minutes	• Road section • Network area	• Hourly • Daily	• Incident activity reports
Lane-hour loss due to incident	Number of freeway lanes partially or completely blocked by the incident, multiplied by the number of hours the lanes are blocked	Lane-hours	• Road section • Network area	• Hourly • Daily	• Incident activity reports
Pavement conditions assessment					
International Roughness Index (IRI)	Accumulated suspension motion of a vehicle divided by the distance traveled by the vehicle during the measurement	Inches/mile	• Road section • Network area	Every 1 to 5 years	• Cumulative suspension motion
Distress Rating (DI)	Rating of overall pavement quality	0 to 50 scale	• Road section • Can be categorized for type of distress	• Every 1 to 5 years	• Pavement distress data • Rating returned by a panel of raters
Pavement Condition Rating (PCR)	Index assessing the general condition of a pavement section as determined by a visual inspection	0 to 100 scale	• Road section	• Every 1 to 5 years	• Distress Index • International Roughness Index (IRI)
PASER Rating	General indicator of ride quality on pavement surfaces as determined by a visual inspection	1 to 10 scale	• Road section	• Every 1 to 5 years	• Rating returned by a panel of raters
Present Serviceability Rating (PSR)	General indicator of ride quality on pavement surfaces as determined by a panel of raters	1 to 5 scale	• Road section • Network area	• Every 1 to 5 years	• Rating returned by a panel of raters
Present Serviceability Index (PSI)	General indicator of ride quality on pavement surfaces as determined by various measurements	1 to 5 scale	• Road section • Network area	• Every 1 to 5 years	• Pavement slope variance • Rut depth • Density of patching and cracking
Remaining Service Live (RLS)	Number of years to when a pavement will start to provide sub-standard service quality	Years	• Road section	• Every 1 to 5 years	• Types of pavement Distress • Distress Index • Rating Scale

Table 7-2 – Performance Metrics Basic Data Needs (cont'd)

Performance metric	Definition	Units	Geographic scale	Time scale	Basic measurement data
Bridge condition assessment					
Structurally deficient	Categorization of a bridge with any major component is in poor condition, insufficient load carrying capacity, or insufficient waterway beneath the structure.		• Structure	• Annually	• Deck rating • Superstructure rating • Substructure rating • Culvert rating • Structural evaluation rating • Waterway rating
Functionally obsolete	Bridge with clearances significantly below current design standards for the volume of traffic being carried on or under the bridge.		• Structure	• Annually	• Deck rating • Superstructure rating • Substructure rating • Culvert rating • Structural evaluation rating • Waterway rating
Environmental assessment					
Fuel consumption per vehicle-mile traveled	Estimate of total number of gallons of fuel consumed on a roadway section divided by the section's vehicle-miles of travel	Gallons of fuel/mile	• Road section • Network area	• Annually • Seasonal	• Spot speed measurements • Traffic speed profiles from vehicle tracking data • Vehicle counts • Fleet characteristics
NOx emission rate	Estimate of total mass of NOx emitted on a roadway section divided by the section's vehicle-miles of travel	Grams/mile	• Road section • Network area	• Annually • Seasonal	• Spot speed measurements • Traffic speed profiles from vehicle tracking data • Vehicle counts • Fleet characteristics
CO emission rate	Estimate of total mass of CO emitted on a roadway section divided by the section's vehicle-miles of travel	Grams/mile	• Road section • Network area	• Annually • Seasonal	• Spot speed measurements • Traffic speed profiles from vehicle tracking data • Vehicle counts • Fleet characteristics
Volatile organic compound (VOC) emission rate	Estimate of total mass of VOC emitted on a roadway section divided by the section's vehicle-miles of travel	Grams/mile	• Road section • Network area	• Annually • Seasonal	• Spot speed measurements • Traffic speed profiles from vehicle tracking data • Vehicle counts • Fleet characteristics
Particulate matter (PM) emission rate	Estimate of total mass of OM emitted on a roadway section divided by the section's vehicle-miles of travel	Grams/mile	• Road section • Network area	• Annually • Seasonal	• Spot seed measurements • Traffic speed profiles from vehicle tracking data • Vehicle counts • Fleet characteristics

8. Estimation of Basic Traffic Performance Measures

This chapter examines how key basic traffic performance measures can be estimated from probe vehicle data. As indicated in the previous chapter, a majority of performance measures considered by applications of interest to state departments of transportation can be derived from a relatively limited set of basic traffic flow parameters. This chapter reviews how the following performance measures can be estimated from probe vehicle data:

- Flow rate
- Flow density
- Speed profile
- Link travel time
- Vehicle delays
- Number of stops
- Queue parameters
- Turn percentages at intersections/junctions
- Vehicle passenger occupancy
- Vehicle classification

The evaluations primarily seek to assess on how well each performance measure could be estimated using probe vehicle data generated according to the prevailing snapshot generation protocols described in Chapter 2. Where deficiencies are identified, the use of alternate protocols is explored. This leads to the identification of various protocol improvements that are summarized at the end of the chapter.

To highlight potential data processing problems, the evaluations also primarily focus on data processing in an environment in which all vehicles are assumed to be reporting data to a DUAP system, i.e., in full market penetration scenarios. For each parameter, the impacts of partial market penetrations on the ability to obtain accurate estimates are also discussed.

8.1. Link Flow Rate

Flow rate is used to assess traffic demand. In existing monitoring systems, flow rates are typically determined using data reported by point vehicle detectors, such as inductive loops embedded in the pavement, or video, infrared and microwave detectors installed on the side of the road. In each case, the flow rate is typically determined by simply counting the number of vehicles passing within the detector's sensing area during a pre-set interval.

A major limitation of existing surveillance systems is that they can only report flow rates from locations where detectors are installed. In urban networks, detectors are usually only found along freeways and at intersections with traffic-responsive or actuated signal control equipment. To obtain flow data from other locations, periodic surveys are conducted by laying down temporary traffic counters or conducting manual counts. This results in uneven network coverage, with some locations providing continuous data streams and others being only periodically surveyed.

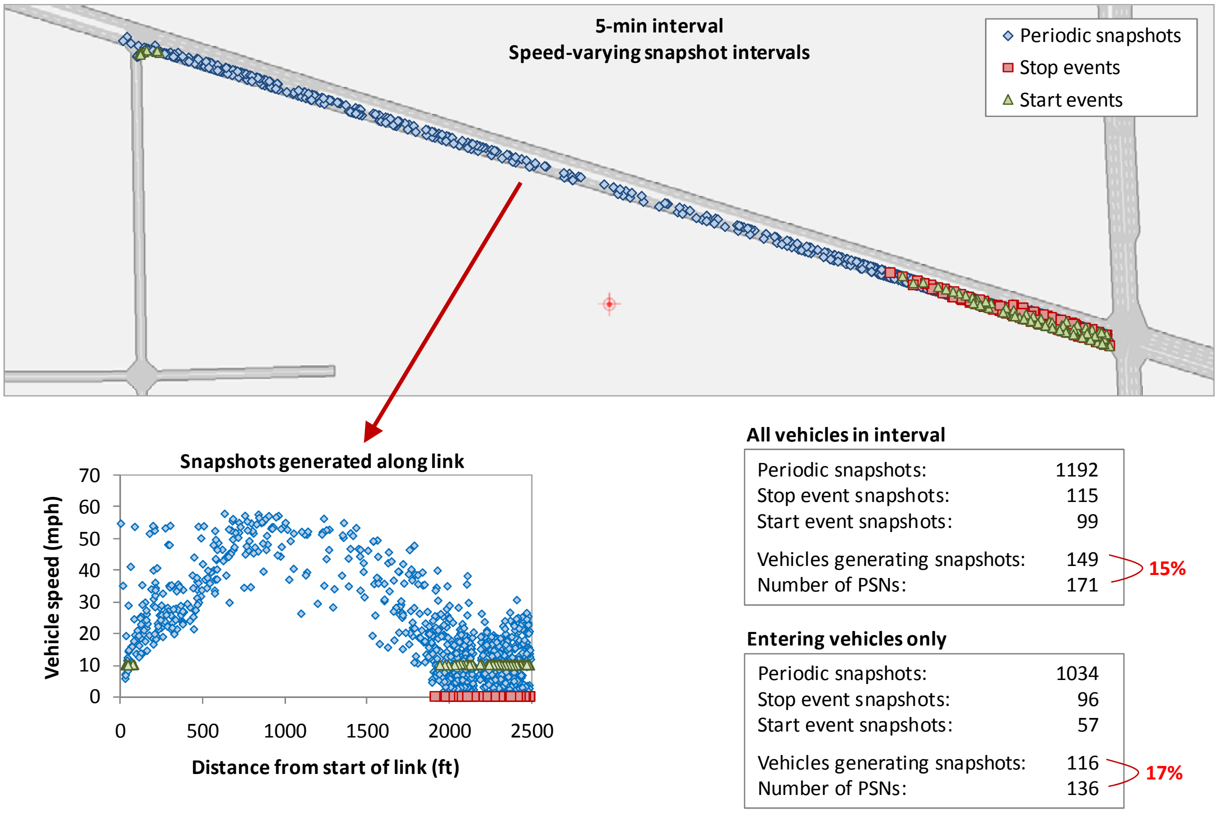
One of the main envisioned benefits of IntelliDrive^{SM} systems is the eventual ability to collect information from any link that a probe vehicle will travel. The following sub-sections examine the adequacy of estimating link flow rates using the following types of probe vehicle data:

- Periodic snapshots generated on a link
- Periodic snapshots generated within a specific detection zone
- Link entry event snapshots
- Link exit event snapshots

8.1.1. Estimation Using All Snapshots Generated along a Link

Under current IntelliDrive^{SM} protocols, probe vehicles are to collect data at intervals set according to their speed. The preferred approach is to have vehicles traveling at speeds at or greater than 60 mph collecting snapshots every 20 s, vehicles traveling at or below 20 mph to generate snapshots every 4 s, and vehicles traveling between 20 and 60 mph to generate snapshots at intervals linearly interpolated between 4 and 20 s. An example of snapshots generated according to such a protocol is show in Figure 8-1. This example, which was produced using UMTRI's virtual IntelliDrive^{SM} probe data generator described in Chapter 5, illustrates the snapshots generated along a two-lane, 2500-ft arterial link leading to a signalized intersection under an assumed 100% IntelliDrive^{SM} market penetration.

Flow rate estimation essentially consists in counting the number of vehicles passing a given point within a specified interval. However, simply counting the number of snapshots generated along the link does not produce a reasonable count for the example of Figure 8-1. This is because some vehicles may generate multiple snapshots while traveling on the link. In the example, 149 vehicles are observed to travel along the link within the 5-min analysis period considered. These vehicles generate a total of 1192 snapshots, 115 stop event snapshots, and 99 start event snapshots. This corresponds to an



All vehicles in interval

Periodic snapshots:	1192
Stop event snapshots:	115
Start event snapshots:	99
Vehicles generating snapshots:	149
Number of PSNs:	171

Entering vehicles only

Periodic snapshots:	1034
Stop event snapshots:	96
Start event snapshots:	57
Vehicles generating snapshots:	116
Number of PSNs:	136

Figure 8-1 – Snapshot Generated along an Arterial using Variable Speed-Based Intervals

average of 9.43 snapshots per vehicle. If the vehicles already present on the link at the beginning of the interval are removed from the analysis, only 116 vehicles are then observed to enter the link within the analysis period. These 116 vehicles can then be linked to 1034 periodic snapshots, 96 stop snapshots and 57 start event snapshots, for an average of 8.0 snapshots per vehicle. As can be observed, simply counting the snapshots generated along the link result in both cases in a significant overestimation of the true number of vehicles traveling on the link.

Estimating link flow rates requires counting one snapshot per vehicle per link. One potential approach to obtain such a count is to remove duplicate snapshots using the Probe Sequence Number (PSN) tagged to each periodic and stop/start event snapshot. As explained in Section 2.5, PSNs are short-lived, vehicle-specific numbers tagged to snapshots to allow short-term vehicle tracking. From a theoretical standpoint, only counting the number of snapshots with different PSNs would allow obtaining vehicle counts that would be closer to the actual number of vehicles generating snapshots.

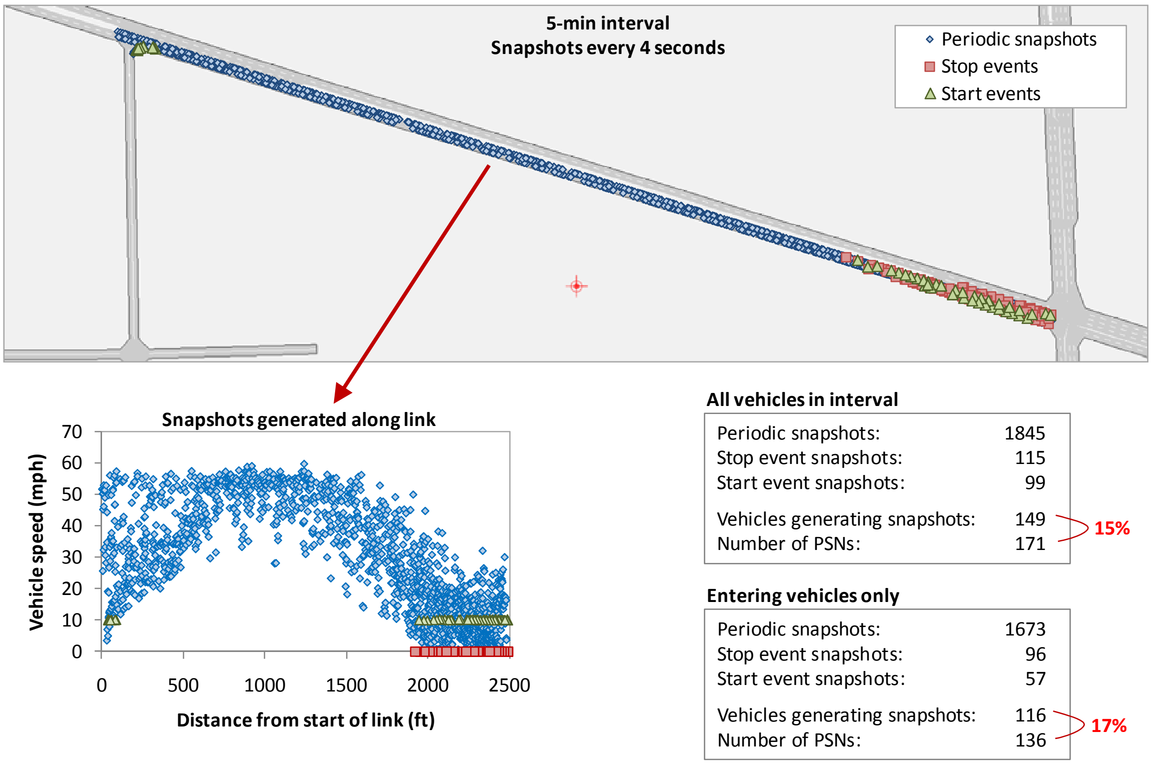
Unfortunately, privacy rules embedded in the snapshot generation protocols complicate the use of PSNs as data filters. First, PSNs are to be changed when a vehicle travels 3280 ft (1000 m) or for 120 s. If a vehicle changes its PSN while traveling on a link, two sequences of snapshots with different PSNs would then be generated on the link, resulting in a double counting of some vehicles. In Figure 8-1, the 116 vehicles entering the link during the 5-min analysis interval generate 136 sequences of periodic snapshots with different PSNs. Simply counting the number of PSNs found along the segment would in this case result in a 17% overestimation of the number of vehicles traveling the link.

A potential solution to the above problem may be to try to link PSN sequences to specific vehicles. This can be attempted by projecting the path of individual vehicles based on information about its speed and heading contained in each snapshot. While this approach is theoretically feasible, a difficulty is associated to the fact that vehicles are prevented from recording snapshots for a mandatory gap following each PSN change. The current approach is to discard all snapshots over a distance of 164 to 820 ft (50 to 250 m), or an interval of 3 to 13 s, whichever occurs first. Such a gap is intentionally imposed to make it more difficult to track vehicles, as it makes it very difficult to determine with high accuracy whether two sequences of snapshots with different PSNs truly come from the same vehicle. Since this approach may have too much uncertainty, its use is therefore not recommended.

An alternative to generating snapshots at intervals based on the speed of the vehicle is to generate them at a fixed interval. However, analyses using the same scenario of the example as Figure 8-1 but with snapshots generated snapshots every 4, 10 and 20 s indicate that the use of fixed intervals leads to the same data processing issues as the speed-based approach. Results of the analysis considering a fixed 4-s snapshot interval are shown in Figure 8-2. In this case, while the fixed interval removes some variability in the spacing of snapshots, the 116 vehicles that enter the link during the analysis period still generate 136 sequences of periodic snapshots with unique PSN values.

Another alternative is to generate snapshots according to distance traveled. The main advantage of this protocol is to ensure that vehicles traveling at different speeds all generate the same number of snapshots per unit distance. However, this protocol does not resolve flow rate estimation issues, as it still results in snapshots being spread across a link. As shown in Figure 8-3, this protocol still results in a significantly higher number of PSN sequences than the number of vehicles generating snapshots.

While the above discussion has focused on the need to avoid double-counting vehicles on long links, short links present other potential problems. Here, the danger is not over-counting vehicles but under-



All vehicles in interval

Periodic snapshots:	1845
Stop event snapshots:	115
Start event snapshots:	99
Vehicles generating snapshots:	149
Number of PSNs:	171

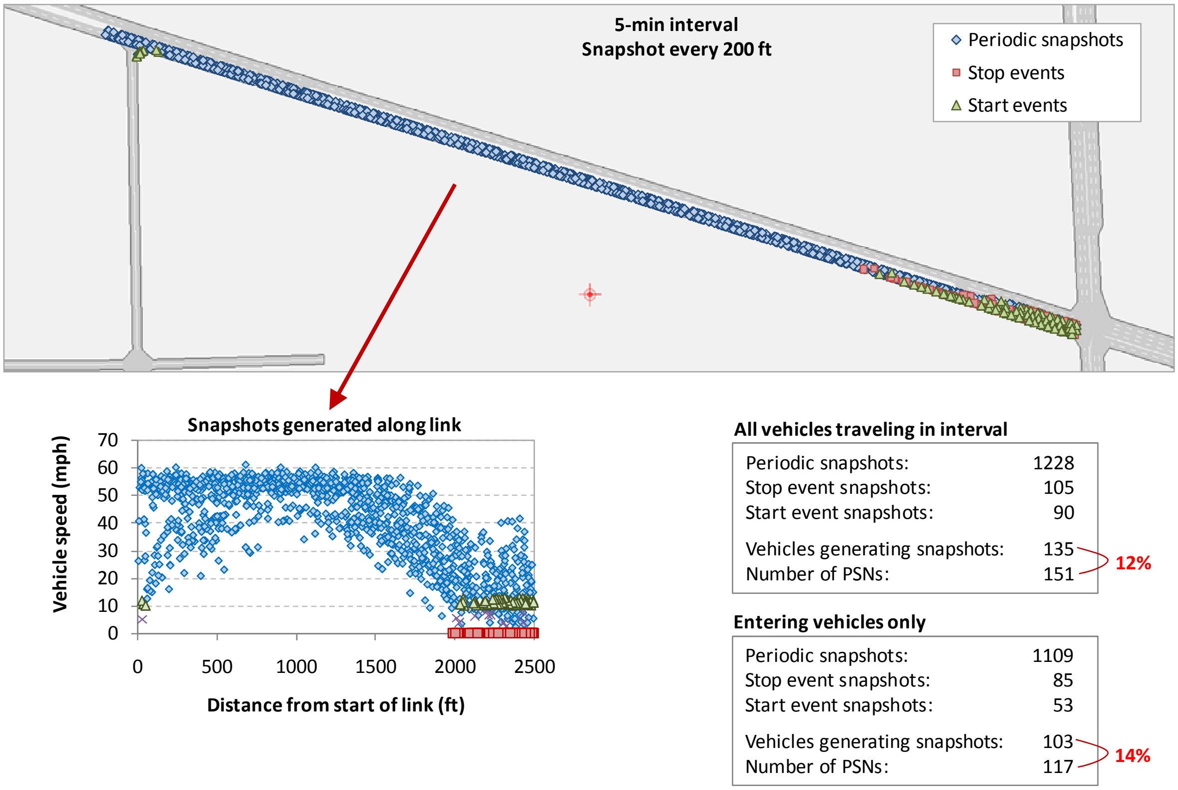
15%

Entering vehicles only

Periodic snapshots:	1673
Stop event snapshots:	96
Start event snapshots:	57
Vehicles generating snapshots:	116
Number of PSNs:	136

17%

Figure 8-2 – Snapshot Generated along an Arterial using a Fixed 4-second Interval



All vehicles traveling in interval

Periodic snapshots:	1228
Stop event snapshots:	105
Start event snapshots:	90
Vehicles generating snapshots:	135
Number of PSNs:	151

12%

Entering vehicles only

Periodic snapshots:	1109
Stop event snapshots:	85
Start event snapshots:	53
Vehicles generating snapshots:	103
Number of PSNs:	117

14%

Figure 8-3 – Snapshot Generated along an Arterial using a Fixed 200-feet Spacing counting them as vehicles may go through short links without generating any snapshot on them. For instance, a vehicle traveling at 55 mph and generating a snapshot every 20 s would travel 1613 ft between two snapshots. Some vehicles could thus traverse links shorter than 1613 ft without generating any snapshot. To minimize this potential, vehicles should be instructed to generate snapshots at a rate that is high enough to ensure that at least one snapshot will be generated on each traveled link by the fastest moving vehicles. The appropriate snapshot generation rate could be determined at the network level with the objective to ensure adequate data collection from as many links as possible without overflowing onboard vehicle memory buffers. Snapshot generation rates could also be modified locally through directives instructing vehicles to reduce the interval between snapshots when approaching short links.

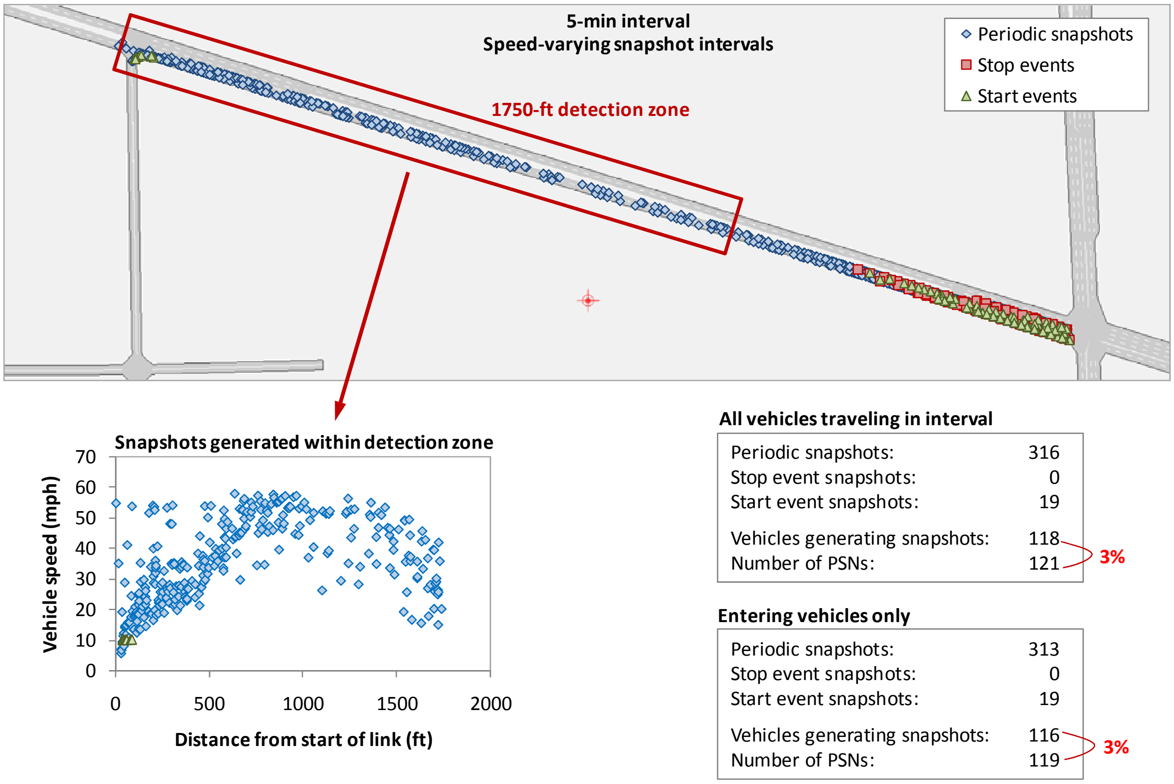
8.1.2. Estimation Using Snapshots Generated within a Defined Analysis Zone

On long links, the problem of vehicles generating multiple sequences of snapshots with different PSNs can be reduced by only considering the snapshots generated within a section of the link rather than its entire length. The key here is to define a detection zone that is long enough to ensure that all vehicles traveling across it generate at least one snapshot within its boundaries. As an example, vehicles traveling at 50 mph and generating snapshots every 16 s will typically generate a new snapshot every 1164 ft. Using an 1164-ft long detection zone would therefore ensure that all vehicles traveling at or below 50 mph would generate at least one snapshot within the detection zone and would theoretically reduce the potential of double-counting some vehicles.

Since not all vehicles travel at the same speed or at a constant speed, the length of a detection zone should not be set according to the average traffic speed. When possible, it should be set according to the speed of the fastest vehicles expected to travel across the zone to reduce the risk of having some vehicles going through without generating a snapshot. Either the absolute fastest speed or a speed corresponding to the average observed traffic behavior could be considered. While this may work for many links, short links may still impose limits on the size of the detection zone. In these cases, there may be no solutions to avoid ghost vehicles, unless snapshots generated from adjacent links can be pooled together.

Figure 8-4 illustrates an application of the detection zone approach to the example of Figure 8-2. Here, a detection zone is placed at the upstream end of the link for counting vehicles entering the link. The length of the zone is set at 1750 ft to allow capturing at least one snapshot from the few vehicles observed to travel at around 60 mph despite the 55-mph speed limit. This analysis zone yields 119 sets of snapshots with unique PSNs from the 116 vehicles entering the zone during the 5-minute analysis period. This is a difference of only 3 vehicles, which is much less than what was obtained when considering the snapshots generated along the entire link.

While the detection zone approach appears reasonable for counting vehicles, it is not without potential problems. Changes in traffic conditions may result in increasing or decreasing traffic speeds. Increasing traffic speeds may increase the proportion of vehicles going through without generating any snapshot and increase the potential for under-counting vehicles. On the other hand, decreasing traffic speeds may cause vehicles to generate more snapshots within the zone and increase the potential for PSN changes, and thus, the potential for over-counting vehicles. Some uncertainty will therefore always exist regarding the true reliability of vehicle counts based on PSN compilations when traffic conditions differ from normal situations.



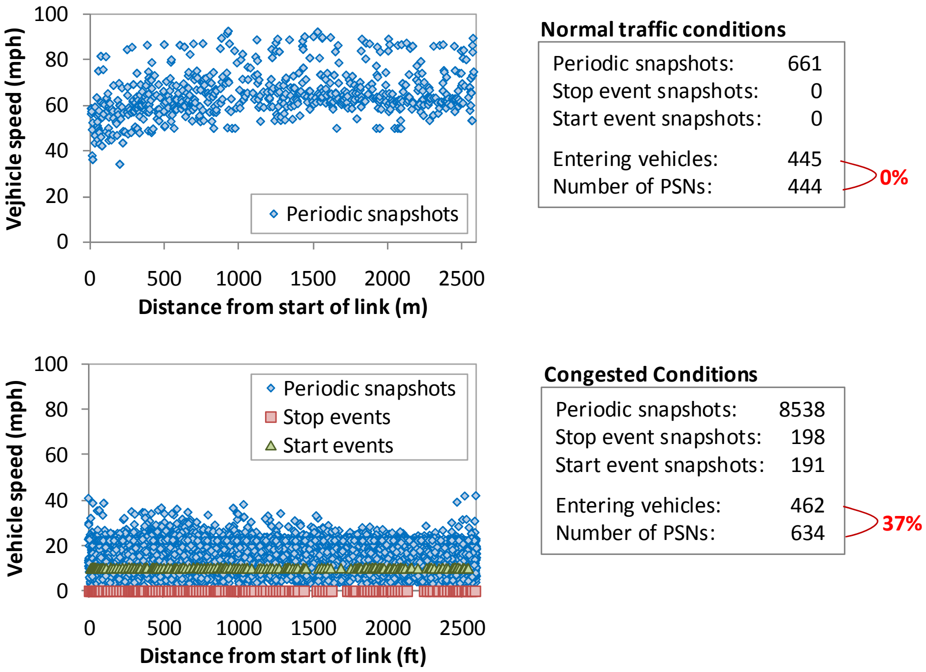
All vehicles traveling in interval

Periodic snapshots:	316
Stop event snapshots:	0
Start event snapshots:	19
Vehicles generating snapshots:	118
Number of PSNs:	121

Entering vehicles only

Periodic snapshots:	313
Stop event snapshots:	0
Start event snapshots:	19
Vehicles generating snapshots:	116
Number of PSNs:	119

Figure 8-4 – Link Entry Count Estimation using Snapshot Detection Zone Approach



Normal traffic conditions

Periodic snapshots:	661
Stop event snapshots:	0
Start event snapshots:	0
Entering vehicles:	445
Number of PSNs:	444

Congested Conditions

Periodic snapshots:	8538
Stop event snapshots:	198
Start event snapshots:	191
Entering vehicles:	462
Number of PSNs:	634

Figure 8-5 – Effect of a Change in Traffic Conditions on Number of PSN Sequences

An example is shown in Figure 8-5. This example shows the snapshots generated over a 2650-ft freeway section with a 70-mph posted speed limit under both normal and congested conditions. The length of the section is long enough to capture at least one snapshot from a few vehicles traveling at around 90 mph. Under normal conditions, there is very good agreement between the number of PSN sequences (444 sequences) and the number of vehicles entering the link (445 vehicles) over the 5-minute analysis period. However, there is a significant difference between the number of vehicles generating snapshots (462 vehicles) and number of snapshot sequences with a unique PSN (634 snapshots) under congested conditions as the slower traffic speeds result in more vehicles reaching the PSN time change threshold while traveling within the analysis zone.

To reduce the problem of vehicles initiating a PSN change within a detection zone, shorter snapshot intervals may be considered. Shorter intervals would allow reducing the size of the analysis zone, and thus the likelihood that a PSN change may be triggered within the zone. As an example, consider replacing a 20-s interval with a 4-s interval for vehicles traveling at 80 mph. With the 4-s interval, a 470-ft detection zone would be required to capture at least one snapshot from the vehicles, instead of a 2400-ft zone with a 20-s interval. While some PSN change may still occur within the zone, the frequency of such changes should be reduced, thus improving the accuracy of the collected data.

A potential issue with the use of short snapshot intervals is the increased risk that vehicles may completely fill their memory buffer, particularly is small buffers are used. If this occurs, some data losses can be expected, as vehicles may discard some snapshots to make room for new ones. The danger is that some of the discarded data may be snapshots recording the passage of a vehicle through a detection zone. These deletions could effectively erase all traces of the passage of a vehicle through the detection zone and thus lead to an under-counting of vehicles.

At some locations, vehicle-RSE interactions cause vehicles to go through a detection zone without leaving any snapshot:

- Under current protocols, vehicles can only communicate once with an RSE. To prevent tracking across RSEs, it is further prohibited to upload snapshots tagged with a specific PSN at more than one RSE. Vehicles allowed to retain their PSN after having communicated with an RSE may thus see some of the snapshots blocked from being uploaded at other RSEs.
- To prevent the above problem, vehicles are normally instructed to change their PSN after their memory buffer has been emptied and when they leave the range of an RSE. However, a PSN change triggers the mandatory discarding of periodic snapshots generated for a few seconds after the change. If short zones are used, a possibility thus exists that a vehicle may completely traverse a zone during the mandatory gap.

The examples of Figure 8-6 illustrate how the above rules may affect the ability to capture data from all vehicles going through a detection zone. The first example considers a vehicle generating snapshots every 20 s while traveling at 70 mph. A 2400-ft detection zone designed to catch at least one snapshot from vehicles traveling at speeds of up to 80 mph is on the path of the vehicle. It is further assumed that a PSN change is triggered right before the vehicle enters the detection zone following interactions with a neighboring RSE. If the PSN change imposes an 820 ft gap (250 m), the longest possible according to current protocols, the next scheduled snapshot will falls within the gap and will therefore be discarded. If it is further assumed that the gap does not affect the scheduling of snapshots, the next snapshot will then be generated only after the vehicle will have exited the detection zone, thus resulting in it going through the zone without leaving any snapshot.

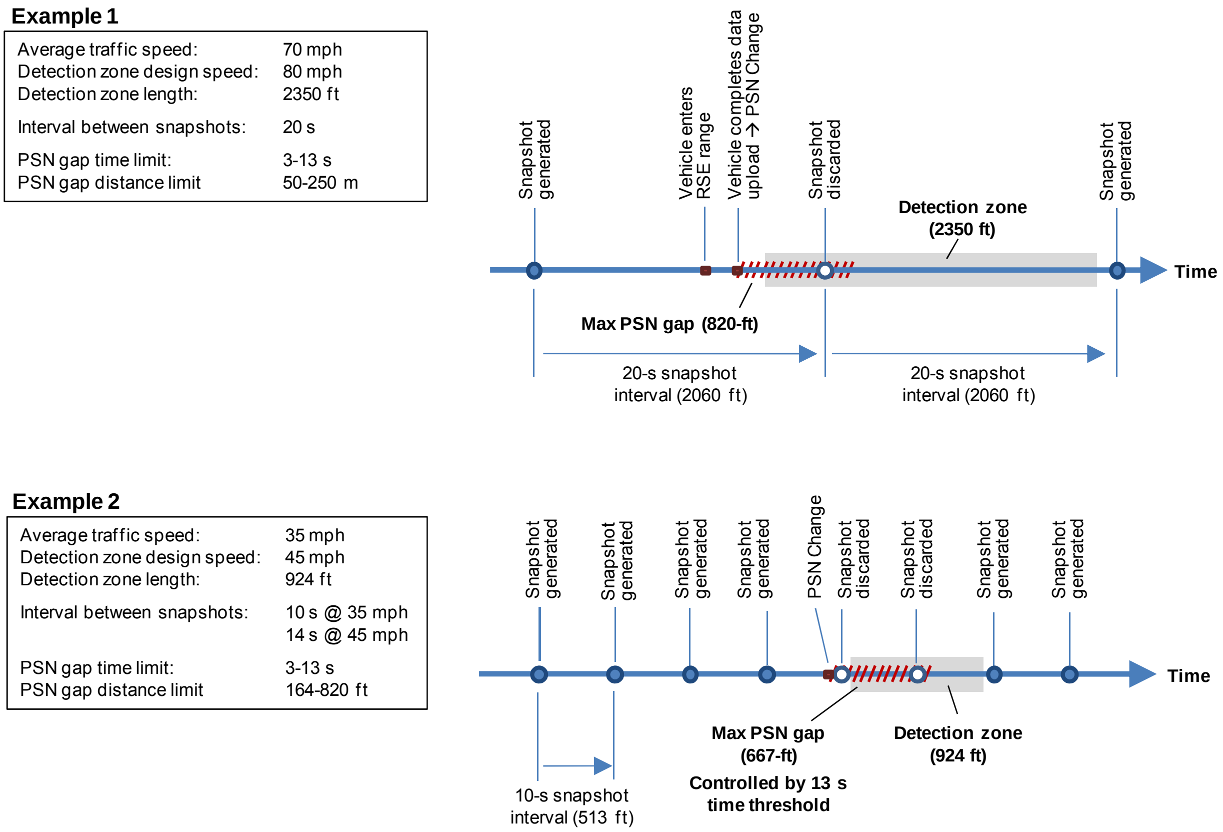


Figure 8-6 – Examples of Vehicles Going through Detection Zones without Leaving Snapshots due to Vehicle-RSE Interactions

The second example considers a vehicle traveling at 35 mph going through a detection zone set up to capture vehicles traveling up to 45 mph. According to the default speed-based spacing protocol, this vehicle would generate snapshots every 10 s, which translates into a snapshot every 513 ft. If a PSN change is triggered slightly before the vehicle enters the detection zone, up to two snapshots could then be discarded if the maximum gap is imposed. Since the gap is terminated as soon as the time or the distance threshold is reached, the distance traveled at 35 mph during a 13 s interval determines a maximum gap size of 667 ft, which is less than the 820 ft that the vehicle could travel under the maximum PSN changeover gap. This scenario thus again results in the vehicle going through the detection zone without leaving any snapshot.

Based on the above considerations, the following guidelines for determining detection zone lengths reducing the potential for over-counting or under-counting vehicles can be proposed:

- A detection zone should be long enough to allow the capture of at least one snapshot from the fastest moving vehicles traveling across the zone.
- The shortest possible detection zone should be used to reduce the potential for vehicles generating snapshots with different PSNs within the zone.
- A detection zone should not be shorter than the distance that vehicles may travel during a PSN changeover gap. This imposes a minimum length corresponding to lesser between 820 ft (250 m) and the distance traveled in 13 s by the fastest vehicles.

8.1.3. Estimation Using Link Entry/Exit Snapshots

Conceptually, the most reliable method for counting vehicles and determining link flow rates using probe vehicle data would be to instruct vehicles to generate a *link entry* or *link exit* event snapshot each time they enter or exit a link. Since each vehicle would be expected to generate a single snapshot for each link traversed, all that would be required to count vehicles traveling on specific links would be to compile the number of event snapshots generated on these links. These snapshots would in effect provide similar information than what would be provided by traditional point detectors installed at the upstream or downstream end of a link. This would notably allow data from link entry/exit snapshots to be easily integrated with data streaming from existing traffic monitoring applications.

When compared to periodic snapshots, link entry/exit snapshots remove many of the impediments created by PSN changeover rules. They also offer less risk of miscounted vehicles since each vehicle is expected to generate only one snapshot per link. However, the addition of these snapshots to other collected snapshots may lead to vehicles filling up more frequently their onboard memory buffers, particularly if small buffers are used. This could result is some data losses. If link entry/exit snapshots are deemed more important than periodic snapshots, they could be categorized as special events. In such a case, these snapshots would only be removed if no periodic snapshots, and possibly no stop/start event snapshots depending on the prioritization level, remain within the buffer.

The generation of link entry/exit event snapshots can be triggered by the crossing pre-defined link boundaries. The crossing of such boundaries could be detected by using electronic maps. This is something that is commonly done in current vehicle navigation systems. A link exit or entry event would be determined each time the vehicle would be found traveling on a new link.

The challenge here is not how to implement trigger points in an electronic map, but to determine where these points should be located. Ideally, the link definition used by onboard vehicle systems should be compatible with the definitions used by the applications expected to rely on the collected data. This requires for instance compatibility with the link definitions used by traffic management, travel demand forecasting, and asset management applications. Potential sources for generic link definitions include:

- **Topographically Integrated Geographic Encoding and Referencing (TIGER) data files.** TIGER is a digital database maintained by the U.S. Census Bureau to support its mapping needs. It provides a modeling of roads, railroads, rivers, lakes, political boundaries, and census statistical boundaries covering the entire United States. Data is available in a format compatible with commonly used Geographic Information Systems (GIS) and mapping software. Geographical elements are modeled at a scale 1:100,000, thus providing a horizontal accuracy of +/- 167 ft.
- **Michigan Geographic Framework (MGF).** The MGF is maintained by the Department of Information Technologies (MDIT) and serves as the digital base map for State of Michigan governmental agencies. It includes road features and attributes based on current TIGER/Line files, as well as an enhanced linear referencing system built from MDOT's Michigan Accident Location Index (MALI). Geographic features are modeled within the framework at a scale of 1:24,000, which corresponds to a horizontal accuracy of +/- 40 ft.
- **Google maps.** Google Maps is a basic web mapping service application that offers street maps of the entire United States. While non-commercial users can use free map data to program applications, a fee may be charge for commercial data users.

Both link entry and link exit snapshots would allow turn movements to be recorded. The specific turn made by a vehicle at the downstream or upstream end of a link could be recorded by simply storing information about the link on which the vehicle is currently located (location of the vehicle when the snapshot is generated) and the link that was previously being traveled.

While a link entry event essentially corresponds to a link exit event, there are conceptual advantages in generating link exit events rather than link entry events. Link entry snapshots focus on what happen at the upstream end of a link. The information they carry identify when a vehicle enters a link, and possibly from where it comes from. There is no characterization of what happens on the rest of the link. Determining the link travel time or whether a vehicle turned left, went straight or turned right at the downstream end of the link requires analyzing link entry events from all adjacent downstream links. Vehicle movements could then only be identified for vehicles generating snapshots with the same PSN on both links, which is likely to be problematic for long links. On the other hand, link exit snapshots focus on what happens at the downstream end of a link, once travel has been completed. This allows them to record observed travel statistics, such as the time taken to traverse the link or the number of stops made. Directional flow analyses are also simplified by the fact that only snapshots generated on the link of interest need to be processed.

8.1.4. Partial Market Penetration Effects

From a technical standpoint, flow rates can only be measured with perfect accuracy if all vehicles passing a survey location can communicate their presence. However, reasonable estimates could still be produced with partial market penetrations if information about the proportion probe vehicles within the traffic stream is known. For instance, if it is known that 5 or 10% of all vehicles in an area are probe vehicles, this information can be used to convert a count of probe vehicles detected to pass at a given location into an estimate of the overall flow rate at that same location. While estimating flow counts using estimated proportions of probe vehicles may be less reliable than the direct count method offered by current point detectors, this approach could still provide significant monitoring improvements for links from which flow data is currently only periodically or never collected.

Estimating the proportion of probe vehicles for an entire network could be done by compiling vehicle sales statistics or by using methods similar to those currently used to assess vehicle mixes. Specific local proportions could further be developed by analyzing the snapshots produced by vehicles at a location where traditional point detectors are also present. The ratio of the number of vehicles identified from processing collected snapshots to the vehicle counts returned by the point detector would provide an estimate of the local proportion of probe vehicles. This measured proportion could be used to estimate overall flow rates on neighboring links as detailed below:

$$Probe\ vehicle\ ratio\ = \frac{Reference\ link\ snapshot\ vehicle\ count}{Reference\ link\ point\ detector\ vehicle\ count}$$

$$Link\ flow\ rate\ = \left(\frac{Link\ snapshot\ vehicle\ count}{Time\ interval}\right) \times \left(\frac{1}{Probe\ vehicle\ ratio}\right)$$

The accuracy of the above estimation process would be dependent on whether the estimated probe vehicle ratio would correctly reflect the actual proportion of probe vehicles on links from which flow rates are estimated. This proportion is likely to fluctuate from one link to the other, as well as from one moment to the next.

To improve accuracy more point detectors could be installed. However, installing detectors on every link would defeat the purpose of using probe vehicles. To ensure that reasonable flow rate estimates could be obtained in early system deployments, point detectors could instead be maintained only on high volume links and links of particular importance. The ratios derived from these links could then be used to assess flow rates on neighboring links without traffic detectors. Increases in the proportion of probe vehicles will then gradually reduce the risk that the ratios estimated from the reference links may differ significantly from the actual proportions of probe vehicles on individual links and gradually improve accuracy.

Attaining a 100% market penetration will not eliminate the risk for errors. Since current snapshot generation protocols do not call for vehicles to generate snapshots at specific locations, a risk will remain that vehicles may traverse short links or a detection zone without generating any snapshot. Current privacy rules may also trigger vehicles to change PSNs and cause them to be double counted. Even if vehicles were to generate snapshots when entering or exiting a link, some snapshots may still be lost during wireless transmission or other data processing. A certain degree of error will therefore always exist, similar to the fact that current traffic detection technologies do not usually guarantee 100% reliability or accuracy.

8.1.5. Conclusions

Based on the above evaluations, the following conclusions are made regarding the use of probe vehicle data generated according to current protocols to estimate link flow rates:

- Since vehicles may generate multiple snapshots while traveling a link, simply counting the number of snapshots generated will likely lead to overestimations of the number of vehicles traversing the link.
- Counting the number of snapshots with different PSNs produces more accurate vehicle counts but can still lead to overestimations as some vehicles may change their PSN while on the link.
- To reduce the risk of double-counting vehicles, snapshots should preferably be only compiled within a section of link long enough to capture at least one snapshot from all passing vehicles. This detection zone should be long enough to accommodate the fastest moving vehicles and the maximum distance that a vehicle may travel during a PSN switchover gap. However, this approach will not fully eliminate the potential for double counting some vehicles.
- Changing the snapshot interval protocol does not significantly affect the accuracy of vehicle counts, as the primary impacting factor is the potential for a vehicle going through a PSN change while traveling on the link or within a detection zone.

The ideal approach for estimating link flow rates would be to instruct vehicles to generate a “link entry” or “link exit” event snapshot each time they enter or exit a link. Since each vehicle would generate only one snapshot, this approach would remove the potential for double-counting or under-counting vehicles, in addition to eliminating the need for special detection zones. The following recommendations are made regarding the use of link entry/exit snapshots:

- Link boundaries should correspond to the links used in various transportation system databases and analysis processes.
- The preference should be given to generating “link exit” snapshots, as these snapshots allow to record observed link travel statistics and simplify the execution of direction flow analyses.

Ideally, a full market penetration is required to accurately estimate flow rates. However, flow rates can be estimated with partial penetrations if an estimate of typical proportions of probe vehicles on or near each link is known. Such a proportion can be estimated by comparing vehicle counts derived from probe data processing to counts provided by traditional point detectors on reference links on which both detection approaches are available.

8.2. Link Flow Density

Flow density is a fundamental macroscopic characteristic of traffic flow. Density is used to assess traffic performance both from the point of view of users and operators. It is used as a primary control variable in freeway control and surveillance systems, as well as a primary measure of level of service in the Highway Capacity Manual for freeways and other uninterrupted flow facilities.

Density is defined as the number of vehicles occupying a length of roadway. While any reference length can be used, most engineering applications define density as the average number of vehicles on a single lane over a 1-mile section of road. Density values range from zero, when there is no vehicle on the road, to a jam density value representing a situation where all vehicles are stopped bumper to bumper.

The most direct and accurate way of measuring density is to photograph a section of road and count the number of vehicles present. Density is the number of vehicles divided by the length of the stretch of road. Since aerial photographs are costly to produce, surrogate estimation approaches based on information provided by point traffic detectors are more commonly used. One of these methods bases its estimation on two easily observed measurements: vehicle flow rate and detector occupancy. The occupancy of a detector is the percent of time within an interval during which the detector senses the presence of a vehicle. Using measurements from neighboring detectors, the number of vehicles between them, and thus the traffic density, can be tracked. Formulas directly converting occupancy into density are also available. However, since these formulas require an estimate of the length of vehicles passing over the detectors, they only provide reasonable estimates of density as long as the traffic mix does not significantly deviate from what is being assumed.

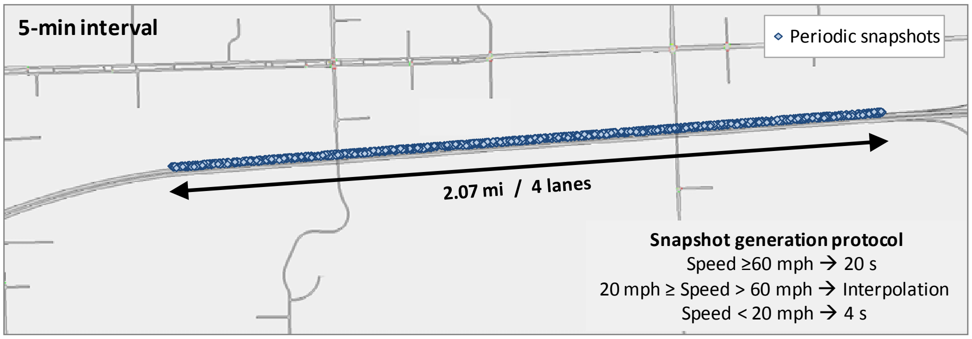
The following subsections discuss how periodic and link entry/exit event snapshots could be used to determine flow density along specific links. To highlight potential estimation problems, the analyses focus primarily on scenarios assuming that probe vehicle data could be collected from all vehicles traveling on a link. Situations with partial data collection are discussed at the end of the evaluations. Items discussed below include:

- Estimation using periodic snapshots only
- Estimation using link exit event snapshots

8.2.1. Estimation Using Periodic Snapshots

Periodic snapshots indicate where individual vehicles were located at a given point in time. By counting the number of snapshots generated along a link within a short interval, an estimate of the number of vehicles present on the link within that interval could be obtained. This number could then be used to determine link flow density.

While the general approach for assessing flow density is conceptually simple, difficulties are introduced by the way snapshots are generated and by privacy rules. As an example, Figure 8-7 illustrates the



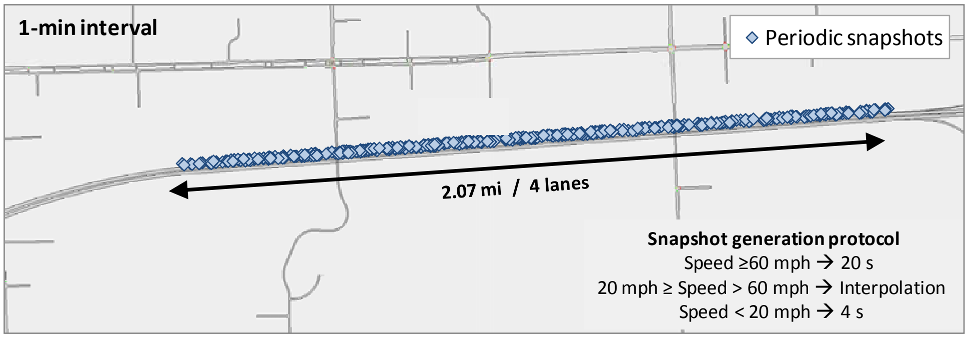
Vehicles traveling on link:	487
Unique PSNs:	545
Periodic snapshots:	2108

Figure 8-7 – Periodic Snapshots Generated along a Freeway Link within a 5-minute Interval

periodic snapshots that were generated along a freeway link within a 5-min interval using existing default snapshot generation protocols by UMTRI's probe data simulator. This scenario features 487 vehicles traveling across the freeway link during the 5-min analysis interval. These vehicles are further observed to generate 2108 periodic snapshots featuring 545 unique PSN values along the link.

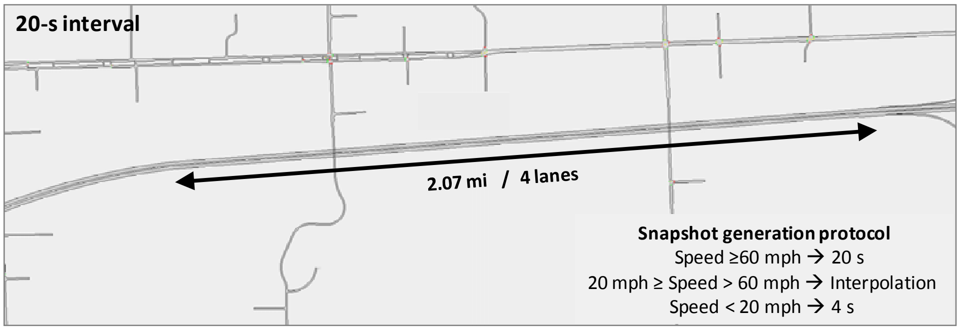
In this case, using the number of snapshots generated to assess the number of vehicles present on the link would be clearly erroneous, as it would overestimate the number of vehicles by 1621, or 333%. Using the number of unique PSNs found on the link would be similarly erroneous, as it would overestimate the number of vehicles by 58, or 12%.

Assessments that are more accurate can be obtained by reducing the length of the analysis period. As illustrated in Figure 8-8, using only the snapshots generated within the first minute of the interval results in the capture of 441 periodic snapshots and 298 unique PSNs from 234 vehicles. If the analysis is further constrained to the first 20 s, 149 periodic snapshots and 142 unique PSNs are then captured from 142 vehicles, as shown in Figure 8-9. While reducing the length of analysis period to 1min did not significantly improved the accuracy of the vehicle count, using a 20-s interval, which corresponds to the longest possible interval between two snapshots, led to an exact match between the number of unique PSNs and actual number of vehicles traveling on the link within the interval.



Vehicles traveling on link:	234
Unique PSNs:	298
Periodic snapshots:	441

Figure 8-8 – Periodic Snapshots Generated along a Freeway Link within a 1-minute Interval



Vehicles traveling on link:	142
Unique PSNs:	142
Periodic snapshots:	149

Flow density: $\frac{142 \text{ veh}}{2.07 \text{ mi} \times 4 \text{ lanes}}$ = 17.15 veh/lane/mi

Vehicles on link at 8:00	137
Vehicles on link at 8:01	145
Vehicles on link at 8:02	140
Vehicles on link at 8:03	120
Vehicles on link at 8:04	140
Vehicles on link at 8:05	156
Average	140

Flow density: $\frac{140 \text{ veh}}{2.07 \text{ mi} \times 4 \text{ lanes}}$ = 16.91 veh/lane/mi

Figure 8-9 – Periodic Snapshots Generated along a Freeway Link within a 20-second Interval

In the above example, using an analysis interval shorter than 20 s is not recommended, as such a short interval could prevent capturing the snapshots generated by some vehicles. To ensure that all vehicles generate at least one snapshot within an analysis interval, the general recommendation is therefore that this interval should never be shorter than the maximum possible interval between successive snapshots. For the current default speed-based spacing protocol, this means that intervals shorter than 20 s should not normally be considered.

An additional element to consider is the potential impacts of PSN rules. As indicated previously, PSN changes trigger a temporary discarding of generated snapshots. Using an analysis interval too short creates a risk that some vehicles may go through the interval without generating any snapshot. The longest possible snapshot-discarding gap defined in the current protocols is 13 s. However, it is possible that a vehicle initiates a PSN change just as it is about to generate a new snapshot. If snapshots are generated every 20 s, this may result in the next snapshot being recorded 20 s into the future, thus creating an effective 40-s spacing between two consecutive snapshots. To compensate for such an eventuality, the length of the analysis interval could be increased to 40 s to cover all potential PSN switch gaps situations. However, while such an increase may ensure that all vehicles generate at least one snapshot within the analysis interval, it also increases opportunities for some vehicles to generate snapshots using different PSNs. This could lead to an overestimation of the number of vehicles present on the link. A compromise may therefore be required for selecting an ideal analysis interval length.

The use of snapshot generation protocols favoring fixed snapshot intervals may further be preferred over protocols implementing variable intervals based on the fact that such protocols reduce the variability in the number of snapshots generated by individual vehicles over a given time interval. This could allow reducing the size of the required analysis window. However, fixed-interval protocols may not eliminate issues surrounding PSN changes. Since such changes are determined based on elapsed time and distance traveled criteria, the same proportion of vehicles may go through a PSN switch whether using a fixed or variable snapshot interval protocol.

Current snapshot generation protocols further recommend that no periodic snapshots be generated while a vehicle is stopped. This creates a potential problem for estimating link density, as it effectively prevents stopped vehicles from being counted and would result in a significant underestimation of flow density on links where queuing occurs. To prevent this situation, vehicles should be required to keep generating snapshots while stopped. This can easily be accommodated with protocols generating snapshots according to elapsed time, but not for protocols generating snapshots according to traveled distance.

8.2.2. Estimation Using Link Exit Event Snapshots

If link exit event snapshots are generated, the number of vehicles present on a link at a given instant can be determined by calculating the difference between the number of vehicles that have entered and exited the link. The number of exiting vehicles would be provided by the event snapshots associated with the link, while the number of entering vehicles could be determined by processing the exit event snapshots from the upstream links.

The above approach is only feasible if event snapshots store vehicle identification data, which is unlikely under current privacy settings. This approach would also be conceptually more complex than the processing of periodic snapshots, as it would require matching event snapshots across sets of links instead of snapshots from single links. For each intersection, the sets of links to consider may further need to be manually defined by system operators, making the data processing network-specific. Finally, estimation errors would still exist due to the likelihood that some vehicles might change their PSN while traveling on a link, resulting in these vehicles being counted more than once.

8.2.3. Partial Market Penetration Effects

Estimating link flow density is subject to the same market penetration effects as the estimation of link flow rates. Estimating flow density along a given section of road requires information about all the vehicles traveling on it. If not all vehicles communicate their presence, an estimate of the flow density could be obtained by using information defining the typical proportion probe vehicles in the area in which the section of road is located:

$$Probe\ vehicle\ ratio\ = \frac{Reference\ link\ snapshot\ vehicle\ count}{Reference\ link\ point\ detector\ vehicle\ count}$$

$$Link\ flow\ density\ = \left(\frac{Link\ snapshot\ vehicle\ count}{Link\ length}\right) \times \left(\frac{1}{Probe\ vehicle\ ratio}\right)$$

Similar to the effects described in Section 8.1.4, the accuracy of the above estimation process is dependent on whether the estimated probe vehicle ratio adequately reflects the actual proportion of probe vehicles on the sections of road of interest. This can be problematic in early system deployments, when the proportions of probe vehicles may be relatively low.

To ensure that reasonable flow rate estimates could be obtained in early system deployments, point detectors could instead be maintained only on high volume links and links of particular importance. The ratios derived from these links could then be used to assess flow density on neighboring links without traffic detectors. Increases in the proportion of probe vehicles will then gradually reduce the risk that the ratios estimated from the reference links may differ significantly from the actual proportions of probe vehicles on individual links and gradually improve accuracy.

Attaining a 100% market penetration will not eliminate the risk for errors. Since current snapshot generation protocols do not require all vehicles to generate snapshots at the same time, a risk will remain that vehicles may travel through short analysis intervals without generating any snapshot. Current privacy rules may also trigger a PSN change and cause some vehicles to be double-counted. Some snapshots may further be lost during wireless transmission or during other data processes. A certain degree of error will therefore always exist, similar to the fact that current traffic detection technologies do not usually guarantee 100% reliability or accuracy.

8.2.4. Conclusions

The following conclusions are made for the determination of flow density using probe vehicle data:

- Link density can be estimated using periodic snapshots only if vehicles are allowed to keep generating snapshots while stopped.
- Periodic snapshots generated according a distance-based spacing criterion cannot be used, as such snapshots may not capture immobilized vehicles.
- Use of snapshots generated according to a fixed interval protocol is generally preferred over the use of current default speed-based variable spacing protocols.
- To reduce the potential for double-counting vehicles generating snapshots with multiple PSNs, short analysis intervals should be used.
- The length of the analysis interval should be long enough to allow the capture of at least one snapshot from each vehicle traveling on the link. The shortest possible interval will correspond to the longest possible snapshot generation interval. Longer intervals may be considered to account for gaps in data collection imposed by privacy rules. While this may allow capturing vehicles that may be missed otherwise, it may also allow some vehicles to go through a PSN change. A compromise may therefore be necessary.

Ideally, a full market penetration is required to estimate density accurately. However, reasonable estimates can be obtained with partial penetrations if an estimate of typical proportions of probe vehicles on or near each link is known. Such a proportion can be estimated by comparing vehicle counts derived from probe data processing to counts provided by traditional point detectors on reference links on which both detection approaches are available.

8.3. Link Speed Profiles

Link speed profiles are diagrams representing the speed at which vehicles travel along successive sections of a link. These profiles are developed for various reasons. In operational analyses, they are used to assess traffic behavior along a link and locate where unusual slowdowns may occur. They can also be used to assess incurred delays. From a safety standpoint, speed profiles can further be used to assess acceleration and deceleration behavior and evaluate safety risks. The captured acceleration and deceleration cycles can finally be used to estimate fuel consumption and vehicle emissions.

Currently, speed profiles are typically developed using probe vehicles equipped with GPS devices, often as part of travel time studies. The vehicles are driven along roads at a speed matching the general traffic, while the onboard GPS device measures the vehicle's instantaneous speed every one or two seconds. To account for variability in traffic conditions, multiple runs are usually made. After the runs are completed, the collected speed data is aggregated into short segments and then averaged across all runs to produce an estimate of the typical traffic speed over each section of road.

The main limitation of the current approach is that it requires data collection runs with specially equipped vehicles. Due to costs and time requirements, these runs are typically executed on an as-needed basis, often only once every few years and for periods covering only a few days. In this context, the availability of IntelliDrive^{SM} probe vehicles offers an opportunity to expand significantly data collection. Since the collected data would be similar to that currently collected in sampling runs, the same techniques used for generating speed profiles could still be applied.

The development of speed profiles from snapshots involves relatively simple algorithms. The first operation is to assign the collected snapshots to a given link section. How a link is segmented will depend on the geometry of the link, the types of snapshots generated, and the quantity of snapshots collected. Segments within a link need not be the same length. The length of each segment can be adjusted to match specific link features, such as a lane drop, a curve, or the position of the stop line. The primary factor is the need to collect enough snapshots within each segment to create an adequate representation of the average traffic behavior within the segment. Typically, shorter segments will capture more successfully short-term speed variations.

The following subsections discuss how speed profiles can be estimated using the following snapshots:

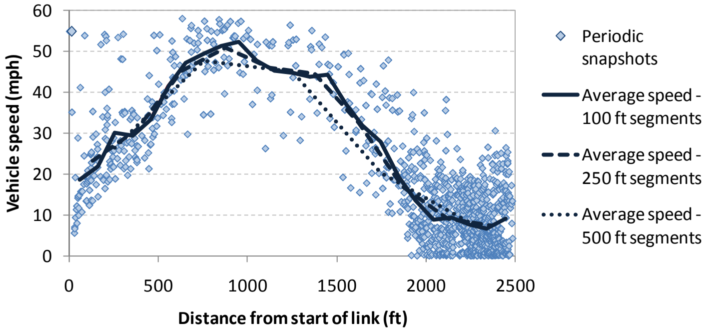
- Periodic snapshots generated according to variable intervals based on the speed of the vehicle
- Periodic snapshots generated according to fixed intervals
- Periodic snapshots generated based on traveled distance

8.3.1. Generation Using Speed-Based Periodic Snapshots

A logical first approach to generate speed profiles is to use periodic snapshots. An example is shown in Figure 8-10, which illustrates snapshots generated along an arterial link at intervals varying between 4 and 20 s based on the speed of the vehicle. The example illustrates the profiles obtained using 100-ft, 250-ft and 500-ft segmentations. Detailed calculations are also provided for the 100-ft segmentation. As can be observed, the three generated profiles appear to match fairly well the general changes in average traffic behavior along the link. As can be expected, the profile using the shortest segmentation matches more closely the observed speed changes along the link.

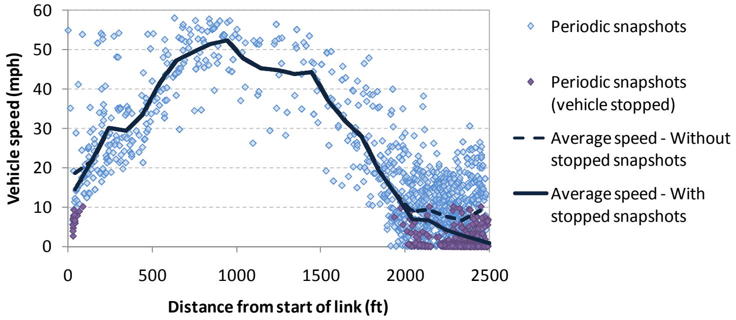
A potential problem in using only periodic snapshots is that current snapshot generation protocols do not call for vehicles to keep generating snapshots while stopped. This creates segments over which the effects of stopped traffic may be underrepresented. This effect is illustrated in Figure 8-11, which reprises the scenario of Figure 8-10 but with vehicles recording snapshots while stopped. As expected, the additional snapshots primarily show up near the downstream end of the link, where a traffic signal periodically forces vehicles to stop. Here, the inclusion of snapshot from stopped vehicles causes a non-negligible reduction of the assessed average travel speed at the downstream end of the link. This further translates into slower average speeds, longer link delays, and longer average travel times.

Instead of requesting vehicles to keep recording snapshots while stopped, queuing effects could be factored by using stop/start event snapshots to generate synthetic data replacing the missing periodic snapshots. This approach is feasible only if stop/start event snapshots are tagged with a PSN, as the absence of this information would make it impossible to determine whether pairs of snapshots are from the same vehicle.



Segment	Count	Average Speed
0-100	27	18.7
100-200	35	21.9
200-300	38	30.1
300-400	29	29.4
400-500	21	33.4
500-600	21	41.5
600-700	19	47.1
700-800	15	49.4
800-900	18	51.3
900-1000	12	52.4
1000-1100	6	47.7
1100-1200	8	45.3
1200-1300	10	44.8
1300-1400	7	43.9
1400-1500	11	44.3
1500-1600	12	37.1
1600-1700	16	31.9
1700-1800	26	27.9
1800-1900	33	19.4
1900-2000	80	13.6
2000-2100	108	8.9
2100-2200	137	9.4
2200-2300	185	7.7
2300-2400	206	6.7
2400-2511	111	9.0

Figure 8-10 – Speed Profile based on Periodic Snapshots Generated using Variable, Speed-Based Intervals



Segment	Count	Average Speed
0-100	42	14.4
100-200	35	21.9
200-300	38	30.1
300-400	29	29.4
400-500	21	33.4
500-600	21	41.5
600-700	19	47.1
700-800	15	49.4
800-900	18	51.3
900-1000	12	52.4
1000-1100	6	47.7
1100-1200	8	45.3
1200-1300	10	44.8
1300-1400	7	43.9
1400-1500	11	44.3
1500-1600	12	37.1
1600-1700	16	31.9
1700-1800	26	27.9
1800-1900	33	19.4
1900-2000	83	13.3
2000-2100	150	6.8
2100-2200	203	6.6
2200-2300	363	4.1
2300-2400	549	2.8
2400-2511	823	1.5

Figure 8-11 – Speed Profile based on Periodic and Stopped Periodic Snapshots Generated using Variable, Speed-Based Intervals

Some of the potentially significant challenges associated with the use of stop/start events to determine speed profiles include:

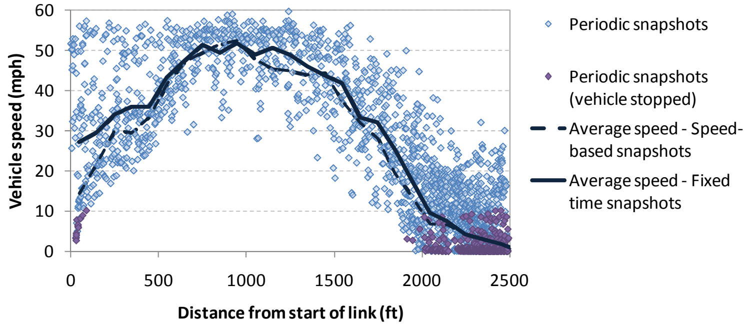
- Stop and start events may be assigned different PSNs if a switch is triggered between the two events. This would prevent linking the stop and start events and determining the time a specific vehicle spent in queue.
- Since start events are defined as vehicles reaching a speed above a certain threshold (typically 10 mph), start event snapshots are not necessarily generated at the same location where the vehicle initially stopped. Such a situation is likely to occur for vehicles stopping near an intersection stop line. While this situation can partly be compensated for by moving the link boundary downstream of an intersection stop line, there may be no guarantees that all relevant start event snapshots could be captured.
- Attempting to match stop and start events on different links would require a search for matching snapshots on every possible pair of entry/exit links from an intersection approach.
- Lowering the speed threshold defining a start event may also not be practical, as it may result in multiple stops and starts being counted in stop-and-go traffic.

When compared to the relative ease of simply allowing vehicles to keep recording snapshots while stopped, a recommendation is try to use stop and start event snapshots only as a source of information complementing stopped periodic snapshots.

While PSN data are not required for processing periodic snapshots, rules governing the use of PSNs may affect the estimation of speed profiles by requiring vehicles to cease generating snapshots temporarily for intervals of up 13 s or distance of up to 820 ft (250 m). Since PSNs are independently generated by each vehicle, these blackouts may be distributed across the link. If this is the case, the expected impact should be minimal. However, if the blackouts occur mostly over the same section of link, significant errors could result if the missing data mask some important speed variations. This could for instance happen if the edge of an RSE range falls within a link.

8.3.2. Generation Using Fixed Time Interval Periodic Snapshots

Using periodic snapshots generated at intervals varying with the speed of a vehicle can potentially bias speed profiles. Since this protocol results in vehicles generating fewer snapshots as their speed increases, this leads to the estimation of lower-than-expected speeds on segments where significant speed variability exists. This problem should not occur on segments in which all vehicles travel at approximately the same speed, as there should then be a relatively small difference in the number of snapshots generated between the faster and slower vehicles.



Segment	Count	Average Speed
0-100	87	27.2
100-200	57	29.6
200-300	54	34.0
300-400	58	36.0
400-500	48	36.1
500-600	49	43.4
600-700	36	47.4
700-800	36	51.3
800-900	45	49.3
900-1000	33	51.9
1000-1100	33	49.0
1100-1200	36	50.6
1200-1300	45	48.9
1300-1400	33	46.1
1400-1500	43	43.9
1500-1600	52	41.8
1600-1700	52	33.4
1700-1800	58	32.1
1800-1900	75	25.3
1900-2000	118	17.1
2000-2100	175	9.5
2100-2200	224	7.3
2200-2300	367	4.2
2300-2400	547	2.8
2400-2511	824	1.6

Figure 8-12 – Speed Profile using Regular and Stopped Periodic Snapshots Generated every 4 seconds

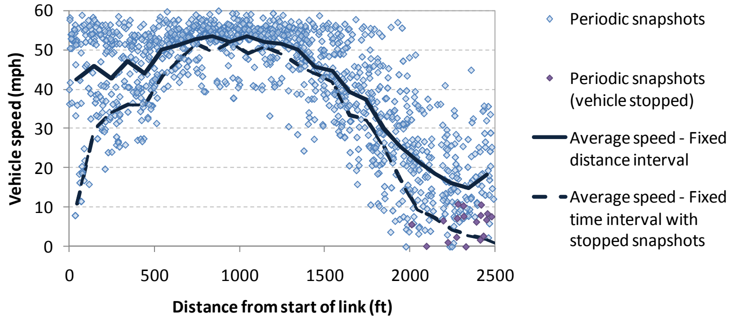
Figure 8-12 replaces the speed-based, variable snapshot interval of Figure 8-11 with a fixed 4-s interval. This change leads to the generation of significantly more snapshots, particularly in the middle portion of the link where vehicles travel near the speed limit. This leads to noticeable increases in average speed estimates. The increases are particularly notable near the upstream end of the link, where snapshots are generated both by vehicles traveling near the speed limit and by vehicles still accelerating after having entered the link from a side street. Notable increases are also observed on segments where vehicles decelerate near the downstream end of the link. Only small changes are observed in the middle of the link, as local speeds contained in a relatively narrow range. Very few changes are also observed where vehicles queue at the downstream end of the link, as the large number of stopped periodic snapshots generated significantly outweighs the increase in periodic snapshots by moving vehicles associated with the switch from a variable to a fixed snapshot interval protocol.

8.3.3. Generation Using Distanced-based Periodic Snapshots

A problem with time-based generation protocols is that vehicles traveling faster will always produce fewer snapshots per unit distance than slower vehicles. This creates a potential bias toward lower speeds on segments with significant speed variability. Since speed profiles are estimated using a distance criterion, a better approach may be to space snapshots according to the distance traveled. However, this approach is not recommended due to inadequate consideration of queuing conditions.

Since vehicles do not move while stopped, they do not generate snapshots while waiting in a queue. This results in an inadequate consideration of travel conditions on segments on which queuing occurs, and in a potential overestimation of average speeds.

The above effect is illustrated in Figure 8-13, which considers the same link as in Figures 8-12 but assumes that snapshots are generated every 200 ft instead of every 4 s. When comparing the two figures, it can be observed that generating snapshots according to a fixed distance results in a uniform distribution of data across all segments. An increase in the estimated average speed is also observed across all segments. For most segments, this increase is explained by removing the difference between the slower and faster vehicles in the snapshot generation rate per unit distance. This also explains why the differences in average speed are more important for the segments with large speed variability than segments with more uniform speeds. The largest differences are for the segments at the upstream end of the link where there are both vehicles accelerating and traveling at full speed.



Segment	Count	Average Speed
0-100	52	42.4
100-200	45	45.9
200-300	62	42.6
300-400	40	47.0
400-500	58	43.9
500-600	46	49.9
600-700	48	51.1
700-800	57	52.6
800-900	47	53.3
900-1000	53	52.0
1000-1100	42	53.3
1100-1200	55	51.9
1200-1300	45	51.3
1300-1400	53	49.9
1400-1500	48	45.5
1500-1600	51	44.6
1600-1700	49	39.3
1700-1800	51	37.3
1800-1900	52	29.9
1900-2000	54	25.2
2000-2100	53	21.6
2100-2200	29	18.5
2200-2300	56	16.0
2300-2400	33	14.8
2400-2511	38	18.3

Figure 8-13 – Speed Profile based on Periodic Snapshots Generated every 200 ft

8.3.4. Partial Market Penetration Effects

Estimating speed profiles does not require collecting data from all vehicles passing on a section of road. While availability of data from a greater proportion of vehicles would typically result in greater statistical accuracy, all that is required to support network operational and analysis needs is to collect enough data to develop a profile adequately representing average traffic conditions, and if needed, the observed variability of traffic conditions. If traffic conditions are stable and relatively uniform, accurate profiles could be obtained by using data from a relatively small proportion of vehicles. Links with greater variability in traffic conditions would require collecting data from a greater proportion of vehicles.

For each section of road for which a speed estimate is required, the target is to collect enough speed samples to ensure that the resulting average falls within a certain confidence range. According to NCHRP Report 398 (Lomax *et al.*, 1997), the correct theoretical formula for estimating sample sizes when the variance of the sample is not initially known is given by:

$$n = \left(\frac{t_{\alpha,n-1} \cdot cv}{e} \right)^2$$

where: $t_{\alpha,n-1}$ = *t*-statistic from Student's distribution for confidence level α (two-tailed test) and *n-1* degree of freedom
α = Confidence level parameter (Example: 95% confidence → $\alpha = (1-0.95)/2 = 0.025$)
n = Total number of measurements to be made

cv = Coefficient of variation of data
e = Allowable error in average travel time measurement

The above formula estimates the number of measurements to be collected based on the coefficient of variation of the measurements. Very frequently, this coefficient is not known ahead of time. An iterative procedure is thus required to estimate the sample size required since the degree of freedom (the *n-1* parameter) of the Student distribution's *t*-statistic is based on the total number of data *n* to be considered to achieve the desired accuracy. Since the coefficient of variation can change with additional data sampling, application of the formula requires continuously reassessing the number of runs needed until the actual number of runs made match or exceed the requirements given by the formula.

A frequent simplification made by practicing engineers is to use the Normal distribution instead of the Student distribution to estimate the sample size. This replacement removes the need to assess a parameter linked to the total number of runs to be made (the degree of freedom *n*) and allows for a straightforward calculation of the required number of data to collect:

$$n \cong \left(\frac{Z_{\alpha} \cdot cv}{e} \right)^2$$

where: α = Confidence level parameter (Example: 95% confidence → α = (1-0.95)/2 = 0.025)
Z_{α} = Standard normal variate based on confidence level α for a two-tailed test (Table 2).
cv = Coefficient of variation of data sample
e = Allowable measurement error

The above equation generally provides reliable estimates when sample sizes are greater than 30, and generally reliable estimates for samples exceeding 20 or 25 observations. For sample sizes of less than 20, the number of data to collect may be underestimated by approximately two observations.

8.3.5. Conclusions

Based on the above evaluations, the following conclusions are made:

- Speed profiles can be generated by compiling the average of the vehicle speeds recorded within the periodic snapshots generated within each section of a link.
- Link segments should be long enough to allow representative averages to be calculated. They can be as short as a few feet, covering an entire link, and do not need to be all the same length.
- To reflect adequately the impacts of queuing on traffic flow behavior, vehicles should keep recording periodic snapshots while stopped.
- Stop/start event snapshots can be used to characterize traffic queuing behavior. However, this approach is more complex than simply allowing vehicles to generate snapshots while stopped.
- Speed profiles should preferably be developed using snapshots generated at fixed time intervals. Some bias will remain because faster vehicles will generate fewer snapshots per unit distance than slower vehicles.
- While periodic snapshots spaced according to distance traveled may remove most of the potential biases associated with time-based intervals, their use is not recommended due to their inability to record data while vehicles are stopped.

- Snapshots spaced in time according to the speed of the vehicle will introduce a bias toward lower average speeds on segments with significant speed variability.
- Data sampling is not required from all vehicles to obtain representative profiles. Statistical techniques can be used to determine the amount of data needed to reach a given accuracy.

8.4. Link Travel Time

Current traffic surveillance systems generally do not provide direct travel time measurements. Such measurements are only possible on toll roads equipped with Automated Vehicle Identification (AVI) systems where the passage of vehicles at successive tollgates can be tracked.

While many freeways are now equipped with traffic detection stations, these stations typically only report vehicle counts and speed measurements. There is no built-in capability for tracking vehicles from one station to the next. To assess travel time between two stations, speed measurements at each station are used to derive an average travel speed in between. Travel time is then calculated by simply dividing the distance between the stations by the estimated travel speed. This approach is subject to the assumption that nothing occurs between the two stations. If speed fluctuations occur, discrepancies may then exist between the calculated and true average travel times.

Measuring travel times along arterials using point detectors is more challenging than on freeways. On arterials, vehicle behavior can be affected by traffic signals, resulting in the detection of both moving and stopped traffic. In the latter case, there is usually no information available about the exact amount of time that each vehicle remains stopped in a queue. Various events, such as vehicles executing parking maneuvers or pedestrians crossing streets, may also contribute to the variability of travel times.

IntelliDrive^{SM} systems offer the potential to improve travel time estimates significantly. The main envisioned benefit is an ability to obtain travel time data from links that are not currently equipped with traffic monitoring devices. For links currently under surveillance, the potential also exists to obtain more reliable travel time estimates, particularly where travel times are only indirectly inferred. Similar to the estimation of speed profiles, reliable travel time estimates could also be produced with partial IntelliDrive^{SM} market penetrations as long a adequate statistical sampling requirements are met.

The following approaches for estimating link travel times are presented in the subsections that follow:

- Estimation by averaging speeds recorded in individual snapshots
- Estimation using speed profiles
- Estimation using default periodic snapshots
- Estimation using default periodic and stop/start event snapshots
- Estimation using default periodic, stopped periodic and stop/start event snapshots
- Estimation using link entry/exit event snapshots

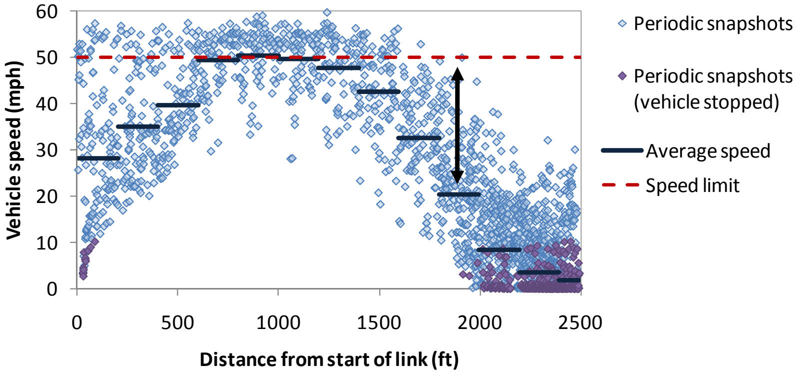
8.4.1. Estimation by Averaging Individual Snapshot Speeds

A first potential approach to estimating link travel times is to calculate the average of the vehicle speeds recorded within all the captured snapshots. While possible, this approach is not recommended, as it may not adequately consider variations in traffic behavior along the link due to the potential sampling bias described in Section 6.3, particularly in cases in which a variable speed-based or distance-based snapshot interval spacing protocol is used.

8.4.2. Estimation Using Speed Profiles

Another approach consists of extending the methodology used for developing link speed profiles. If a speed profile is known, the travel time can be estimated by calculating the time needed to travel across each successive segment within the profile. An example using the profile of Figure 8-12 is shown in Figure 8-14. In this example, the actual average travel time of the 116 vehicles entering the link during the 5-minute analysis interval is 133.9 s. With 200-ft segments, the estimated travel time is 141.4 s. The 7.5-second difference is due in part to the averaging process used to develop the speed profile and in part to a bias in the snapshot generation process. Since vehicles traveling at slower speeds generate more snapshots per unit distance, there is a tendency to underestimate the average speed, and thus overestimate travel times, on segments with large speed variations.

The accuracy of link travel times further depends on the segmentation used. Typically, more accurate travel time estimates can be expected from finer segmentations. As shown in Figure 8-14, using 500-ft segments yields an average travel time of 133.9 s instead of the 141.4 s obtained with 200-ft segments. The ability to use shorter segments also depends on the ability to maintain the collection of sufficient data samples within each segment to allow statistically valid averages to be developed. Potential gains from the use of a finer segmentation must also be weighed against the higher computational loads that may be introduced. The general recommendation is to use the shortest practical segment length that will allow sufficient data to be collected within each segment to characterize adequately the observed conditions for the intended data uses.



Segment	Segment Length (ft)	Snapshot count	Average speed (mph)	Travel time at average speed (mph)
0-200	200	144	28.2	4.8
200-400	200	112	35.1	3.9
400-600	200	97	39.8	3.4
600-800	200	72	49.4	2.8
800-1000	200	78	50.5	2.7
1000-1200	200	75	49.8	2.7
1200-1400	200	78	47.7	2.9
1400-1600	200	95	42.7	3.2
1600-1800	200	110	32.7	4.2
1800-2000	200	193	20.3	6.7
2000-2200	200	399	8.3	16.5
2200-2400	200	914	3.4	40.1
2400-2511	111	824	1.6	47.5
			Link total:	141.4

Segmentation	Average travel time (sec)
100 ft	141.5
200 ft	141.6
300 ft	140.7
400 ft	140.9
500 ft	133.9

Figure 8-14 – Link Travel Time Estimation using Estimated Link Speed Profile

As outlined in previous sections, the protocol used to generate snapshots may have a significant impact on the accuracy of link travel time estimates developed from a speed profile:

- With snapshots spaced in time according to the speed of a vehicle, slower moving vehicles will tend to generate more snapshots than faster vehicles. This results in a bias toward low-speed estimates on segments where there is a significant variability in observed speeds.
- Using snapshots generated at fixed time intervals reduces the bias toward lower speeds by imposing a uniform spacing between snapshots. However, the bias is not eliminated, as slower moving vehicles will generate more snapshots per unit distance than faster moving vehicles.
- Snapshots generated according to a fixed travel distance remove all potential biases associated with vehicles traveling at different speeds. However, this approach also results in an inability to generate snapshots while stopped and in an inadequate consideration of queuing conditions.
- Time-based protocols also result in inadequate consideration of queuing conditions if they prevent vehicles from recording snapshots while stopped.

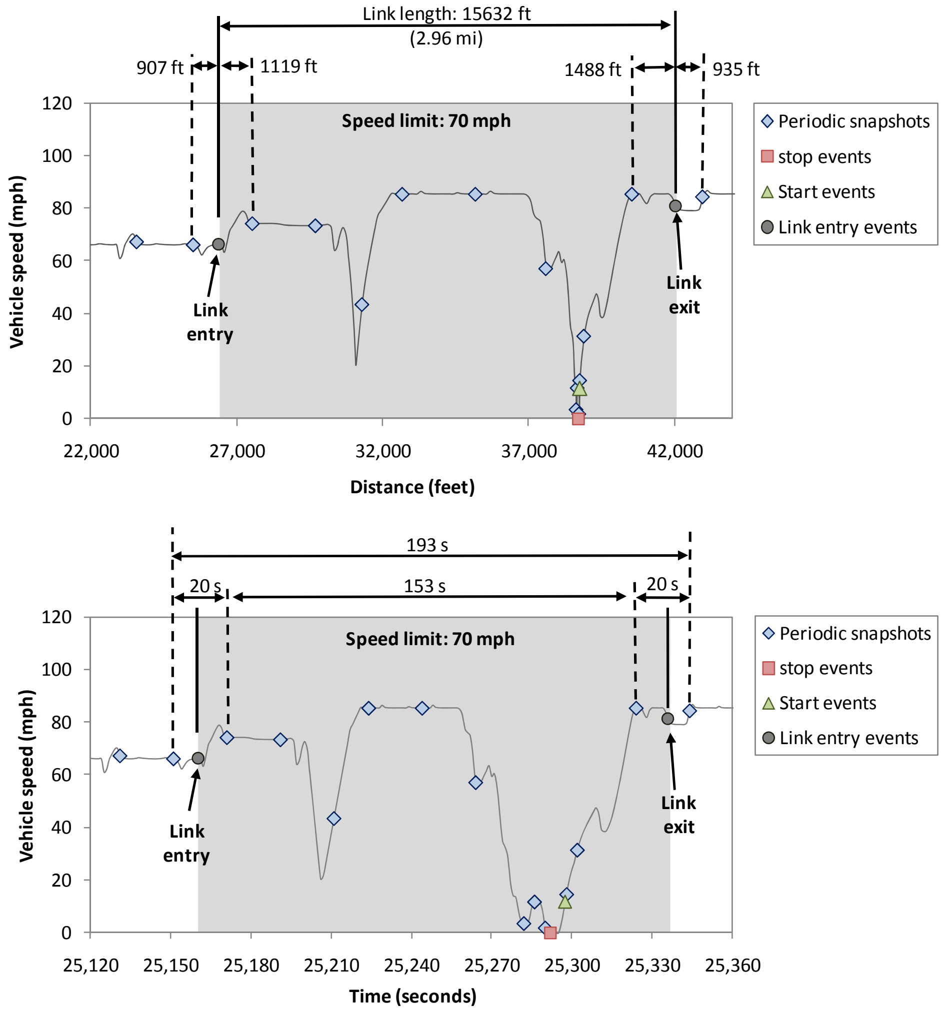
8.4.3. Estimation Using Default Periodic Snapshots

The most reliable way to estimate link travel times is to measure directly the time taken by a vehicle travel across a link. This method notably eliminates the need to consider explicitly all the potential factors that could influence travel times.

Although possible, determining link entry and exit times from probe vehicle data is subject to a number of potentially limiting constraints:

- To safeguard privacy, vehicles cannot be tracked over long distances. While provisions are made to allow tracking over short distance by tagging periodic and stop/start event snapshots with short-lived, vehicle-specific PSNs, the PSNs must be changed after 3280 ft or 120s. This may cause vehicles to change their PSN while traveling along long links, thus resulting in an inability to determine both link entry and link exit times.
- Current data collection systems do not instruct vehicles to generate a periodic snapshot at the exact moment they enter or exit a link. Entry and exit times must therefore be estimated by interpolating between the last snapshot generated before a link boundary and the first snapshot generated after the boundary. This may cause estimation errors, particularly where snapshots are far apart and where traffic conditions vary significantly between snapshots.
- When long intervals are used between snapshots, vehicles may travel across short links without generating any snapshot. This effect not only opens the possibility for vehicles traversing links undetected but may also limits the quantity of data that can be collected from short links and require higher market penetration levels to obtain reliable travel time estimates. The effect may also make it more difficult to assess link entry times by creating a need to scan snapshots across multiple links to track snapshots with identical PSNs.
- Current protocols do not require vehicles to generate snapshots while stopped. This creates significant difficulties in trying to estimate link travel times for queued vehicles.

An application example featuring a vehicle traveling along a congested freeway link is provided in Figure 8-15. This example assumes that all snapshots generated along the link can be traced to a specific vehicle. The top diagram illustrates the snapshots generated according to traveled distance, while the bottom diagram illustrates snapshot generated according to time. At each end of the link, the vehicle's entry and exit times are determined by linearly distributing the time spanning the last upstream and first downstream snapshot relative to the link boundary based on the traveled distance between the two snapshots. As can be observed, the available data is adequate in this case to produce a reasonable estimate of the vehicle's actual link travel time.



Actual travel time = 175.5 s

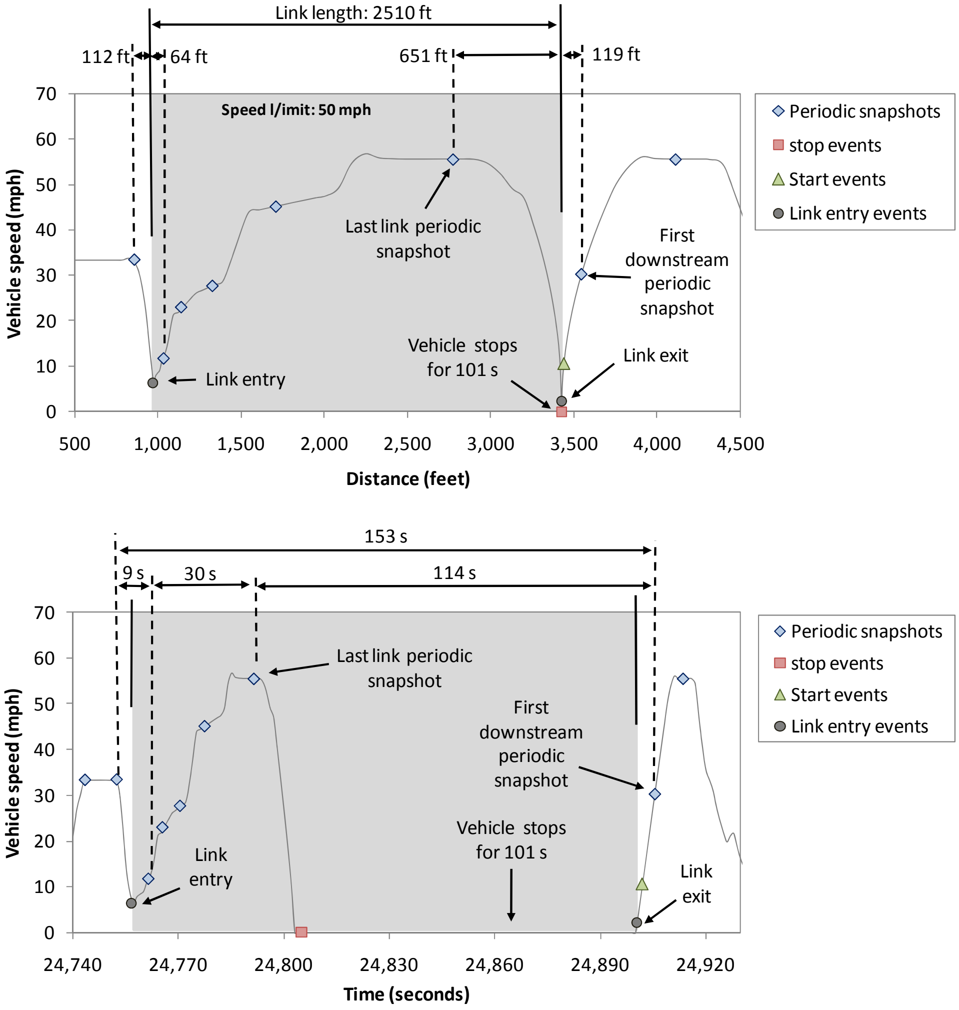
$$\text{Link entry time} = 25{,}171.0\text{ s} - 20\text{ s} \times \frac{1119}{(1119 + 907)} = 25{,}160.0\text{ s}$$

$$\text{Link exit time} = 25{,}324.0 + 20\text{ s} \times \frac{1488}{(1488 + 935)} = 25{,}336.3\text{ s}$$

Estimated travel time = 25,336.3 s - 25160.0 s = 176.3 s

Figure 8-15 – Link Travel Time Estimation through Link Entry/Exit Time Determination using Periodic Snapshots Only: Example 1

An example with a larger error is presented in Figure 8-16. This example illustrates a scenario in which a traffic signal forces the vehicle to queue near the downstream end of the link. If the vehicle is not generating periodic snapshots while stopped, an interval of 114 s then exists between the last periodic snapshot generated on the link and the first snapshot generated past the link. Interpolating data between the periodic snapshots leads here to an incorrect distribution of travel times along the two links and a travel time estimate with a 10% error.



Actual travel time = 144.0 s

$$\text{Link entry time} = 24{,}761.5\text{ s} - 9\text{ s} \times \frac{64}{(64+112)} = 24{,}758.2\text{ s}$$

$$\text{Link exit time} = 24{,}791.5 + 114\text{ s} \times \frac{651}{(651+119)} = 24{,}889.2\text{ s}$$

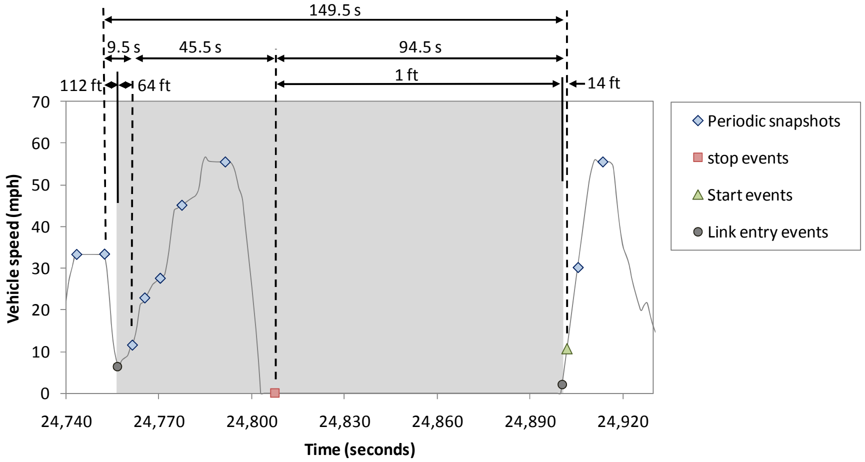
Estimated travel time = 24,889.2 s - 24,758.2 s = 130.9 s

9% error

Figure 8-16 – Link Travel Time Estimation through Link Entry/Exit Time Determination using Periodic Snapshots Only: Example 2

8.4.4. Estimation Using Default Periodic and Stop/Start Event Snapshots

Figure 8-17 illustrates the potential benefits of considering stop/start events in addition to default periodic snapshots. In this case, the stop/start event snapshots reduce the interval between the last snapshot generated on the link and the first snapshot generated past it. An interval of 94.5 s now separates the last and first snapshots generated around the link boundary instead of 114 s. However, a significant error still results from linearly distributing time between the upstream and downstream links based on the distance between the two snapshots. Since the vehicle only moves 1 ft from its initial stop location before exiting the link, a linear interpolation results in too much time being assigned to the downstream link. This leads to a travel time estimate of 53.3 s and an estimation error of 63%.



Start event on downstream link, where recorded

Actual travel time = 144.0 s

$$\text{Link entry time} = 24{,}761.5\text{ s} - 9.5\text{ s} \times \frac{64}{(64+112)} = 24{,}758.0\text{ s}$$

$$\text{Link exit time} = 24{,}805.0 + 94.5\text{ s} \times \frac{1}{(1+14)} = 24{,}811.3\text{ s}$$

Estimated travel time = 24,811.3 s - 24,758.0 s = 53.3 s

63% error

Assuming start event at downstream end of link

Actual travel time = 144.0 s

$$\text{Link entry time} = 24{,}761.5\text{ s} - 9.5\text{ s} \times \frac{64}{(64+112)} = 24{,}758.0\text{ s}$$

Link exit time = 24,807.5 + 94.5 s = 24,902.0 s

Estimated travel time = 24,902.0 s - 24,758.0 s = 144.0 s

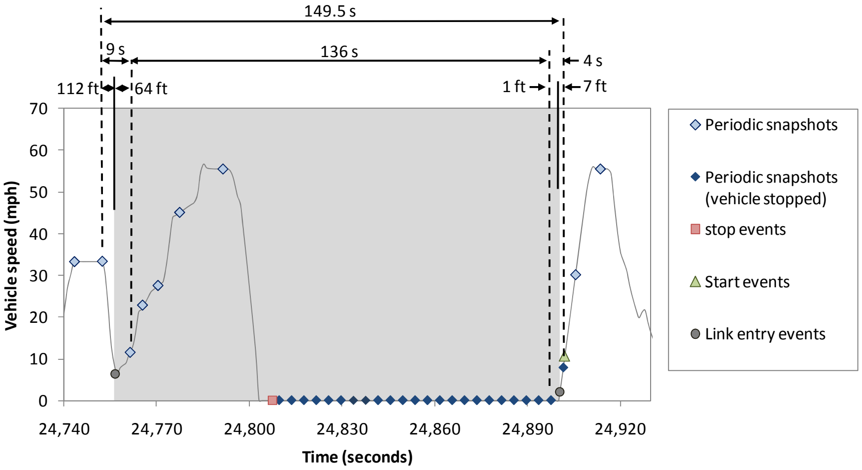
Same delay

Figure 8-17 – Link Travel Time Estimation through Link Entry/Exit Time Determination using Periodic Snapshots and Stop/Start Event Snapshots

A much better estimate results from arbitrarily assuming that the start event occurs on the link being exited. However, this approach is not recommended, as it would require developing potentially complex rules for determining when stop and start event could be arbitrarily assigned to a link upstream or downstream from the one where they actually occur.

8.4.5. Estimation using Default Periodic, Stopped Periodic and Stop/Start Event Snapshots

Allowing vehicles to keep generating snapshots while stopped should improve the accuracy of link entry/exit time estimates. The primary effect of these snapshots would be reduce the interval between the last snapshot generated on a link and the first snapshot generated on the following link, whether these snapshots are default periodic, stop event, or start event snapshots.



Actual travel time $= 144.0$ s

Link entry time $= 24{,}761.5\text{ s} - 9.5\text{ s} \times \frac{64}{(64+112)} = 24{,}758.0\text{ s}$

Link exit time $= 24{,}897.5 + 4\text{ s} \times \frac{1}{(1+7)} = 24{,}898.0\text{ s}$

Estimated travel time $= 24{,}898.0\text{ s} - 24{,}758.0\text{ s} = 140.0\text{ s}$

3% error

Figure 8-18 – Link Travel Time Estimation through Link Entry/Exit Time Determination using Periodic and Periodic Stopped Snapshots

Figure 8-18 considers a situation in which the vehicle shown in the examples of Figures 8-15, 8-16 and 8-17 continues generating periodic snapshots while stopped. Here, the generation of stopped periodic snapshots results in only a need to interpolate between snapshots spaced 4 s apart. This means a maximum travel time error of 4 s, or 2.8% of the actual travel time of 144 s. This is the error that is obtained by interpolating between the last and first snapshots generated around the link boundary when considering that the vehicle travels 1 ft before crossing the stop line after it starts to move and 7 ft on the downstream link before it generates the next periodic snapshot.

In the above example, further considering stop/start event snapshots would not change the calculation results, as these snapshots are not the last or first ones to be generated on each link. However, it is very likely that such snapshots may affect calculations in other cases.

8.4.6. Effects of Snapshot Generation Protocols on Link Entry/Exit Estimates

While the calculations presented in the previous sections clearly indicate the possibility of estimating link entry and exit times using snapshots generated by vehicles, it must be noted that the protocols used to generate the snapshots may influence the calculations. For instance, protocols resulting in a wider spacing of snapshots, in either space or time, will tend to have a higher potential for errors than protocols producing a shorter spacing. The calculations presented above further rely on the assumption that all snapshots generated by a vehicle while traveling on a link could be associated to it. While this is highly plausible for short links, privacy constraints may force vehicles to change their PSN while traveling on long links, thus resulting in an impossibility to estimate both link entry and exit times, and thus travel times. Typically, the data processing of sections 8.4.3, 8.4.4 and 8.4.5 are only applicable to links from which sequences of snapshots extending from at least one snapshot upstream of the link to one snapshot downstream of it could be assigned to specific vehicles. While it is not required to trace every vehicle, the possibility should at least exist to obtain a sufficient number of traces to ensure that statistically valid average travel times could be estimated.

Under current protocols, the probability for obtaining sufficient data decreases with link length due to the requirement that vehicles periodically change their PSN every 3280 ft (1000 m) or 120 s, whichever occurs last. Full-link vehicle traces could therefore theoretically be obtained only for links shorter than 3280 ft. For longer links, traces could be obtained for any distance covered in a 2-min interval. A vehicle traveling at 65 mph could for instance use the same PSN over a distance of 2.16 mi (3.5 km). However, because PSNs are to be changed when a vehicle's memory buffer is emptied and when the vehicle leaves the range of an RSE, much shorter traces may be obtained in practice. This could significantly reduce the number of valid travel time samples that could be obtained by strictly considering periodic and stop/start event snapshots.

8.4.7. Travel Time Estimation using Link Entry/Exit Snapshots

A potential solution to the problems of processing periodic and stop/start event snapshots is to have each vehicle keeping track of their actual link entry and exit times. This would allow vehicles to calculate link travel times directly, thus eliminating potential errors associated with the need to interpolate between snapshots at each end of the link.

A first approach is to allow vehicles to generate event snapshots marking the moment they exit (or enter) each link. These events could be determined by correlating the vehicle's position, as given by a GPS device, to the information contained in an electronic map. Travel times could then be determined by attempting to match the link exit event snapshots generated by each vehicle across successive links.

A potential problem with the above approach is that it requires a way to track the progression of vehicles across links. Difficulties may arise when considering long links as privacy rules may cause vehicles to change their PSN while traveling on the link. This would prevent associating successive link exit snapshots to the same vehicle, and thus, in an impossibility to calculate travel times. Another potential complexity is the need to use search algorithms to scan each possible pair of exit event snapshots generated at each intersection to retrieve valid vehicle traces.

A more efficient approach is to allow individual vehicles to determine travel times directly and store this information in the exit event snapshots. Each time a vehicle would enter a link it would capture its entry time and store it in its onboard buffer. When the vehicle would exit the link, the observed travel time would then be calculated and recorded in the newly generated link exit snapshot. Information about the link being entered could also be recorded in the snapshot to allow turn-specific analyses. This could be the latitude and longitude coordinates of the link's entry point. This information would allow the travel time measurement to be uniquely identified to the correct link without having to process vehicle identification data. This process would have the notable advantage of not requiring any information about the identity of the vehicle generating snapshots and would thus allow observed link travel times to be collected without compromising driver privacy.

8.4.8. Partial Market Penetration Effects

Estimating link travel times does not require collecting data from all vehicles traveling on a link. While collecting data from a greater number of vehicles should result in greater statistical accuracy, all that is required to support network operational and analysis needs is to collect enough data to develop reliable representations of average traffic conditions.

For each link, the practical target is to collect enough travel time samples to ensure that the resulting average falls within a certain confidence range. According to NCHRP Report 398 (Lomax *et al.*, 1997), the correct theoretical formula for estimating sample sizes when the variance of the data is not initially known is given by:

$$n = \left(\frac{t_{\alpha, n-1} \cdot cv}{e} \right)^2$$

where: $t_{\alpha, n-1}$ = t-statistic from Student's distribution for confidence level α (two-tailed test) and *n-1* degree of freedom
α = Confidence level parameter (Example: 95% confidence → α = (1-0.95)/2 = 0.025)
n = Total number of measurements to be made
cv = Coefficient of variation of data
e = Allowable error in average travel time measurement

Because of the above formula requires an iterative procedure (see explanation in Section 8.3.5), the Normal distribution is frequently used instead of the Student distribution to estimate the sample size. This removes the need to assess a parameter linked to the total number of runs to be made (the *n-1* degree of freedom) and enables a straightforward calculation of the required number of data to collect. This results in the following simplified equation:

$$n \cong \left(\frac{Z_{\alpha} \cdot cv}{e} \right)^2$$

where: α = Confidence level parameter (Example: 95% confidence → α = (1-0.95)/2 = 0.025)
Z_{α} = Standard normal variate based on confidence level α for a two-tailed test (Table 2).
cv = Coefficient of variation of data sample
e = Allowable measurement error

According to NCHRP Report 398, the simplified equation provides reliable estimates for sample sizes greater than 30, and generally reliable estimates for samples exceeding 20 or 25 observations. For sample sizes of less than 20, the number of observations to collect may be underestimated by approximately two.

Table 8-1 illustrates an application of the above formulas to assess travel time data sampling requirements under various market penetrations. The scenario considered in this example is illustrated in Figure 8-19 and focuses on traffic approaching the middle intersection from both the east and west ends. Sampling requirements are calculated with both the iterative and simplified formulas for a 95% confidence interval and a 10% tolerable error.

As the simulation data indicate, unreliable traffic time estimates can be obtained with very low market penetrations, particularly when the traffic conditions vary significantly over time. In this case, the source of variation is the periodic traffic flow interruptions caused by the traffic signals. However, increases in market penetration quickly reduce the estimation error. For both approaches, errors of less than 4% are generally obtained once a 5% penetration is reached.

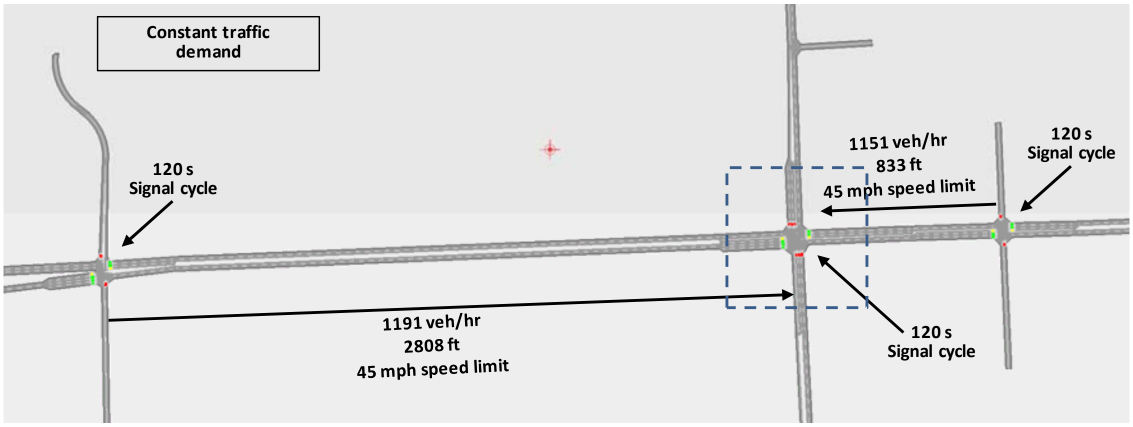


Figure 8-19 – Scenario for Example of Table 8-1

Table 8-1 – Effect of Market Penetration on Travel Time Sampling Requirements

Market penetration	Eastbound								Westbound							
					Required sample size								Required sample size			
	Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Iterative formula	Time to sample size	Simplified formula	Time to sample size	Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Iterative formula	Time to sample size	Simplified formula	Time to sample size
1.0%	13	51.3	-34.1	0.56	194	> 0:60	121	> 0:60	16	77.8	71.7	0.37	88	> 0:60	52	> 0:60
2.5%	31	77.8	11.6	0.38	80	> 0:60	55	> 0:60	28	45.3	4.4	0.64	225	> 0:60	155	> 0:60
5.0%	58	69.6	2.9	0.41	89	> 0:60	65	> 0:60	57	43.4	1.0	0.62	207	> 0:60	150	> 0:60
7.5%	86	67.7	0.1	0.41	87	0:54	64	0:41	94	42.9	4.2	0.65	220	> 0:60	162	> 0:60
10.0%	119	67.6	1.0	0.41	85	0:42	64	0:34	121	41.2	3.3	0.67	230	> 0:60	171	> 0:60
15.0%	168	67.0	-2.1	0.40	81	0:27	61	0:22	191	39.9	3.3	0.68	239	> 0:60	179	> 0:60
20.0%	228	68.4	-1.9	0.40	81	0:20	61	0:16	244	38.6	-1.5	0.69	242	> 0:60	183	0:49
25.0%	284	69.7	1.7	0.40	81	0:17	61	0:12	297	39.2	1.9	0.69	240	0:51	182	0:40
50.0%	594	68.5	1.7	0.40	81	0:10	62	0:08	556	38.5	2.1	0.68	238	0:19	181	0:24
75.0%	884	67.4	0.2	0.40	82	0:05	63	0:04	876	39.3	1.0	0.67	228	0:16	174	0:12
100.0%	1151	67.2	--	0.40	83	0:02	63	0:04	1192	38.9	--	0.68	230	0:12	175	0:10

Confidence level: 95% / Tolerable error: 10%

While increases in market penetration generally improve the reliability of travel time estimates, low penetrations may not enable enough data to be collected to reach the desired accuracy. For the eastbound traffic, enough data is collected within an hour to produce a 95% percent confidence travel time with a 10% tolerable error with penetration levels at or above 7.5%. For the westbound traffic, the same threshold is obtained with penetration levels around 20-25%, depending on the sampling size formula used. The greater penetration requirement is due to the higher variability of travel times in this direction. The data of Table 8-1 further indicate a difficulty in the example scenario to collecting enough data over short intervals, such as 5 or 10 minutes, to achieve the desired statistical accuracy. In the westbound direction, it would take 10 min under full penetration to collect the required data. In the eastbound direction, enough data could be collected in 10 minutes with a 50% penetration level due to the lower variability of travel times in that direction.

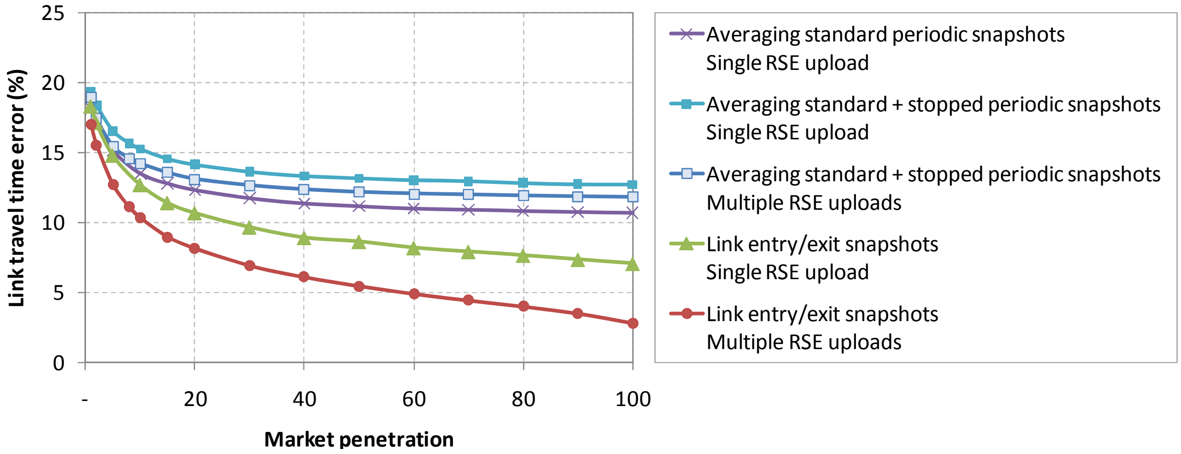


Figure 8-20 – Effect of Market Penetration and Snapshot Protocols on Travel Time Errors

Figure 8-20 takes a different look at the ability to obtain accurate link travel time estimates from collected probe vehicle data. Using the test network of Figure 6-1 as a case study, the figure illustrates the average relative link travel time error across the test network that is obtained by averaging the relative error produced for each link within the network under alternative snapshot protocols. As was demonstrated in the previous example, the simulation results indicate than an increasing market penetration leads to greater accuracy. However, the simulation results also indicate that the benefits of collecting additional snapshots tend to decrease with an increasing penetration level, particularly when using standard periodic snapshots.

Contrary to the data of Table 8-1, estimates matching observed travel times perfectly are not obtained in Figure 8-20 due to various data processing effects. In each scenario, not all vehicles have the opportunity to upload to an RSE the snapshots they generate. This causes some data losses that lead in turn to some estimation errors. For the estimates based on collected periodic snapshots, an additional source of error is associated to the sampling bias created by the use of variable, speed-based snapshot generation protocols. As described in Section 6.2, this bias can result in an oversampling of either high or low speed traffic conditions, and thus in inaccurate representations of travel times when simply averaging the speed recorded within individual snapshots.

The data of Figure 8-20 further indicate that the penetration required to reach certain accuracy depends on the data collection process. For travel time estimates based on the processing of periodic snapshots, the travel time error never drops below 12%. While there are significant benefits of increasing the proportion of probe vehicles, only marginal benefits are obtained for market penetrations exceeding 20%. When using link entry/exit event snapshots, an average error of less than 10% is obtained with penetrations above 5% when vehicles are allowed to perform multiple data uploads to an RSE. Reaching a full deloyment eventually leads to an average error of only 3%.

8.4.9. Conclusions

The most reliable method to estimate link travel times is to calculate directly the time that elapses between the moments a vehicle enters and exits a link. The effectiveness of this approach will depend on the following elements:

- Link travel times can be determined by associating link entry or link exit snapshots generated by individual vehicles across successive links. However, this is only feasible if a reliable way is provided to associate snapshots generated on different links to specific vehicles.
- A recommended alternative is to instruct vehicles to keep in an onboard memory the time they are assumed to have entered a link and to use this information upon exiting a link to calculate the link's travel time. This approach would have the advantage of not requiring any vehicle identification data to be recorded and would allow accurate travel times to be recorded while preserving traveler privacy.

Link travel times can also be estimated using sequences of periodic snapshots. Use of this approach will be affected by the following considerations:

- Periodic snapshots can only be used when there is a sequence of snapshots with an identical PSN covering an entire link and including at least one snapshot upstream and one snapshot downstream of the link being considered.
- Since vehicles do not necessarily generate a snapshot at the exact moment they enter or exit a link, interpolation between snapshots may be required to estimate link entry and exit times.
- To reduce the size of the interpolation interval, snapshots should be generated using protocols implementing short time-based or distance-based intervals. If time-based intervals are used, vehicles should also be instructed to keep generating snapshots while stopped. Benefits would also be obtained by pooling periodic and stop/start event snapshots

Link travel times can further be estimated using speed profiles developed from periodic snapshots. In this case, the same general conclusions as for the development of speed profiles would apply:

- To reduce biases, travel times should be estimated from profiles developed from snapshots generated at fixed time intervals and should include periodic snapshots generated by stopped vehicles.
- To better capture speed variations within a link, profiles featuring short segments should be used rather than profiles featuring long segments.

In all cases, it is not required to collect data from all vehicles to obtain representative link travel time estimates. Statistical techniques can be used to determine the amount of data to process to reach a given accuracy.

8.5. Vehicle Delays

Delay is commonly used to assess quality of travel. The higher the delay is, the lower the quality of service is. On freeways and highways, delay is used to assess the additional travel time that individuals must allocate due to traffic slowdowns caused by heavy traffic, work zones, incidents or other factors. At stop-controlled intersections, delay is used to assess the difficulty with which vehicles can go across an intersection and determine whether other forms of control may be warranted. At signalized intersections, delay is similarly used to quantify the impacts of signal operation on traffic operations and assess quality of service.

Various definitions of delay exist. Figure 8-21 illustrates the most commonly used ones:

- **Stopped delay:** Amount of time a vehicle spends immobilized in a queue.

- **Deceleration / acceleration delay:** Delay incurred while a vehicle is decelerating or accelerating.
- **Control delay (approach delay):** Delay directly attributable to a traffic control device, such as a traffic signal, stop sign or yield sign. This delay typically includes both stopped delay and deceleration/acceleration delay.
- **Congestion delay:** Delay attributable to a reduction in traffic speed due to high traffic volumes.
- **Total delay:** Effective difference between the time a vehicle actually takes to travel across a link and the time that the vehicle would have take to travel across the same link if it were unaffected by traffic control devices and other traffic. On freeway links, total delay often corresponds to the congestion delay. On links controlled by traffic signals or other control devices, it is typically a combination of both control and congestion delay.

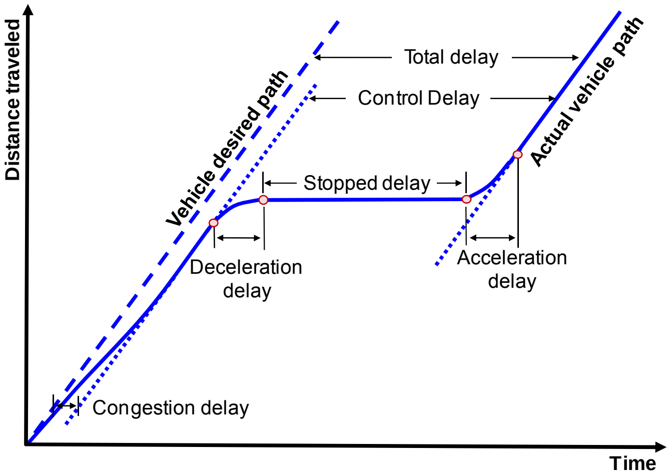


Figure 8-21 – Delay Definitions

Similar to link travel times, the estimation of average link delays does not require that information be collected from all passing vehicles. Reliable estimates can be estimated from relatively small samples if the collected sample satisfies some statistical requirements.

The following subsections assess how probe vehicle data can be used to estimate total delay, stopped delay and control delay. The evaluations consider the use of periodic and stop/start event snapshots collected under current data generation protocols, as well as additional snapshot types that have been considered in previous evaluations, such as periodic snapshots generated while a vehicle is stopped and link exit event snapshots. The use of speed profiles derived from probe vehicle data is also considered.

8.5.1. Total Delay

Total delay is typically estimated by comparing the time taken to travel across a link against an ideal travel time representing free-flow conditions. The most common approach is to calculate the ideal travel time using the speed limit. The actual travel time can be determined using various techniques. The most frequent one is the floating car technique, which consists of instructing GPS-equipped test vehicles to travel along a link at speeds reflective of the general traffic behavior. Travel times can also be determined by tracking the time taken by ordinary vehicles to travel through the link. This can be done using license plate matching techniques or data provided by Automated Vehicle Identification (AVI) systems, such as toll RFID systems.

On links leading to signalized intersections, delay models such as those defined in the Highway Capacity Manual (HCM) are frequently used to assess the average total delay incurred by vehicles due to the presence of traffic signals. These models estimate delays based on parameters that are normally relatively easy to obtain, such as signal timing parameters (cycle length, green signal duration, etc.), road geometry data, and information about traffic flow rates. While these models have proved to be useful and can provide reasonable delay estimates in many situations, they cannot explicitly consider all elements that may cause delays. There is for instance still significant research focusing on how to estimate delays when traffic flow is unstable.

A primary benefit of envisioned IntelliDrive^{SM} systems would be to allow delay measurements to be made from each link on which probe vehicles venture. Since total delay can be determined by comparing an observed travel time to an ideal one, the techniques available for estimating link total delay using probe data will typically be extensions of those used for determining link travel times described in Section 8.4. Of the various techniques described in that section, only those deemed valid for estimating delays are discussed further below:

- Estimation using full link vehicle traces
- Estimation through speed-profile processing
- Estimation using link entry/exit snapshots

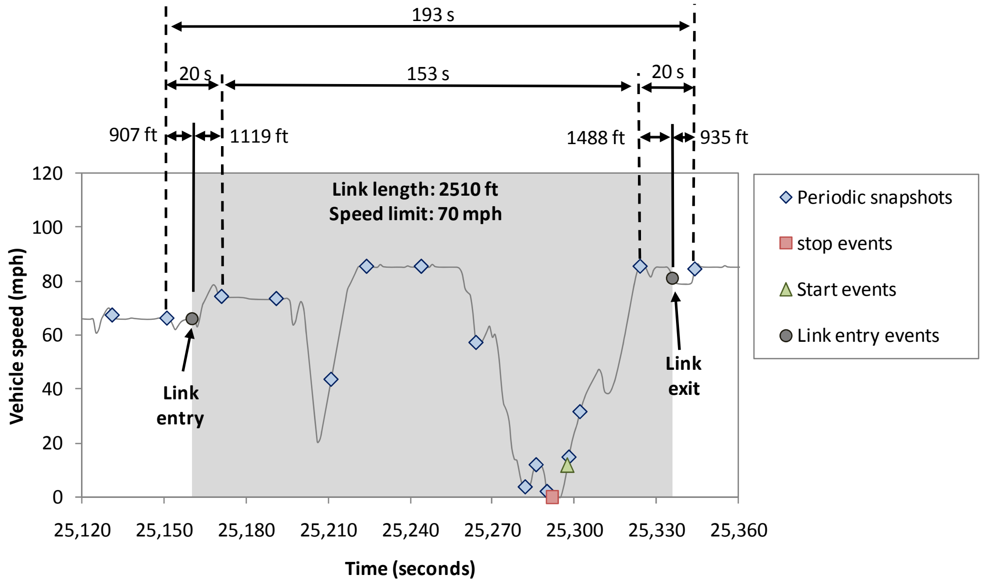
8.5.1.1. Estimation Using Full Link Vehicle Traces

Where it is possible to track the progression of individual vehicles across entire links, the time taken by a vehicle to traverse the link can be determined by simply comparing the vehicle's link entry and exit times. Total delay is then calculated by comparing the observed travel time to the reference free-flow travel time.

An example based on the scenario of Figure 8-16 is shown in Figure 8-22. This example considers the delay incurred by a single vehicle traveling along a congested freeway segment. In this case, the processing of collected periodic snapshots leads to an estimated link entry time of 25,160 s and an exit time of 25,336 s. This yields a link travel time of 176 s. Since the time that would be needed to travel the 2610-ft long freeway segment at a constant 70 mph speed would be approximately 24 s, it is then estimated that the vehicle incurs a total delay of 152 s.

In some cases, the observed travel time may be shorter than the reference free-flow time. This will yield negative delay values. Since reference speeds generally correspond to posted speed limits, the common operational practice is to convert any negative delay value to a zero value to prevent the consideration of travel behavior that may be in violation of speed limits.

Delay calculations based on link travel time estimates would be subject to the same sources of error as those affecting the estimation of link travel times. In systems relying only on the processing of periodic and stop/start snapshots, a primary source of error would be the need to estimate link entry and exit times by interpolating between the last snapshot generated before entering or exiting a link and the first snapshot generated past each link boundary. While such errors could be reduced by using shorter intervals between snapshots or allowing vehicles to continue recording snapshots while stopped, a potential for errors will always remain as long as there is a need to interpolate data.



Actual travel time = 175.5 s

$$\text{Link entry time} = 25171\text{ s} - 20\text{ s} \times \frac{1119}{(1119+907)} = 25160\text{ s}$$

$$\text{Link exit time} = 25324 + 20\text{ s} \times \frac{1488}{(1488+935)} = 25336\text{ s}$$

Estimated travel time = 25336 s - 25160 s = 176 s

Free - flow speed = 70 mph = 102.67 ft/s

$$\text{Free - flow travel time} = \frac{2510\text{ ft}}{102.67\text{ ft/s}} = 24.4\text{ s}$$

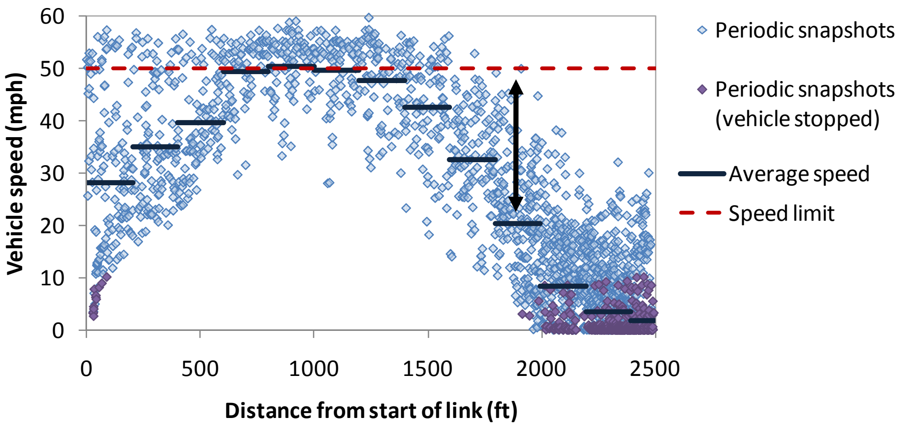
Total delay = 176 s - 24 s = 152 s

Figure 8-22 – Total Delay Estimation Using Estimated Link Entry and Exit Times

8.5.1.2. Estimation by Processing Speed Profiles

Speed profiles developed from periodic snapshots can be used to estimate average delays. Since these profiles provide an estimate of the average traffic speed within each defined segment, the delay incurred while traveling across each segment can be calculated by comparing the estimated average speed to the reference free-flow speed associated with each segment. The link total delay is then the summation of delays incurred across all segments. An example based on the scenario of Figure 8-14 is shown in Figure 8-23. For each 200-ft segment, travel at speed limit requires in this case 2.73 s. Summing the difference between the observed travel time and ideal travel time of 2.73 across all segments yields an estimated total delay of 107.2 s.

For segments with estimated travel speeds above the reference speed, the operational practice is either to cap the speed used in the calculations to the reference speed or to convert any negative delay to a zero value to avoid considering travel conditions that may be in conflict with posted speed limits. If Figure 8-23, this adjustment only results in a marginal change in the delay estimate since the average speed estimates only slightly exceed the reference free-flow speed. However, changes will likely be more significant on links where vehicles routinely travel significantly faster than the posted limits.



Segment	Segment Length (ft)	Snapshot count	Average speed (mph)	Speed limit travel time (sec)	Travel time at average speed (mph)	Segment delay (sec)	Adjusted segment delay (sec)
0-200	200	144	28.2	2.73	4.84	2.12	2.12
200-400	200	112	35.1	2.73	3.89	1.16	1.16
400-600	200	97	39.8	2.73	3.43	0.70	0.70
600-800	200	72	49.4	2.73	2.76	0.03	0.03
800-1000	200	78	50.5	2.73	2.70	-0.02	0.00
1000-1200	200	75	49.8	2.73	2.74	0.01	0.01
1200-1400	200	78	47.7	2.73	2.86	0.13	0.13
1400-1600	200	95	42.7	2.73	3.19	0.46	0.46
1600-1800	200	110	32.7	2.73	4.17	1.45	1.45
1800-2000	200	193	20.3	2.73	6.72	3.99	3.99
2000-2200	200	399	8.3	2.73	16.52	13.79	13.79
2200-2400	200	914	3.4	2.73	40.10	37.37	37.37
2400-2511	111	824	1.6	1.51	47.53	46.02	46.02
			Link totals:	34.24	141.46	107.22	107.24

Figure 8-23 – Delay Calculation Using Segmented Speed Profiles

When using speed profiles, estimation errors will primarily be linked to the method used to generate snapshots. As explained in Section 8.3, using snapshots generated according to a speed-based variable interval protocol may result in a bias toward lower speeds and higher delays. Generating snapshots at fixed time intervals reduces the bias but does not eliminate it, as slower vehicles would still generate more snapshots per unit distance than faster ones. While using protocol spacing snapshots according to a fixed distance resolves this particular problem, such a protocol also prevents vehicles from generating snapshots while stopped. This results in an underestimation of queuing condition and leads to higher average speed and lower delay estimates. The same issue also arises when using time-based protocols if vehicles are not allowed to continue generating snapshots while stopped. Whether the bias will be toward lower or higher delays will depend at the end on how the above factors interact on a link.

8.5.1.3. Estimation Using Link Entry/Exit Event Snapshots

Similar to the estimation of link travel times, the best approach for assessing link total delays would be to allow vehicles to generate link entry/exit event snapshots. This would remove uncertainties as to when exactly a vehicle enters or exits a link. If vehicles would record within a snapshot the time they took to travel across a link, the delay incurred along each link could then be obtained by simply subtracting the link's free-flow travel time from the observed travel time.

As explained in Sections 8.4, the preference is to use link exit event snapshots instead of link entry event snapshots. The use of such snapshots would not only remove many of the estimation errors associated with the processing of periodic and stop/start event snapshots, but could also allow vehicles to provide actual travel time data without compromising traveler privacy.

8.5.2. Stopped Delay

Stopped delay quantifies the amount of time that vehicles spend immobilized on a link. Because it is easier to estimate in the field than total delay, stopped delay has frequently been used to assess the performance of traffic signals and other traffic control devices. Until the 1994 edition of the Highway Capacity Manual, stopped delay was for instance used to characterize the level of service at signalized intersections. However, since total delay is thought to reflect better overall operations efficiency, later version of the manual replaced the stopped delay by the total delay as the primary criterion for determining level of service. Despite this change, stopped delay is still being used to characterize the impacts of control devices on traffic flow performance.

A method commonly used to estimate stopped delay involves counting vehicles in a queue. Every few seconds, the vehicles stopped are counted. The stopped delay incurred in each interval is then estimated by multiplying the number of queued vehicles by the duration of the interval. However, because this approach does not explicitly consider the exact time that individual vehicles remain immobilized, it is often thought to overestimate slightly stopped delays.

This section evaluates how stopped delay can be estimated from stop/start event snapshots, as well as periodic snapshots.

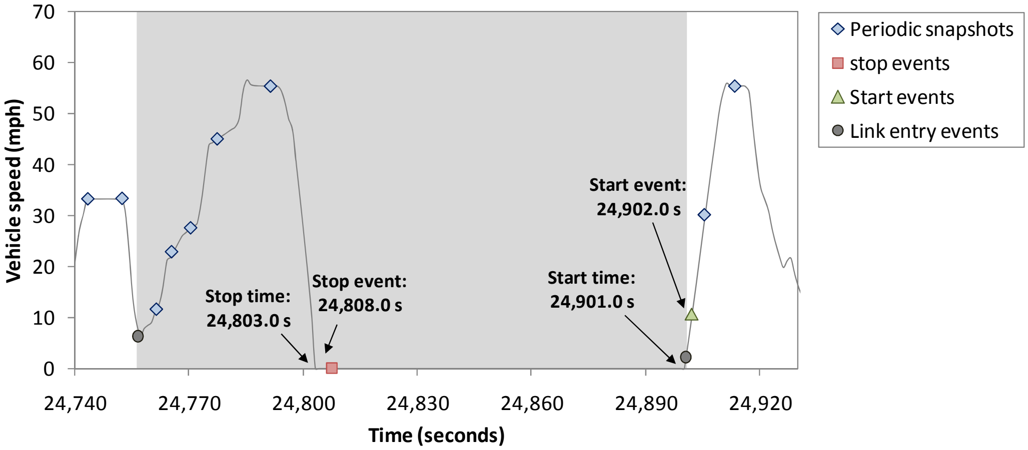
8.5.2.1. Estimation Using Stop/Start Event Snapshots

If stop/start event snapshots are assigned a PSN, each pair of stop and start event snapshots could be linked to specific vehicles as long as a PSN change does not occurs between the two events. The stopped delay incurred by the vehicle generating the snapshot could be determined by simply comparing the time between the two events.

An example is provided in Figure 8-24. The figure illustrates the speed profile of a vehicle stopping at a signalized intersection. The profile indicates that the vehicle remains immobilized for exactly 98 s while waiting for the red signal to turn green. A stop event snapshot is generated at time 24,807 s, after the vehicle has been immobilized for least 5 s, and a start event snapshot at time 24,902 s, after the vehicle reaches a speed of 10 mph. Comparing the time that elapses between the two snapshots yields a stopped delay estimate of 94 s, just 4 s short of the actual time that the vehicle spends immobilized.

While the above example illustrates the ability to use stop/start event snapshots to estimate stopped delay, it also outlines factors that may affect the accuracy of the estimates:

- To confirm that a valid stop has occurred, a wait of few seconds is imposed before generating a stop event. This results in the first few seconds of a stop not being considered in the calculation.
- To avoid generating a start event snapshot each time a vehicle crawls ahead, an event is generated only after a vehicle has reached a certain speed. This results in some time being added to the estimated stopped delay.



Actual stop duration = 94,901.0 – 24,803.0 = 98.0 s
Stop duration based on stop/start events = 94,902.0 – 24,808.0 = 94.0 s

Figure 8-24 – Stopped Delay Calculation Using Stop and Start Event Snapshots

In Figure 8-24, the above factors cause a 4-s delay underestimation. 5 s is lost due to the delay in generating the stop event snapshot, and an extra 1-s is counted due to the delay in generating the start event snapshot. While a 4-s error may be small, it could become larger if the underlying snapshot generation protocols impose a longer wait time for confirming a stop or a higher speed threshold to identify a start event.

To reduce the potential for errors, the both the definitions of stop and start events could be modified to allow the respective snapshots to be generated as close as possible to the actual events. However, doing so may cause more stop and start events snapshots to be generated in stop-and-go situations. For this reason, this approach is therefore not recommended unless deemed necessary.

The following potential adjustments are instead recommended to evaluate the portion of stopped delay that may be incurred before a stop event is generated:

- The wait time used to confirm that a stop has occurred could be automatically added to the delay estimates. In the above example, this would mean adding 5 s to the delay estimate.
- A better approach would be to adjust automatically the event time when generating a stop event snapshot. In the above example, this would mean assigning a stop time of 24,802.5 s instead of 24,807.5. This solution would then allow calculating the stopped delay by simply comparing the time that elapses between the stop and start events.

The following potential adjustments are further recommended to consider the delay that may be incurred before a start event is generated:

- Not adjusting for the time a vehicle is moving before a start event is identified will not create significant calculation errors for passenger cars since less than a second is often needed to reach a speed of 10 mph from standstill. Since using thresholds higher than 10 mph is unlikely, the adjustment could therefore generally be ignored for passenger cars.

- Adjustments should be considered for heavy trucks to account for their smaller acceleration capability. For instance, a truck with a 100 weight-to-power ratio may only accelerate from a standstill at a rate of 1.87 ft/s^2 [NCHRP, 2003] and would take nearly 8 s to reach 10 mph (14.67 ft/s). A truck with a 400 weight-to-power ratio may only accelerate at a rate of 0.71 ft/s^2 and could take as much as 20 s to reach 10 mph. In such cases, the stopped delay estimates should be adjusted to account for the time needed to reach the start event triggering speed. Using a constant, typical acceleration rate, the time spent accelerating would then be subtracted from the delay estimate. This approach is however only possible if the type of vehicle generating the stop/start event snapshots can be determined.

Another potential problem is what to do when stop and start events snapshots are generated on different links. This is likely to occur for vehicles queuing near a stop line, as the speed triggering a start event is often reached after having crossed the line and thus after having exited the link. This situation is illustrated in Figure 8-24, where a start event snapshot is generated 1 s after the vehicle starts to move and 0.5 s after it crosses the stop line.

To address the above problem, delay estimates resulting from the processing of stop/start events could be entirely assigned to the link where the stop is deemed to have occurred. If a relatively low speed threshold is used, such as 10-mph, start event snapshots will typically be generated close to the stop location. In Figure 8-24, since the start event occurs only one second after the vehicle has started moving, the assumption that the it occurs at the boundary of the link, represented here by the stop line, is therefore not far from reality.

For many intersections, the problem of processing start event snapshots generated downstream of a stop line could also be resolved by moving the link boundary slightly downstream. The boundary could for instance correspond to the farthest location where vehicles generate start event snapshots. Slow accelerating vehicles could travels 20 ft before reaching a 10 mph speed. Moving the link boundary 20 ft from the stop line would thus ensure that all generated stop and start events could be assigned to the same link. An example is shown in Figure 8-25. In this case, the farthest location where a 10-mph speed is reached is about 17 ft past the stop line. Moving the link boundary to the middle of the intersection would allow here all start event snapshots to be captured on the same link as the corresponding stop snapshots.

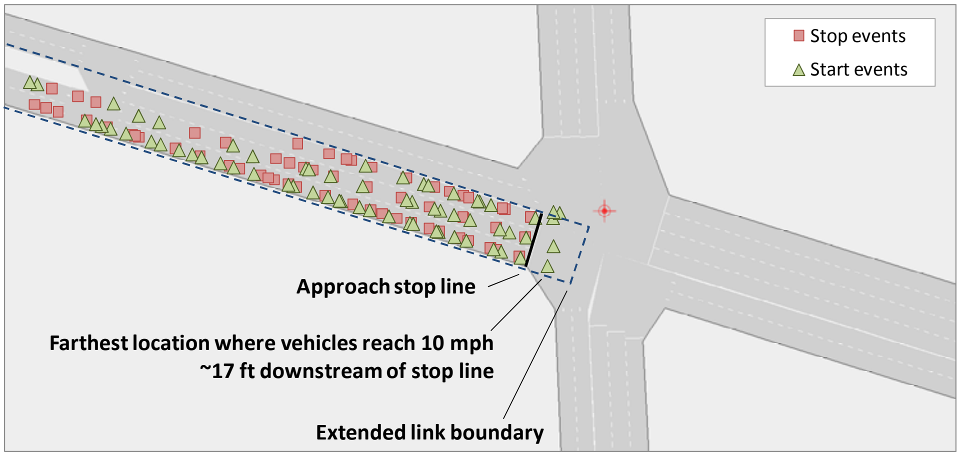


Figure 8-25 – Stop and Start Event Snapshots near an Intersection Stop Line

However, adjusting the link boundary may not prevent all vehicles from generating stop and start event snapshots on different links. To account for these situations, the following approach is recommended:

- For vehicles generating both stop and start event snapshots on the same link, the stopped delay can be calculated by considering the time associated with the stop and start event snapshots.
- For vehicles generating snapshots on different links, the link exit time should be considered instead of the start event time for calculating the stopped delay incurred on the link being exited. The stopped delay on the downstream link would then be given by the time that elapses between the link entry and the start event snapshot.

The above solution would effectively solve stopped delay estimation problems for situations in which a queue remains contained to one or two links. Calculations for queues spanning more than two links would require a more complex analysis approach, mainly to estimate delays on intermediate links. However, such a situation is expected to occur rather infrequently, as standard snapshots generation protocols require vehicles to change their PSN every 3280 ft (1000 m). This would prevent tracking vehicles over greater distances and thus estimating delays in queues exceeding 3280 ft.

8.5.2.2. Estimation Using Stopped Periodic Snapshots

Periodic snapshots can be used to estimate stopped delay if two conditions are met:

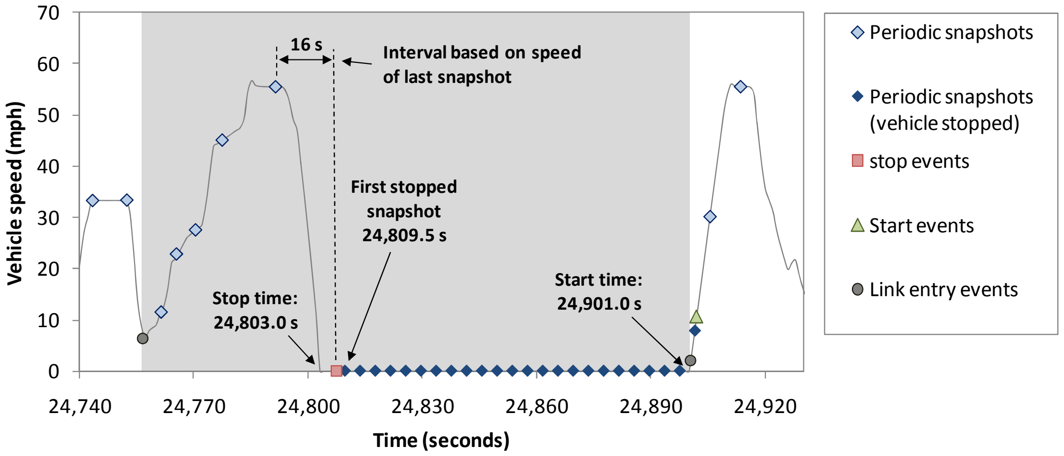
- Snapshots are generated according to elapsed time
- Vehicles keep generating periodic snapshots while stopped

When the above conditions are met, stopped delay can be estimated by compiling the number of snapshots with a zero speed value. Since stopped vehicles would typically generate snapshots at a constant interval, an estimate of the delay incurred by a vehicle could be obtained by simply multiplying the number of snapshots with zero speed collected by the interval separating the snapshots. An example based on the scenario of Figure 8-24 is shown in Figure 8-26. In this case, if the vehicle is allowed to generate snapshots while stopped at an interval of 4 s, 23 zero-speed snapshots are generated while it waits in queue. Multiplying the 23 stopped snapshots produced by the 4-s interval thus yields a stopped delay estimate of 92 s, which is slightly less than the actual delay of 98 s.

If the last stopped periodic snapshot generated before the start event is further considered, a stopped delay of 96 s is obtained. This snapshot was initially excluded because it was generated on a different link. While this exclusion was justified, it resulted in underestimating the stopped delay incurred on the link being exited since the last stopped periodic snapshot on the link being exited was generated shortly before the vehicle started to move. In this case, the difference is however relatively small.

A primary advantage of using stopped periodic snapshots to estimate stopped delay is to make delay calculations independent of the process used to determining stop and start events. This allows capturing delays from a series of short stops that may not generate stop and start events, such as when vehicles crawl at low speed towards the front of a queue in a stop-and-go situation. In this case, additional delay would be compiled each time a zero-speed periodic snapshot would be generated. It would also allow appropriately assigning delays to the link where they are incurred in situations in which a vehicle gradually crawls across multiple links.

The use of stopped periodic snapshots is however not without potential problems:



Actual stop duration = 94,901.0 – 24,803.0 = 98.0 s

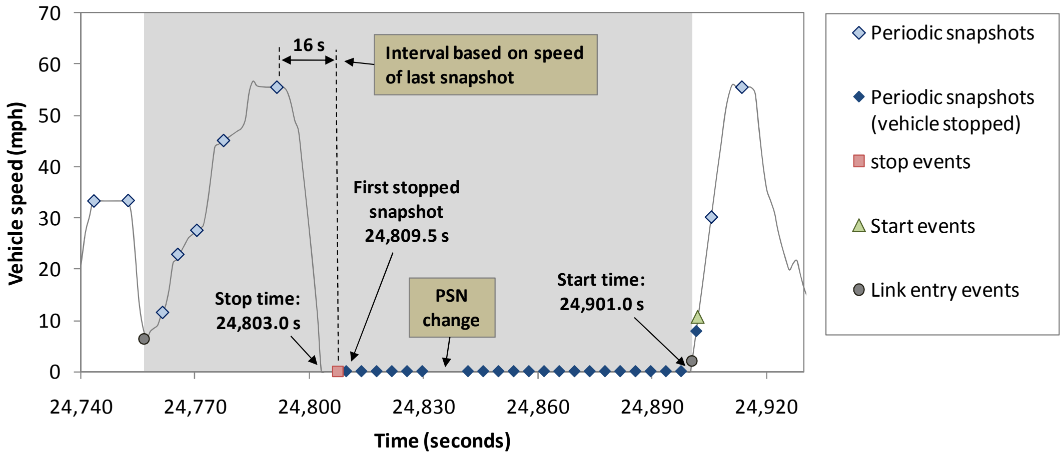
Number of stopped periodic snapshots within link = 23

Interval between stopped snapshots = 4.0 s

Stop duration based on snapshots = 23 x 4 s = 92.0 s

6 s difference

Figure 8-26 – Stopped Delay Calculation Using Stopped Periodic Snapshots



Actual stop duration = 94,901.0 – 24,803.0 = 98.0 s

Number of stopped periodic snapshots within link = 21

Interval between stopped snapshots = 4.0 s

Stop duration based on snapshots = 21 x 4 s = 84.0 s

14 s difference

Figure 8-27 – Effect of PSN Change on Stopped Delay Calculation when Using Stopped Periodic Snapshots

- The estimation approach assumes that a vehicle remains stopped for the entire interval between two snapshots. Similarly, it is assumed that no stop delay is incurred before the first snapshot with a zero speed. In many cases, vehicles will stop or start moving at times different from those assumed. This may cause potential overestimation or underestimation of delays, particularly where long intervals are used between snapshots.
- If the intervals between snapshots are based on the speed of the vehicle when the last snapshot was recorded, no periodic snapshots may be recorded for the first few seconds of a stop following a rapid deceleration. This effect is shown in Figure 8-27.
- If stopped periodic snapshots are tagged with a PSN, some vehicles may initiate a PSN switchover while stopped. As illustrated in Figure 8-27, snapshots will then not be produced for a certain amount of time, leading to some underestimation of the incurred stopped delay
- Calculating the stopped delay incurred by a given vehicle is only possible if a sequence of snapshots with identical PSN covers the entire queuing event.

8.5.3. Average Control Delay

The control delay, also frequently referred to as the intersection approach delay, represents the time loss by travelers that can be attributed to the operation of traffic control devices. This delay typically includes the stopped delay and the travel time lost during deceleration and acceleration on the approach to a controlled intersection.

On short urban links, the control delay is typically assumed to correspond to the link total delay, as it is often not possible to isolate the effects of heavy traffic from the effects of the operation of traffic signals. On longer links, it may be possible to isolate the control delay from the total delay. In such a case, the control delay would typically be the delay incurred at the downstream end of a link within the zone of influence of a traffic signal or other traffic control device.

The zone of influence of a traffic signal typically corresponds to the portion of a link where queuing occurs. This zone could be determined by identifying the furthest location upstream where stop snapshots are generated. To account for the delay caused by vehicles decelerating before reaching a queue, the influence zone should be expanded a few additional hundred feet upstream of the location of the most upstream stop snapshot. Alternatively, a speed profile analysis could be done to determine the location where vehicles typically start to slow down. After a zone of influence is established, the control delay could be determined by processing data within the zone as if it were on a separate link.

8.5.4. Partial Market Penetration Effects

Estimating total, stopped and control delay does not require collecting data from all vehicles. While greater accuracy would be obtained with larger samples, data uses often only require that an adequate representation of traffic conditions be obtained. Statistical sampling techniques such as those described in Section 8.4.8, can thus theoretically be used to determine the number of vehicles from which data must be collected to obtain reliable measurements.

Data sampling requirements for developing reliable delay estimates will typically be greater than for travel time estimates. While all vehicles experience a certain minimum travel time when traversing a link, not all have to stop or slow down. At a signalized intersection, vehicles arriving during the green may experience no delay while vehicles arriving at the start of the red may incur delays of a minute or more. Proportionally speaking, there is a much greater potential for variability when measuring delays than travel times. Because of this increased variability, much larger data samples, and thus higher minimum market penetration levels, will typically be required to assess average delays at a given confidence level and within a specified tolerable error.

The need for greater sampling requirements is illustrated in the data of Table 8-2 an Table 8-3, which reprise the scenario of Figure 8-19. As can be observed, very low penetration levels tend to produce estimates of average delays with potentially significant errors. However, as the penetration increases,

Table 8-2 – Effect of Market Penetration on Delay Sampling Requirements

Market penetration	Eastbound								Westbound							
					Required sample size								Required sample size			
	Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Iterative formula	Time to sample size	Simplified formula	Time to sample size	Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Iterative formula	Time to sample size	Simplified formula	Time to sample size
1.0%	13	38.9	4.1	0.729	330	> 0:60	205	> 0:60	16	37.1	12.2	0.727	347	> 0:60	204	> 0:60
2.5%	31	37.4	26.2	0.750	317	> 0:60	217	> 0:60	28	33.1	6.0	0.861	413	> 0:60	285	> 0:60
5.0%	58	29.6	6.6	0.926	456	> 0:60	330	> 0:60	57	31.2	1.3	0.862	394	> 0:60	286	> 0:60
7.5%	86	27.8	0.0	0.960	479	> 0:60	354	> 0:60	94	30.8	6.0	0.899	421	> 0:60	311	> 0:60
10.0%	119	27.8	2.6	0.961	476	> 0:60	355	> 0:60	121	29.0	4.7	0.939	455	> 0:60	339	> 0:60
15.0%	168	27.1	-5.0	0.958	469	> 0:60	353	> 0:60	191	27.7	4.8	0.973	484	> 0:60	364	> 0:60
20.0%	228	28.5	-4.0	0.927	437	> 0:60	330	> 0:60	244	26.5	-2.2	0.997	506	> 0:60	382	> 0:60
25.0%	284	29.7	4.6	0.910	421	> 0:60	319	> 0:60	297	27.1	2.9	0.987	495	> 0:60	375	> 0:60
50.0%	594	28.4	4.3	0.942	449	0:48	341	0:37	556	26.3	-3.0	0.994	499	0:50	380	0:39
75.0%	884	27.3	0.5	0.976	481	0:33	367	0:25	876	27.1	1.5	0.966	471	0:32	359	0:24
100.0%	1151	27.1	--	0.981	485	0:24	370	0:18	1192	26.7	--	0.974	479	0:20	365	0:25

Confidence level: 95% / Tolerable error: 10%

Table 8-3 – Effect of Market Penetration on Delay Sampling Requirements

Market penetration	Eastbound								Westbound							
					Required sample size								Required sample size			
	Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Iterative formula	Time to sample size	Simplified formula	Time to sample size	Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Iterative formula	Time to sample size	Simplified formula	Time to sample size
1.0%	13	12.69	10.7	1.443	1291	> 0:60	800	> 0:60	16	9.92	-2.5	1.043	713	> 0:60	418	> 0:60
2.5%	31	11.46	29.5	1.363	1047	> 0:60	714	> 0:60	28	10.18	2.7	1.623	1468	> 0:60	1013	> 0:60
5.0%	58	8.85	3.5	1.746	1618	> 0:60	1172	> 0:60	57	9.91	-16.6	1.747	1617	> 0:60	1172	> 0:60
7.5%	86	8.55	-3.2	1.849	1774	> 0:60	1313	> 0:60	94	11.88	5.7	1.680	1470	> 0:60	1085	> 0:60
10.0%	119	8.83	8.2	1.870	1801	> 0:60	1343	> 0:60	121	11.25	13.1	1.732	1546	> 0:60	1153	> 0:60
15.0%	168	8.16	-7.2	1.903	1849	> 0:60	1391	> 0:60	191	9.95	4.2	1.852	1755	> 0:60	1318	> 0:60
20.0%	228	8.80	-15.4	1.865	1770	> 0:60	1337	> 0:60	244	9.54	-7.7	1.962	1961	> 0:60	1480	> 0:60
25.0%	284	10.40	5.9	1.797	1639	> 0:60	1241	> 0:60	297	10.33	9.5	1.854	1746	> 0:60	1321	> 0:60
50.0%	594	9.83	3.5	1.819	1672	> 0:60	1272	> 0:60	556	9.44	-5.0	1.946	1913	> 0:60	1455	> 0:60
75.0%	884	9.49	0.8	1.874	1771	> 0:60	1349	> 0:60	876	9.94	1.2	1.906	1831	> 0:60	1395	> 0:60
100.0%	1151	9.42	--	-1.907	1832	> 0:60	1397	> 0:60	1192	9.81	--	1.935	1886	> 0:60	1439	> 0:60

Confidence level: 95% / Tolerable error: 10%

the estimates quickly converge towards the true average delay. For the eastbound direction, errors of less than 5% are obtained when the penetration attains 10%. In the westbound direction, the same threshold is obtained when the penetration reaches 7.5%.

When comparing the data of both tables to that of Table 8-1, it can indeed be observed that much higher sampling requirements are needed to obtain delays estimates falling within a 10% tolerable error at a 95% confidence level. In most cases, not enough data would be collected in an hour to obtain such an estimate. Under a full deployment, almost 500 data samples would be required to estimate reliable total delay estimates, and almost 1900 for the stopped delay. For the stopped delay, the fact that the required sample size if greater than the actual number of vehicles traveling on the simulated within an hour is an indication that the high variability of travel times makes it impossible to estimate an average delay within the defined statistical boundaries. In this case, selecting instead an 80% confidence level with a 10% tolerable error would produce a sampling requirement between 615 and 1015, depending on the formula used. This level of accuracy could therefore be achieved with the observed flow rate.

8.5.5. Conclusions

The following conclusions can be made regarding the estimation of link total delay:

- It is not required to collect data from all vehicles. However, more data will typically need to be collected for estimating delays than travel times if it is desired to reach certain accuracy.
- Total delay can be estimated by calculating the difference between an observed link travel time and the time it would have taken a vehicle to travel the link at a given free-flow speed.
- The free-flow speed for a link or link's segment can be taken as the posted speed limit or any other cruise speed deemed relevant. A constant speed will typically be used for each link.
- Where it is possible to track vehicles across an entire link, delay can be calculated by extracting link entry and exit times from periodic snapshots. Since snapshots are not necessarily generated at the exact moment a vehicle enters or exits a link, interpolation may be required to extract link entry and exit times, yielding some estimation errors. To reduce errors, snapshots should be generated at short intervals and vehicles should keep generating snapshots while stopped.
- Delay can also be estimated using speed profiles generated from periodic snapshots. For each segment defined within a link, the incurred delay can be estimated by the difference between the estimated average travel time and the segment's free-flow travel time. Link delay is then the sum of the all the segments' delays. To reduce evaluation biases, delays should be estimated from profiles developed from snapshots generated at a fixed time interval and including snapshots generated by stopped vehicles. The preference is also to use profiles featuring smaller segments.
- Calculations returning negative delay values indicate vehicles traveling above the assumed free-flow speed. To avoid considering speeds above posted speed limits, any negative delay should be adjusted to a zero value.
- The ideal approach for calculating link delays is to generate link exit snapshots, record in the snapshot the time taken to traverse the link being exited, and compare the resulting link travel time to the link's ideal travel time.

The following recommendations are made regarding the estimation of stopped delays using stopped periodic snapshots:

- The total stopped delay incurred on a link can be estimated by multiplying the number of periodic snapshots with zero speed generated on a link by the snapshot time interval.
- Periodic snapshots can only be used if they are generated according to an elapsed time protocol and if vehicles keep generating snapshots while stopped.
- Using stopped periodic snapshots to compile delay allows capturing delays from short stops that may not lead to the generation of stop and start events.
- Compiling stopped delay from periodic snapshots facilitates assigning delays to specific links in cases in which stop and start events may be generated on different links.
- Vehicles going through a PSN switchover while queuing will result in missing snapshots and in an underestimation of stopped delay.

The following conclusions are made regarding the estimation of stopped delays using stop/start event snapshots:

- Stop/start event snapshots can only be used if it is possible to assign these snapshots to specific vehicles. This will allow compiling stopped delay by comparing the time that elapsed between the generation of a stop and a start event.
- The time recorded within a stop snapshot should not be the time at which the snapshot is generated but the time at which the stop is assumed to have occurred.
- If an interval threshold is used to confirm that a stop has occurred, the time of occurrence of the stop is the snapshot generation time minus the length of the interval.
- Adjustments to account for the time a vehicle spends accelerating before a start event are not necessary for passenger vehicles as this adjustment is likely to be less than one second.
- Delay adjustments to account for the time a vehicle spends accelerating before generating a start event snapshot may be necessary for heavy trucks with slow acceleration. This adjustment is only possible if vehicle types can be identified.
- To reduce the number of stop/start event snapshots generated on different links, the boundary of links ending at an intersection should be extended a few feet within the intersection to cover the location where start event snapshots are typically generated.

If stop/start events can be assigned to individual vehicles, using these snapshots should produce reliable estimates of stopped delay in a majority of cases. The only potentially significant problem would be from vehicles generating stop and start events on different links. However, this situation is not expected to occur often if using a 10 mph speed threshold for defining a start event. If this occurs, stopped periodic snapshots could then be used to estimate stopped delay if available.

8.6. Number of Stops

The number of stops is an important measure of quality of traffic flow progression. Along urban arterials, signal timings across successive intersections are often coordinated to minimize the number of stops made by vehicles. While reducing stops usually leads to delay reductions, fewer stops also lead to reduced fuel consumption and vehicle emissions.

Current traffic surveillance systems do not provide a direct way for compiling the number of stops made by vehicles. This has led traffic engineers to rely primarily on mathematical models based on queuing theory to determine the number of stops occurring on approaches to signalized intersections or other traffic control devices. Models evaluating the operation of traffic signals estimate the number of stops by considering the average arriving traffic flow rate, the maximum rate at which vehicles can flow across the intersection, the proportion of time that a traffic signal is red, and the difficulty in making turn maneuvers across the intersection. To account for differing traffic dynamics, different models are also often used for estimating the number of stops made in under-saturated and over-saturated conditions.

Existing mathematical models only allow stops to be estimated where traffic control devices impose controlled interruptions to traffic flows. They cannot be applied to estimate stops that may result from congested conditions developing on freeways. To assess the stops occurring in such conditions, traffic simulation models are more frequently used. While these models can produce estimates of the number of stops made, these estimates are subject to the degree to which a simulation model is adequately calibrated and its ability to replicate the complexity of driving behavior.

The following sections detail how the number of stops made by vehicles on roadway links could be measured from data provided by IntelliDrive^{SM} probe vehicles. Two specific cases are considered:

- Estimation of number of standing stops
- Estimation of number of standing and partial stops

8.6.1. Estimation of Number of Full Stops

The number of full stops made by vehicles can easily be measured using snapshots generated under current protocols. If vehicles are generating a stop event snapshot each time they come to a standstill, the number of stops made on a given roadway link can then be determined by simply compiling the number of stop event snapshots generated on the link. When not all vehicles generate snapshots, the total number of stops made by all vehicles could be estimated using information about the typical proportion of probe vehicles traveling on the link.

Aside from errors that may be caused by inaccurate estimates of the proportion of probe vehicles, the accuracy of the number of stops obtained from processing stop snapshots is affected by the approach used to identify what constitutes a stop. For instance, to avoid generating stop and start events each time a vehicle crawls ahead in a queue, it is currently recommended that stop event be identified only after a vehicle has been immobilized for at least 5 s and if no other stop had occurred in the past 15 s. Changes in these two parameters will result in higher or lower estimates of the number of stops made by each vehicle.

An example is shown in Table 8-4. This example compiles the number of stop event snapshots generated on an intersection approach within a 5-minute interval using various combinations of parameters. As can be observed, changing the time-immobilized threshold has a significant impact. As the time threshold is increased, an increasing number of vehicles making short stops at the back of the queue are prevented from generating stop snapshots. However, changing the time threshold since the last stop event has no impact in the example. This is because vehicles typically do not stop before reaching the queue. Vehicles thus always travel for more than 15 seconds before stopping. This parameter is more likely to affect results in congested situations where vehicles gradually crawl ahead in a queue.

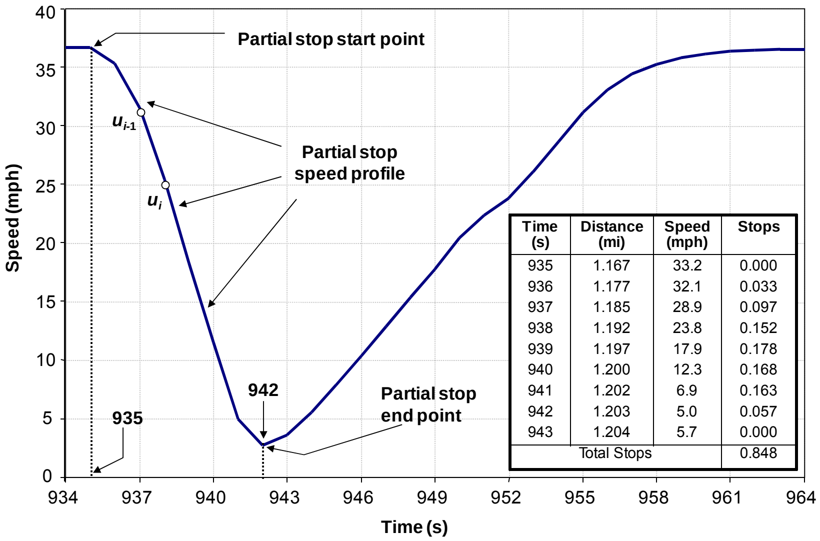
Table 8-4 – Effect of Change in Parameters Used to Identify Stop Events

Time immobilized (s)	Interval since last stop (s)	Number of stop events
0	15	120
1	15	110
2	15	105
3	15	93
4	15	86
5	15	76
5	10	76
5	5	76
5	0	76

8.6.2. Estimation of Full and Partial Stops

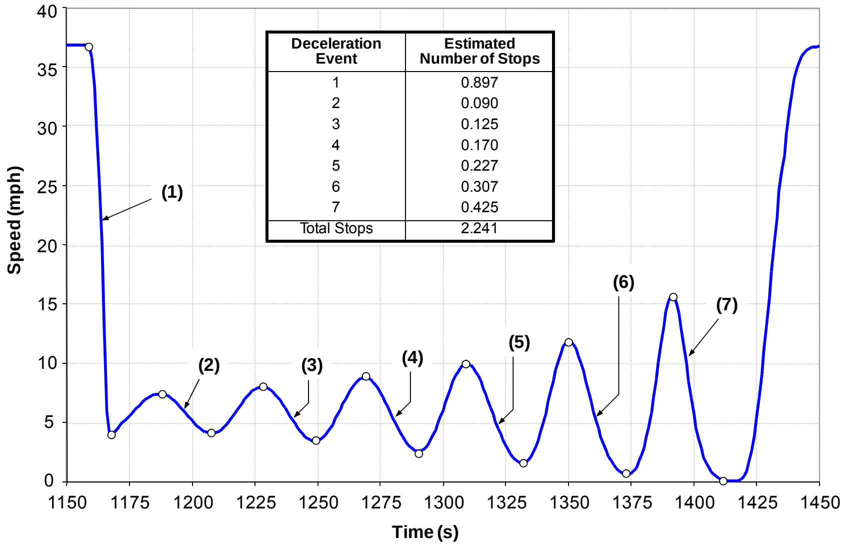
While the processing of stop snapshots allows determining the number of full stops, these snapshots cannot be used for compiling partial stops. In many situations, decelerating vehicles may not come to a complete stop before starting to accelerate again. This occurs frequently for vehicles reaching the back of a queue that is nearly dissipated. In such a situation, no stop snapshot would be generated, which would lead to assume that no stop has occurred even though drivers may think otherwise.

An approach to account for partial stops that is proposed in the literature and used is some simulation models consists of determining an equivalent number of stops produced by all deceleration events [Rakha *et al.*, 2001]. In this context, a stop is defined as a full deceleration from a link's free-flow speed to a standstill. A deceleration from a link's free-flow speed to a speed corresponding to half the free-flow speed would be considered as 0.5 stop. Similarly, a deceleration from half the free-flow speed to a full stop would also be considered as a 0.5 stop. Examples are provided in Figure 8-28 and Figure 8-29. In the first case, the single deceleration event is estimated to produce 0.848 equivalent full stops. In the second case, the series of partial deceleration and acceleration cycles yields 2.241 stops.



Time (s)	Distance (mi)	Speed (mph)	Stops
935	1.167	33.2	0.000
936	1.177	32.1	0.033
937	1.185	28.9	0.097
938	1.192	23.8	0.152
939	1.197	17.9	0.178
940	1.200	12.3	0.168
941	1.202	6.9	0.163
942	1.203	5.0	0.057
943	1.204	5.7	0.000
Total Stops			0.848

Figure 8-28 – Partial Stop Determination Approach for a Single Deceleration/Acceleration Event



Deceleration Event	Estimated Number of Stops
1	0.897
2	0.090
3	0.125
4	0.170
5	0.227
6	0.307
7	0.425
Total Stops	2.241

Figure 8-29 – Partial Stop Determination for a Series of Partial Deceleration/Acceleration Events

Estimating stops using the above approach requires vehicles to generate periodic snapshots at fixed intervals to allow proper identification of deceleration/acceleration cycles. To ensure that all cycles are adequately captured, snapshots should ideally be generated every second or two. If wider intervals are used, such as 4 or 10 s, the likelihood then increases that some cycles may not be captured, which would then cause an underestimation of the number of equivalent stops.

While feasible, generating snapshots every second or two creates a risk of overloading the memory buffer used to store snapshots onboard each vehicle. If this occurs, some data may be lost, which could again result in an underestimation of the equivalent number of full stops. For this reason, it is only recommended to compile partial stops from periodic snapshots if it can be demonstrated that no significant loss of data would occur from the use of short intervals between periodic snapshots.

8.6.3. Partial Market Penetration Effects

Similar to other parameters, estimating the number of stops made on a link does not require collecting data from all vehicles. As shown in Table 8-5, which reprises the example of Figure 8-19, reasonable averages can be obtained with penetration levels as low as 5 or 7.5%, depending on traffic patterns. However, similar to the estimation of delays, relatively large sample sizes again appear to be required to attain certain statistical accuracy.

Estimating an average number of stops per vehicle would have the advantage of not requiring the determination of the proportion of probe vehicles within the traffic stream to estimate the total number of stops incurred by all vehicles. However, it will always be possible to estimate the total number of stops by simply counting the number of stop event snapshots generated on a link and dividing this number by an estimated ratio of probe vehicles, as described in Section 8.2.3.

Table 8-5 – Effect of Market Penetration on Number of Stops Sampling Requirements

Market penetration	Eastbound								Westbound							
	Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Required sample size				Sample size (1 hour)	Mean (s)	Estimation error (%)	Coefficient of variation	Required sample size			
					Iterative formula	Time to sample size	Simplified formula	Time to sample size					Iterative formula	Time to sample size	Simplified formula	Time to sample size
1.0%	13	0.56	-12.5	0.911	515	> 0:60	319	> 0:60	16	0.62	36.3	0.823	444	> 0:60	261	> 0:60
2.5%	31	0.64	30.9	0.759	325	> 0:60	222	> 0:60	28	0.45	9.1	1.120	699	> 0:60	483	> 0:60
5.0%	58	0.49	7.4	1.096	638	> 0:60	462	> 0:60	57	0.41	-1.1	1.201	764	> 0:60	554	> 0:60
7.5%	86	0.46	2.5	1.185	729	> 0:60	540	> 0:60	94	0.42	1.7	1.185	732	> 0:60	540	> 0:60
10.0%	119	0.45	4.0	1.226	774	> 0:60	578	> 0:60	121	0.41	4.8	1.281	846	> 0:60	631	> 0:60
15.0%	168	0.43	-5.6	1.251	799	> 0:60	602	> 0:60	191	0.39	12.0	1.366	955	> 0:60	717	> 0:60
20.0%	228	0.45	-4.9	1.233	774	> 0:60	585	> 0:60	244	0.35	-2.3	1.489	1129	> 0:60	852	> 0:60
25.0%	284	0.48	10.8	1.216	751	> 0:60	569	> 0:60	297	0.36	2.1	1.456	1077	> 0:60	815	> 0:60
50.0%	594	0.43	3.3	1.291	843	> 0:60	641	> 0:60	556	0.35	-6.3	1.465	1084	> 0:60	824	> 0:60
75.0%	884	0.42	2.9	1.332	895	> 0:60	682	0:46	876	0.38	0.5	1.420	1018	> 0:60	776	0:52
100.0%	1151	0.41	--	1.361	933	0:36	712	0:36	1192	0.37	--	1.428	1028	0:53	784	0:53

Confidence level: 95% / Tolerable error: 10%

8.6.4. Conclusions

The following conclusions are made regarding the use of probe vehicle data to estimate the number of full stops made by vehicles on roadway links:

- The number of full stops can be estimated by compiling the number of stop snapshots generated on each link.
- The total number of stops made on a link in a partial market penetration situation can be obtained by dividing the number of stop snapshots collected by an estimate of the ratio of probe vehicles within the traffic stream. An average number of stops per vehicle can also be calculated.
- Changes in the definition of what constitutes a full stop may affect the number of stop event snapshots being generated and may result in different stop estimates.

The following additional recommendations are made for the estimation of partial stops:

- Partial stops should be estimated using periodic snapshots generated at fixed interval to identify deceleration/acceleration cycles.
- Accuracy will depend on the interval between snapshots. To allow adequate capture of all deceleration/acceleration events, snapshots should be generated every second or two.
- Generating snapshots every second or two creates a risk to fill the memory buffer, which may then result in data losses and estimation errors.

Similar to other parameters, reasonable estimates of the number of stops made by vehicle can be obtained with penetration levels as low as 5 or 10%. However, higher penetrations may be needed if certain statistical accuracy is desired.

8.7. Queue Parameters

Information about queues of vehicles is used to evaluate the operation of traffic control devices. Longer queues are, for instance, indicative of longer delays. Queue length is further used to determine the length of turn bays, assess which driveways may be affected by queues along commercial streets, or determine whether queues of vehicles may reach and block an upstream intersection.

Existing traffic surveillance systems offer some means of monitoring queues. This is typically done using point detectors. Presence detectors may be placed at intersection stop lines to determine whether vehicles are waiting for a green signal or at some distance from the stop line to determine if a queue has reached a certain size. Detectors can also be placed at regular intervals on intersection approaches to improve queue-tracking capabilities. For instance, detectors could be placed every 20 ft to provide information that is more accurate where vehicles are queued. While this approach improves queue tracking, there is still no information available about what happens between detectors. All that is known is whether a queue grows or shrinks by 20 ft.

Probe vehicle data offer in this case an ability to improve queue tracking without requiring the deployment of large numbers of detectors. Since probe vehicles are expected to generate event snapshots marking where and when they stop and start moving again, these snapshots could theoretically be used to track vehicle queues. Additional tracking capabilities could also result from allowing vehicles to keep generating snapshots while stopped. The following subsections evaluate how both types of snapshots could be used to estimate the following commonly used queue parameters:

- Back of queue
- Front of queue
- Maximum queue reach
- Queue length

8.7.1. Estimation of Queue Parameters Using Stop/Start Event Snapshots

Stop and start event snapshots can be used in the following manner to estimate queue parameters:

- The **back of a queue** at any given time can be located by the position of the more recently generated stop snapshot.
- The **front of a queue** at any given time can be located by the position of the more recently generated start event snapshot.
- The **maximum reach of a queue** can be located by the location of the stop snapshot that has been generated the farthest upstream from the intersection stop line.
- The **queue length** at any given time can be determined by comparing the locations of the more recent stop and start event snapshots.

Figure 8-30 provides two examples of how stop event snapshots can be used to estimate the above queue parameters. The examples consider snapshots generated by vehicles approaching a signalized intersection over a 15-min period. In the top diagram, stop events are assumed to have occurred after a vehicle has been immobilized for 5 s when at least 15 s has elapsed since the last stop, as per current snapshot generation protocols. In the bottom diagram, the 15-s wait time is removed to allow stop events to be identified as soon as a vehicle has been immobilized for five seconds.

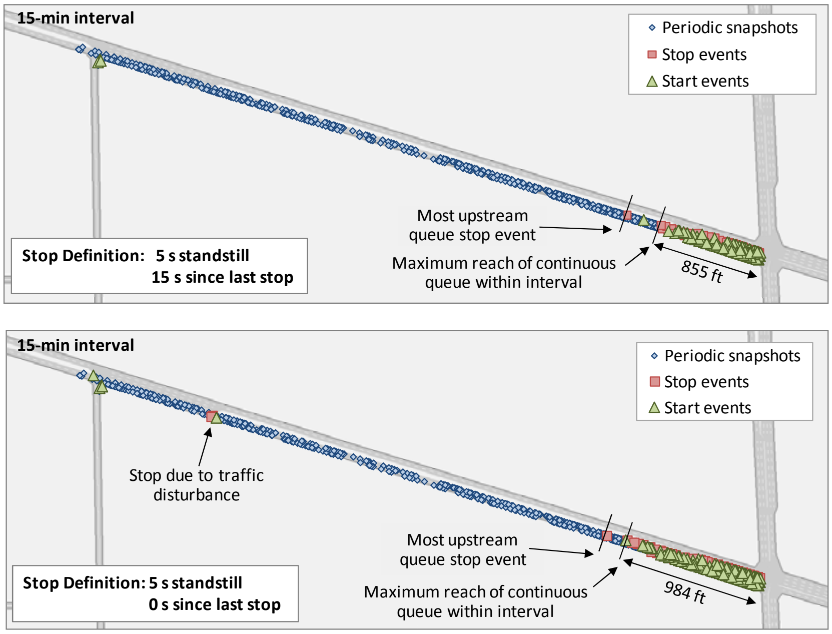


Figure 8-30 – Determination of Maximum Queue Reach Using Stop Snapshots

In each case, the maximum extent of the queue resulting from the signal operation can easily be determined. In the first example, a maximum queue reach of 855 ft can be identified. In the second example, a maximum queue reach of 984 ft is identified if the isolated stop event occurring near the upstream end of the link is ignored (this event can be the results of simulation effects). Since both examples consider identical traffic scenarios, the difference between the two estimates is primarily due to the ability of the second set of stop event triggers to capture vehicles making short stops at the upstream end of the queue when it is almost dissipated.

A comparative analysis of the two scenarios of Figure 8-30 leads to the following observations regarding the ability to track the front of a queue using start event snapshots:

- When considering individual lanes, the front of a dissipating queue can generally be tracked using the sequence in which start event snapshots are generated, as vehicles will typically start moving according to their position within the queue.
- Tracking the front of a dissipating queue spanning multiple lanes is complicated by the fact that vehicles in each lane do not necessarily start moving at the same time. This effect is illustrated in the example of Figures 8-31. If all data are processed as a single group, start events from the curb lane defines the front of the queue for the first 6 s. Departures from the middle lane then define the front of queue for the next 4 s. Beyond that point, start events from the middle again define the front of the queue until the left-turn signal switches to green. At that point, the apparent front of the queue moves back toward the stop line as the left-turning vehicles are the only ones still generating start event snapshots.

The following observations can further be made from the example of Figure 8-32 regarding the ability to use stop event snapshots to track the back of a queue:

- The collection of stop event snapshots from a link during an interval within which no start event snapshots are generated provides a strong indication that vehicles may be prevented

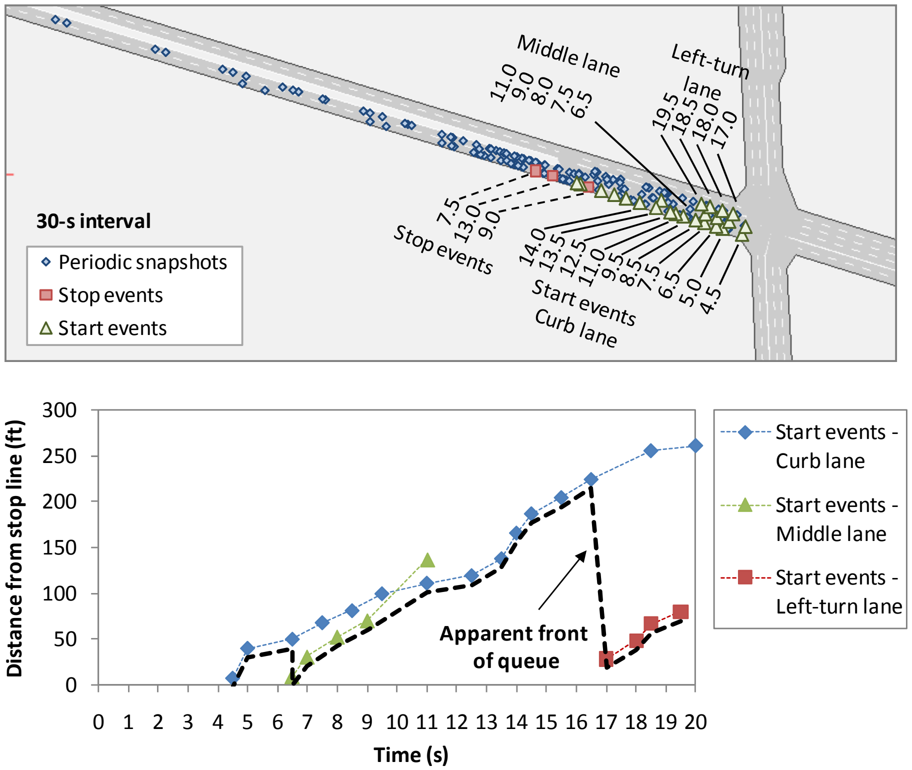


Figure 8-31 – Queue Tracking using Stop/Start Events – Example 1

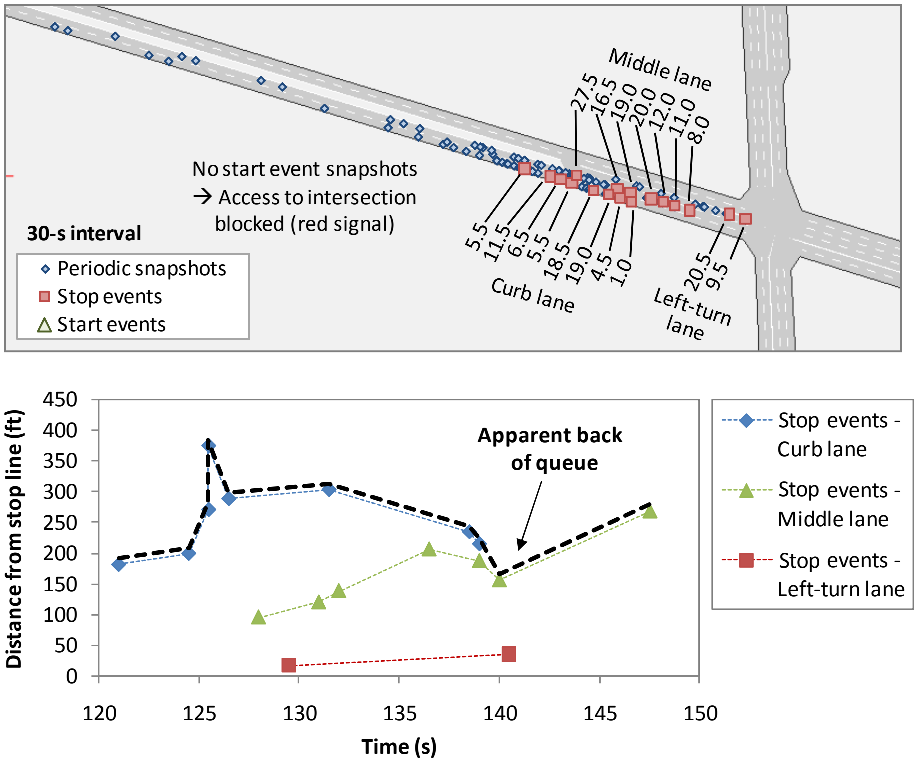


Figure 8-32 – Queue Tracking using Stop/Start Events – Example 2 from exiting the link and that a queue is likely growing. In the example, it can easily be assumed that the queue is generated by a red signal. However, determining the cause of the blockage may not always be straightforward. In some cases, vehicles may be prevented from exiting the link while the signal is green by a downstream queue reaching the intersection. Pedestrians crossing side streets may also prevent vehicles to turn right and delay the start of queue dissipation on single-lane approaches. Confirming whether a queue is growing may thus require compiling information from various sources to assess correctly the traffic condition generating the stop event snapshots being collected.

- Tracking the growth of the back of a queue on multilane links is not necessarily straightforward since vehicle queues may grow at different rates on each lane. In this example, the queue is longest on the curb lane and significantly shorter in the left-turn bay. Because of this difference, simply tracking the location of the latest collected start event snapshots results in the apparent location of the back of the queue jumping back and forth, as shown in the bottom diagram of the figure. Special queue tracking algorithms may therefore need to be developed to adequately process stop event snapshots to track the back of queues.

Other potential data processing difficulties arise from the fact that stop/start event snapshots are generated only once for each stop occurrence. This can lead to problems when analyzing data from short intervals. If no start or stop event snapshot is generated, there then is no direct indication that a queue or congested conditions may exist. An example can be seen in the top diagram of Figure 8-32. In this case, vehicles are instructed to stop generating periodic snapshots while stopped, as per default protocols. Since all vehicles near the stop line remain immobilized during the 30-s analysis interval, no periodic or start event snapshot is generated near the stop line. The only indication that a queue exists is given by the stop snapshots collected further upstream on the link. Ensuring that queues do not remain undetected within any analysis interval thus requires developing processes for keeping track of the locations of identified queues from one analysis interval to the next, as well as for determining when previously identified queues may have dissipated.

8.7.2. Estimation of Queue Parameters using Stopped Periodic Snapshots

Instructing vehicles to keep generating periodic snapshots while stopped would provide a mechanism for clearly identifying where queues of vehicles may be located at any given time. An example is shown in Figure 8-33. This example reprises the traffic scenario of Figure 8-31 but allows in this case vehicles to keep generating periodic snapshots while stopped. As can be observed, the stopped periodic snapshots generated on each lane upstream of the start event snapshots clearly indicate that while some vehicles have started to move others remain queued on the middle and left-turn lanes at the end of the analysis

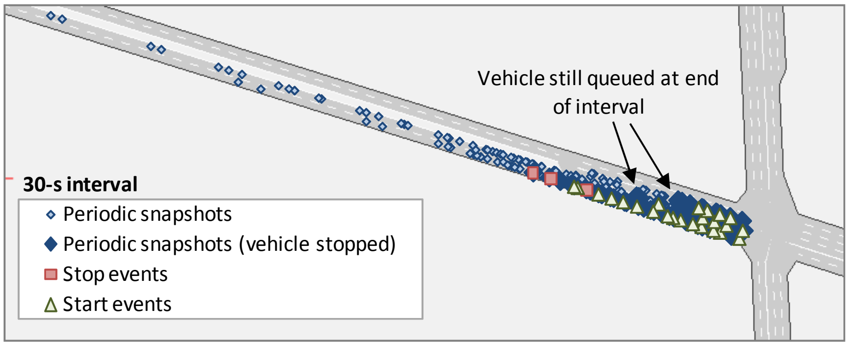


Figure 8-33 – Queue Tracking using Stopped Periodic Snapshots – Example 1

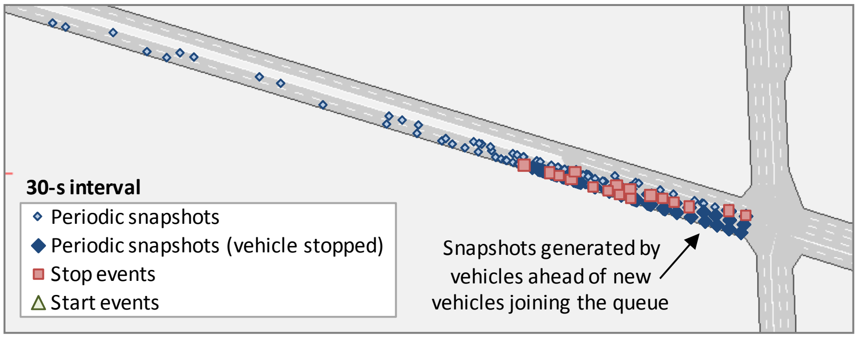


Figure 8-34 – Queue Tracking using Stopped Periodic Snapshots – Example 2

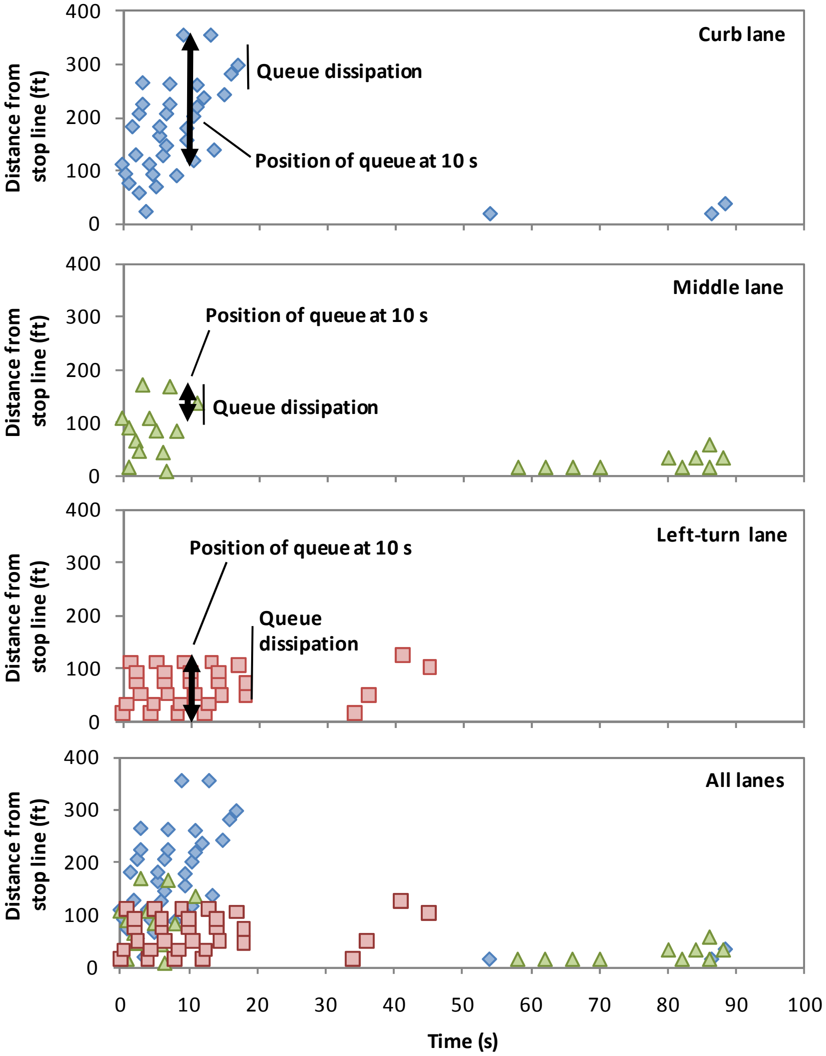


Figure 8-35 – Queue Tracking using Stopped Periodic Snapshots – Example 1: Snapshot Plots interval. Another example based on the scenario of Figure 8-32is provided in Figure 8-34. In this case, the generation of stopped periodic snapshots downstream of the collected stop event snapshots clearly indicates the presence of queued vehicles near the stop line, ahead of the vehicles observed to be making a stop. The collected stopped periodic snapshots thus provide here a very clear indication that the stopping vehicles are joining the back of an existing queue.

Similar to stop/start event snapshots, difficulties may arrive when using stopped periodic snapshots to track the front and back of a queue on links with multiple lanes. If the positioning instruments onboard vehicles are not precise enough to place them on a specific lane, as is typically the case, simply looking at the distance from the stop line at which stopped periodical snapshots are generated may cause some fuzziness in the data. This effect is illustrated in Figure 8-35. This figure plots on a time-space diagram the stopped periodic snapshots illustrated in Figure 8-33. As can be observed, processing the data on a link-by-link basis results in a reasonable ability to identify the position of the queue on each lane at any given instant, as well as to determine when queue dissipates on each lane. However, when merging data from all lanes, it becomes difficult to provide accurate estimates of the position of the queue at any given moment or of the time at which the queue dissipates.

Another potential factor that may affect queue determination is the interval between snapshots. Results that are more accurate will be obtained if vehicles are instructed to generate stopped periodic snapshots using short intervals, such as intervals of 1 or 2 s. However, the feasibility of this approach will depend on the capability of each vehicle to store the snapshots generated. If the onboard memory is too small, using a short interval between snapshots may lead to vehicles frequently filling it and in some data being dumped to make room for newer ones. Using longer intervals would prevent this problem but may also reduce the ability to track accurately the location of queues.

8.7.3. Partial Market Penetration Effects

Partial deployments may have significant effects on the ability to estimate queue parameters using probe vehicle data, particularly when considering very short sampling intervals. For instance, determining the maximum reach of queue requires detecting vehicles stopping the farthest away from a signalized intersection. If only 10% of vehicles are providing probe data, there is only a 10% chance that stop or start event snapshots may be collected in each signal cycle from the vehicle that stops the farthest from the intersection. A 90% chance will thus exists that the observed queue length in the signal cycle period may be longer than what is assumed by the data. In this case, considering the proportion of probe vehicles in the traffic stream would not help determining the location of the back of the queue. Similar issues would also exist with the tracking of the front and back of a queue, thus resulting in limited capabilities of using probe vehicle data to track queues over very short intervals with partial market penetrations.

Data sampling over intervals of at least 10 or 15 minutes may still allow determining the average length and location of queues. All that is required for such analyses is to compile where vehicles typically stop. Collecting data over multiple cycles thus increases the chance that snapshots may be collected from most locations where vehicles queue over time. To ensure that enough snapshots are collected for an accurate depiction of queuing activities, the length of the sampling period should be adjusted with the market penetration. In this case, lower penetrations will typically require longer sampling periods. However, an accurate depiction of queue conditions through snapshot analysis will theoretically only be possible if the traffic demand remains relatively constant during the sampling interval.

8.7.4. Conclusions

The following conclusions are made regarding the use of probe vehicle data to analyzing queuing on individual roadway links:

- The best approach for tracking queues is to use both stop/start event and periodic snapshots generated by stopped vehicles. Stop/start event snapshots provide an accurate record of when and where each vehicle stops and starts moving. Stopped periodic snapshots provide complementary information that help address situations in which collected stop/start events may not be sufficient to help identify what is happening.
- If considering only stop/start events, intervals may exist during which no vehicle joins or leaves a queue if short interval durations are used. In such cases, an algorithm to track the progression or dissipation of queues across successive analysis intervals may be needed to keep track of queue location.
- Changes in the thresholds used to identify stop and start events will affect queue tracking. To ensure adequate accuracy, the preference is to use thresholds allowing snapshots to be generated as close as possible to the actual stop and start events, but without causing too many snapshots to be generated in stop-and-go situations.
- Changes in the interval between the periodic snapshots generated by stopped vehicles will also affect queue determination. The recommendation is the use the shortest interval possible.
- Tracking the front of a queue will typically be simpler than tracking the back of a queue, as vehicles often depart from the front of a queue in a more orderly fashion than when joining its back.
- The inability to position vehicles on specific lanes may create a need to develop nontrivial algorithms to track the front and back of a queue.
- Average queue behavior can be determined under partial market penetrations by compiling snapshots generated over a sufficient long interval to obtain an adequate depiction of where vehicles typically stop.

8.8. Turn Percentages

Many road design activities and traffic performance evaluations require information about directional traffic flows. An example is for the design of signalized intersections, where information about vehicles intending to turn left, go straight or turn right help determining the number and duration of signal phases, the lane configuration, and evaluating potential conflicts with pedestrians. Another example is for the development of traffic simulation models. Many models use turn percentages at intersections to define the traffic patterns to be simulated within a road network. While some models rely on origin-destination matrices instead, these matrices are often developed using procedures that attempt to develop traffic patterns replicating observed directional flows at intersections.

Traffic surveillance systems based on point detectors do not readily allow the determination of turn movements. Many commonly used technologies, such as inductive loop detectors and tube counters, cannot provide a clear indication of the intended direction of travel of detected vehicles. While video detection technologies theoretically offer opportunities for tracking vehicles approaching an intersection, most existing systems only attempt to emulate the functionalities provided by traditional loop detectors and only provide detections when vehicles cross a trip line. Existing surveillance systems, can thus typically only determine directional movements where detectors are placed on dedicated traffic lanes, such as a left-turn bay, exclusive through lanes, or freeway ramps. Because of this limitation, many traffic studies still rely on manual labor to observe traffic movements at intersections. While some methods have been proposed to estimate directional flows by correlating vehicle detections from point sensors placed around an intersections, these methods generally remain confined to a research realm. Finally, while systems capable of uniquely identifying vehicles at each detection point exist, such as license plate readers and electronic identification tag readers, the use of such systems remains primarily confined to freeway toll operations.

In the above context, IntelliDrive^{SM} systems offer an opportunity to expand significantly data collection capabilities by allowing the tracking of probe vehicles across individual intersections. In this case, it is not required to have continuous tracking. The only requirement is the ability to obtain at least one snapshot positioning a vehicle on an intersection approach and a subsequent snapshot positioning the same vehicle on one of the intersection's exit links.

The following paragraphs evaluate how turning movements could be obtained by processing:

- Special event snapshots marking the moment a turn signal is turned on or off
- Periodic snapshots
- Stop and start event snapshots
- Link exit/entry snapshots

8.8.1. Determination by Processing Vehicle Status Data

Turn signal activations recorded within periodic snapshots or as part of special vehicle event snapshots can be used to obtain information about directional flow movements. In a full deployment, this approach could allow the identification of all turning vehicles if all drivers always signal their turn intentions. However, if a non-negligible proportion of drivers omit to activate their turn signals, using only turn signal activations to assess turn proportions could lead to significant estimation errors. Another potential difficulty is how to distinguish vehicles using their turn signal near an intersection not to turn right or left but to change lane. For these reasons, it is not currently recommended to use turn signal activation data alone to determine directional flows at intersections and decision points.

8.8.2. Determination by Matching Periodic Snapshots

Periodic snapshots can be used to determine directional flow movements at intersections only if a mechanism exists to allow snapshots to be associated to specific vehicles. Such a capability is theoretically offered by the unique PSN value tagged by each vehicle to the snapshots it generates. Since the snapshots generated by each vehicle would normally exhibit a different PSN value, correlating snapshots with identical PSNs would thus allow tracking the movements of specific vehicles across an intersection if snapshots with a given PSN are generated on both an intersection entry and exit links.

Since PSNs are randomly determined and independently set by each vehicle, different vehicles may produce identical PSNs during the course of a day. This imposes a need to constrain the search of matching snapshots to a relatively narrow time interval and geographical space. For most intersections and junctions, the length of the search interval simply needs to cover the longest interval that may occur between the last snapshot generated on an intersection approach link and the first snapshot generated on an exit link. In most cases, this search interval will only need to be a few seconds long.

A potential difficulty associated with the use of PSNs to track individual vehicles is the risk that a vehicle may change its PSN while traveling across an intersection. Such a change may occur if both the distance and time thresholds triggering a PSN change are reached when within an intersection. A change may also occur if communication with an RSE is temporarily dropped. In the later case, difficulties would still arise if vehicles were allowed to retain their PSN. Since vehicles are currently allowed to communicate only once with an RSE, a vehicle successfully re-establishing communication with an RSE would then be denied permission to upload to the RSE, or any other RSE, snapshots featuring a previously used PSN. While such events may occur only in a minority of cases, they may occur sufficiently frequently to affect significantly counts of vehicle traversing an intersection.

To minimize the potential effects of PSN changes, vehicles may be instructed to keep generating periodic snapshots while stopped. Such a protocol would reduce the probability that a long interval may occur between the last snapshot generated on an intersection approach and the first snapshot generated on an exit. Shorter intervals would then reduce the window during which a PSN change following entry into an intersection could invalidate a vehicle track.

Since vehicles are expected to record in periodic snapshots the status of various onboard systems, including whether the left or right turn signal is activated, this information could be used to validate turn movements determined by matching periodic snapshots. It could also be used to assign turn movements when this information cannot be extracted from periodic snapshots. However, because drivers may not always signal their intent to turn or may use a turn signal to make a lane change, various filters would need to be developed to ensure that turn signal information is correctly used.

8.8.3. Determination by Processing Stop/Start Event Snapshots

Snapshots generated to record stop and start events can only be used to estimate turn percentages if it is possible to assign pairs of stop and start event snapshots to specific vehicles. This will be possible if the PSNs used to link periodic snapshot are also tagged to stop and start event snapshots. In such a case, stop/start event snapshots could then be treated similarly to periodic snapshots. Potential difficulties in using stop/start event snapshots would then include:

- Vehicle tracking would only be possible if PSNs are maintained through an intersection.
- Stop/start events only allow considering vehicles making a stop.
- At many locations, stop and start events are likely to be generated on the same link. Only vehicles stopping at the very front of a queue have a potential for having stop and start event snapshots generated on different links.

For the above reasons, it is not recommended to use strictly stop/start event snapshots to track vehicles movements across intersections. These snapshots would best be used in combination with other types of snapshots.

8.8.4. Determination by Processing Link Exit/Entry Event Snapshots

One of the proposed recommendations from earlier analyses is to allow vehicles to generate link exit snapshots. Upon entering a link, a vehicle would record in an onboard memory the link entered. When subsequently exiting the link, the vehicle would then generate a link exit snapshot that would record both the link being exited and the link being entered. Such a snapshot would allow turn movements to be identified without ambiguity while not requiring the use of PSNs or other vehicle identification data.

8.8.5. Conclusions

The following recommendations are made for the determination of directional flows at intersections using probe vehicle data:

- Under current snapshot generation protocols, the most reliable approach is to attempt to match periodic snapshots generated on an intersection approach with snapshots featuring the same PSN generated on one of the intersection exits.
- When using periodic snapshots, a small risk exists that vehicles may reach the thresholds triggering a PSN change just before or after entering an intersection. This risk can be reduced by instructing vehicles to keep generating snapshots while stopped to reduce the interval between snapshots.
- Using only special event snapshots marking when a right-turn or left-turn signal is activated is not recommended, as not all drivers signal their turn intentions. Such snapshots may however be used in parallel to periodic snapshots to provide supplemental turn movement identification capabilities.
- Using only stop and start event snapshots is not recommended, as these snapshots may not always provide usable information. However, these snapshots may be used to complement periodic snapshots.
- The best approach would be to allow vehicles to generate link exit snapshots recording information about both the link being exited and the one being entered.

8.9. Vehicle Passenger Occupancy

Transportation planners have long used vehicle occupancy rates to convert person-trips to vehicle-trips in the four-step travel demand forecasting process, as well as to determine required parking spaces for fixed-seat venues. Vehicle occupancy rates are now also being used by traffic engineers to compute person-delays, derive person-miles traveled and set policies for managed traffic lanes. Transit system operators may further use transit occupancy rates to identify routes that may need service expansion or reduction.

Despite a need for measuring vehicle occupancy, such a measurement cannot easily be made with commonly used traffic surveillance technologies. Where needed, vehicle occupancy data is typically collected through windshield observations. This data collection approach has individuals standing on the side of the road counting the number of persons they can see in a vehicle. Systems capable of automatically counting the number of persons sitting on the front seat of a vehicle through the processing of windshield photographs have also been developed. While such systems have been tested in Europe, they are not currently in used in the United States due to potential issues regarding driver privacy. Such systems also do not yet offer the capability to detect passengers sitting on the rear seat.

IntelliDrive^{SM} systems also offer opportunities to collect information about the number of individuals riding in a vehicle. Since many vehicles now use weight sensors to detect front seat occupancy and activate passenger-side airbags, the information collected by these sensors could be used to determine whether a vehicle has one or at least two occupants. However, since the sensor information is tied to the operation of a vehicle safety system, there are indications that it may not readily be available through a vehicle's CAN bus. In addition, the use of a weight sensor alone to determine occupancy would not prevent cheating, as the sensors could be easily tricked to believe that a person occupies a seat by placing heavy objects on it.

Another potential issue is how to address the needs of applications requiring detection of passengers on the rear seat of a vehicle, such as to support the enforcement of high-occupancy vehicle lanes restricted to vehicles having at least three passengers. Currently, no vehicle has sensors installed on its rear seat. With the advent of side impact and seatbelt airbags, it can be expected that sensors may eventually be installed on the rear seat. However, deployment schedule is uncertain. Car manufacturers will likely only install such sensors is a benefit is perceived, unless there is a government mandate to do so.

8.10. Vehicle Classification

Many traffic and transportation studies require information about the types of vehicles traveling along a given section of road. Vehicle classification data are commonly used for designing pavements, scheduling the resurfacing, reconditioning and reconstruction needs of highways based on projected remaining pavement life, predicting commodity flows and freight movements, assessing the capacity of highways, developing weight enforcement strategies, analyzing alternative highway regulatory and investment policies, assessing roadway safety, analyzing factors leading to accidents, and conducting environmental impact analysis.

Typical classification schemes distinguish between passenger cars, motorcycles, buses, and various types of trucks based on the number of axles and trailers pulled by the vehicle. Existing detection technologies offer a number of approaches for automatically classifying vehicles. A first approach measures the number of axles associated with each passing vehicle and the spacing between the axles. This information is then fed into an algorithm that associates a given number and spacing of axles with a particular vehicle class. Another approach uses two inductive loops to measure the length of passing vehicles. While this approach does not allow distinguishing among sub-types of vehicles sharing the same length, it allows distinguishing basic vehicle types. A third approach uses video image processing. Many of these systems simply try to replicate the functionalities of loop detectors and thus still primarily attempt to classify vehicles in terms of their length. More advanced systems also try to use radar or infrared sensor technologies to classify passing vehicles based on their vertical profile.

A common feature of all existing detection systems is that no system is perfect. Some errors may result from inaccurate calibration, vehicles being occluded from the sensor's field of view, sensor limitations, or a range of other factors. These problems can be virtually eliminated by allowing IntelliDrive^{SM} vehicles to broadcast vehicle type along with other vehicle status parameters. The simplest approach would be to broadcast the portion of the Vehicle Identification Number (VIN) defining the model type. While each vehicle has a unique VIN, the leading numbers typically characterize the vehicle's manufacturer (first 3 characters), model type (4th to 9th characters), and model year (10th character). Broadcasting only the first 10 characters would not allow identifying a specific vehicle and would therefore not compromise driver privacy.

8.11. Summary

This chapter looked at how various key traffic performance measures could be estimated using probe vehicle data collected by RSE-based systems implementing currently envisioned snapshot generation and retrieval protocols. The analyses indicate that the following performance measures could be estimated within certain accuracy using periodic and stop/start event snapshots if specific effects associated with the snapshot generation protocols and rules imposed to safeguard the privacy of travelers are considered:

- Traffic flow rate
- Flow density
- Link speed profile
- Link travel time
- Vehicle delays
- Number of stops
- Length and position of vehicle queues
- Intersection/junction turning counts

It was also determined that vehicle classification data could be obtained by simply requiring each vehicle to record the first nine digits of their Vehicle Identification Number (VIN). While an interest also exists in obtaining vehicle occupancy data, such information cannot currently be automatically obtained from existing vehicles.

The analyses led to various recommendations to improve snapshot generation protocols:

- While the default approach is to generate snapshots at intervals based on speed, this approach may bias data samples on links on which vehicles do not always travel at the same speed, such as approaches to signalized or stop-controlled intersections. For these links, snapshots generated at fixed intervals would provide a better assessment of actual traffic conditions.
- While vehicles are instructed to discard the periodic snapshots they generate while stopped, likely to reduce the size of the required onboard memory buffer, benefits could be obtained by retaining these snapshots, particularly when considering using probe vehicle data to track vehicle queues and assess incurred delays.
- Measures imposed to protect traveler privacy may have significant impacts on parameter estimations. Frequent PSN changes may cause significant overestimation or underestimation of the number of vehicles traveling on a link if snapshots are not handled adequately. Frequent changes also significantly restrict the ability to track vehicle movements across individual links or intersections. Allowing vehicles to be tracked over longer distances could significantly expand data analysis capabilities, as well as the accuracy and reliability of the performance parameters that can be derived from the collected data.
- While vehicles are not currently instructed to generate snapshots every time they exit/enter a link, such snapshots would allow producing more reliable travel time estimates without compromising traveler privacy, in addition to facilitating the estimation of directional flows at intersections and junctions.

While the analyses focused on scenarios featuring full deployments, most of the above parameters can be estimated when only a fraction of the vehicles is providing data. Estimating average link travel times only requires obtaining data from a statistically significant sample of vehicles. Estimating flow rates or density is also possible if a method exists to determine the average proportion of probe vehicles in the traffic stream. Such a proportion may be determined by comparing counts of vehicles derived from probe data with counts provided by traditional point detectors at strategic locations. The accuracy of the full traffic estimates will then depend on the estimated proportion of probe vehicles, with greater accuracy expected with increasing proportions of probe vehicles. For most parameters, reasonably close average estimates could be obtained with relatively small market penetration levels, such as 5 or 10%. Extremely small penetrations, such as those that would be observed in early deployments, carry a significant risk of error.

Relatively large data samples, and thus high market penetration levels, may finally be required to estimate some of the parameters if it is desired to reach a certain confidence level within a given tolerable error. This is particularly true for estimating delays and the number of stops occurring around signalized intersections due to the variety of traffic conditions experienced by travelers at these locations.

9. Concept of Operations for IntelliDrive^{SM} Traffic Flow Monitoring Application

Transportation system operators heavily depend on the collection of information characterizing traffic flow conditions along individual roadway segments to assess how well a system is operating and determine whether corrective actions may be necessary. To support various needs and performance assessments, data on the number and type of vehicles traveling on each roadway segment during specific periods, as well as on the average behavior of these vehicles, are typically sought. Examples of data uses include:

- Determination of annual average daily traffic (AADT) volumes on roadway links
- Determination of commercial trucks percentages on roadways
- Determination of congestion level on individual roadway links
- Operational analysis of traffic control devices
- Evaluation of queuing behavior and storage needs at intersections
- Determination of typical time-of-day, weekday, monthly and seasonal traffic demand patterns
- Evaluation of year-over-year traffic demand trends
- Identification of unusual traffic congestion
- Provision of traffic speed and travel time data to traveler information systems
- Pavement and bridge life-cycle analyses
- Determination of crash risk probabilities
- Input data to travel demand forecasting models
- Input data and calibration of microscopic traffic simulation models

9.1. Current Situation

Existing traffic monitoring systems essentially rely on point vehicle detectors to sense traffic conditions on specific roadway segments. In most systems, vehicle detection primarily relies on inductive loops embedded in the pavement. While the technology dates back to the 1960s and is by now well understood, it has the disadvantage of requiring pavement cuts that may threaten the integrity of the pavement in addition to requiring temporary traffic lane closures for their installation and maintenance. To alleviate these problems, a growing number of transportation agencies are now favoring sensors that can be installed on the side of the road or over traffic lanes. Examples include sensors based on Doppler radar, microwave, infrared, ultrasonic and passive acoustic technology. Video cameras linked to image processing software also fit in this category. This type of sensor is now commonly used to support traffic signal operations at urban intersections. Video cameras installed along freeways and highways further allow system operators to assess traffic conditions visually. However, they are not typically used to exact traffic flow parameters.

Most of the existing point vehicle detectors operate in presence mode, i.e., turn on and stay on as along as a vehicle remains within their sensing zone. This allows the following basic performance metrics to be obtained:

- **Vehicle presence:** Indication of whether a vehicle is present within the sensing field.
- **Vehicle count:** Number of times a sensor has been activated.
- **Vehicle speed:** Direct speed measurement is possible where two detectors are installed a few feet apart to create a speed trap. Speed measurement is also possible from roadside sensors

with multi-zone sensing capability. Doppler radar sensors also allow speed measurements, but can only detect moving vehicles. At locations where a single sensor is used, vehicle speeds are often estimated by using an assumed average vehicle length to obtain an average speed estimate from detector occupancy data (amount of time a sensor remains activated over a given interval) and vehicle counts.

- **Vehicle classification:** The capability to classify vehicles depends on the type of technology used. Classification may be based on the number of axles detected, length, magnetic signature or detected vertical profile of a vehicle. Typically, not all detection stations within a traffic surveillance system have the required instrumentation for classifying vehicles. Such sensors are usually only installed along major roads where it is desired to monitor trucking activities.

Where automated reporting capabilities exist, data from individual sensors may be polled at intervals ranging from once every 20 s to once every few minutes. Depending on local capabilities, individual or aggregate vehicle detection data can be retrieved from each station. Vehicle-specific data usually include detection time, measured speed (if available) and vehicle type (if available). Aggregate data typically provide the total number of vehicles detected since the last polling, the average time occupancy of the detector, the number of detected vehicles of each type (if classification is available), and a distribution of vehicle counts according to predefined speed ranges (typically 5-10 mph intervals).

Depending on the location, additional data collected by private enterprises such as Traffic.com, INRIX or TrafficCast may also be available (see Section 4.6.5). While these enterprises often heavily rely on data supplied by detection stations operated by public transportation agencies to support their traffic reporting services, they are increasingly attempting to use proprietary sensing capabilities to improve the accuracy and real-time nature of their reports. For instance, Traffic.com collects data from additional roadside point vehicle detectors that are installed in areas of interest deemed to have inadequate sensing capabilities from public transportation agencies. INRIX further collects probe vehicle data from participating fleets of vehicles equipped with GPS or other tracking devices. These data collection efforts typically produce information on traffic speeds or travel times along major travel corridors, which are then fed to travelers and fleet operators to help them schedule trips.

Traffic monitoring at individual intersections further depends on the traffic signal control needs. Detectors are usually only installed at intersections operating semi actuated, fully actuated, or real-time traffic signals. At intersections with semi-actuated signals, detectors are typically used to monitor traffic on minor streets only. Intersections with fully actuated signals would have detectors on all approaches. Depending on the traffic signal control algorithm, vehicle detections may be used to determine if one or more vehicles are waiting to enter an intersection from a specific approach or lane, or to monitor the gap between successive approaching vehicles. This information is then used to temporary green signal extensions or order the green signal to be transferred to an approach only if there are queued vehicles waiting for it. Real-time signal control systems usually have detectors installed on all approaches and use detections to re-optimize the timings of individual or groups of intersections at periodic intervals. Examples of such systems in Michigan are the SCATS and SCOOT control systems used respectively by the Road Commission of Oakland County and the City of Ann Arbor. The SCATS system uses stop line detectors to monitor how vehicles are using each green signal and make appropriate adjustments in subsequent signal cycles to improve system efficiency, while the SCOOT system uses detectors to predict arrivals over the next few seconds and continuously update cyclic arrival patterns.

9.2. Motivation for Enhanced Traffic Flow Monitoring Application

Traffic and system operations monitoring capabilities are a cornerstone of many activities conducted by state and local departments of transportation. Without the ability to assess quantitatively traffic conditions on individual roadway links and at intersections it is difficult to evaluate whether problems exist and develop appropriate courses of action to mitigate identified problems. While MDOT and other public transportation agencies already operate real-time traffic monitoring systems, these systems often only provide data from a limited number of roads. In addition, the heavy reliance on point vehicle detectors leads to very narrow observation capabilities. When needed, costly manual surveys must therefore be conducted to fill information gaps critical to the execution of specific activities or projects.

This section describes the limitations of existing monitoring systems, relevant stakeholder needs, assumptions and potential constraints associated with an enhanced traffic monitoring capability, and key desired operations and processes.

9.2.1. Limitations of Existing Monitoring Systems

One of the main limitations of existing traffic monitoring systems is the low percentage of roads covered. Excluding systems supporting the operation of traffic signals, vehicle detection stations are predominantly installed along urban freeways, with occasional stations placed along rural freeways, rural highways and urban arterials. In Michigan, approximately 225 miles of major roads are currently equipped with traffic sensors, out of a total of 9,700 miles of primary roads. This represents coverage of less than 3%. Most of the sensors are further located on major freeways across the Metropolitan Detroit, with some additional stations covering freeways in the Grand Rapids area. This results in very poor coverage outside urban areas.

While sensors are also frequently used to support the traffic signal operations, the extent of traffic monitoring capabilities at each intersection depends on the type of signal control provided. Intersections operated in fixed time often do not have detectors, while intersections with semi-actuated signals typically only have sensors covering minor traffic movements. In most cases, sensors are set to operate in a simple presence detection mode. This allows determining when vehicles are present on individual approaches and counting them. However, it does not allow tracking vehicles across intersections to determine turn percentages, which is an important element influencing the design of traffic signal timing plans.

The ability to use the vehicle detections from sensors installed to support traffic signal operations further depends on the ease with which sensing data can be retrieved. Some sensors may be directly linked to a traffic signal control cabinet with no data storage capability or remote capability to retrieve the collected data. While a growing number of cities are deploying signal control systems with remote monitoring capabilities, the vast majority of intersections are still operated without such capability, particularly in rural areas, where predefined fixed-time operations dominate. This still results in a frequent need to send individuals to retrieve sensing data from traffic signal control cabinets or detector storage devices, thus resulting in relatively infrequent, and inefficient, data collection.

A general issue with many existing monitoring systems is sensing accuracy. Inductive loop detectors, which comprise the majority of sensors in use today, can only measure speed when laid out in a dual arrangement to create speed traps. At single-loop stations, which still comprise the majority of detection stations in Michigan, an approximation is used to estimate average travel speed based. Average traffic speeds are based on data characterizing the average time a detector is activated by a vehicle (detector occupancy) and an assumed average vehicle length. Even with sensors working properly, the speed estimates produced by such an approximation can be very inaccurate for traffic flowing at speeds greater than 50 mph (Coifman, 2001). Dual–loop stations, which normally provide more accurate measurements than single-loop stations, have also been found to produce significant amounts of error in specific circumstances (Coifman, 1999). Many systems are further plagued by frequent or significant sensor malfunctions. As an example, Hoh *et al.* (2008) recently reported that approximately only 35% of all the detectors within the California Performance Measurement System (PeMS) were working properly. Payne and Thompson (1997) reported earlier a malfunction rate of 21% along a stretch of freeway in California despite significant efforts to maintain the sensors. These evaluations are consistent with anecdotal evidences from MDOT professionals working with sensor data, who have indicated that a sizeable proportion of permanent traffic count stations across the state often exhibit some form of operating problems.

Another issue regarding systems using point vehicle detectors is the inability to observe directly what happens between each station. In the best cases, traffic detectors may be installed every half mile or every mile along freeways. Many systems, such as those deployed in Michigan, have detectors more sporadically located based on strategic monitoring needs. This results in relatively few monitoring stations from which overall network traffic conditions must be evaluated.

Since sensors do not generally allow tracking individual vehicles between successive stations, the traffic conditions between each station must further be inferred based on observation from the stations at each end of the segment. For instance, average speeds along roadway segments reported on traveler information websites are often simply assumed to correspond to the average speeds observed at the upstream station, or to an average of the speeds observed at both ends of the segment. This may result in inaccuracies where traffic conditions vary significantly between each station, particularly where detection stations are relatively far apart.

While some systems allow tracking vehicles between stations, such systems are not currently used in Michigan. They are almost exclusively used to support freeway toll operations. While these tracking systems can also be used to monitor travel times between toll plazas or to determine trip origins and destinations along a freeway, particularly where stations are located on off and on ramps, they still do not allow determining what may be influencing traffic conditions between successive stations. All that can be determined is that something is causing changes in observed travel times.

In many areas, data from additional roadside detectors or probe vehicle fleets can be obtained through contractual data sharing agreements with private traffic monitoring enterprises such as Traffic.com or INRIX. While this data may allow public transportation agencies to obtain traffic flow information from areas currently not being monitored, such as rural freeways, rural roads and urban arterials, limitations still exist regarding overall network coverage. Coverage tends to follow major travel needs. This results in most of the data being collected from urban freeways and major urban arterials, where public transportation agencies may already have sensing capabilities. While data may be collected from rural freeways and highways, this data may be closely linked to roads used by commercial fleets. There may also be a bias introduced by the types of vehicles providing data. For instance, travel data supplied by commercial fleets may not adequately reflect the behavior of typical commuters, particularly in states where trucks are subject to different speed limits and route restrictions. Furthermore, since detection capabilities are primarily being developed to obtain speed and travel time data, concerns also exist regarding the validity of traffic counts reported by sensors operated by private enterprises, as accurate counts require more extensive calibration than travel time sampling.

9.2.2. Stakeholder Needs

The primary stakeholders of an enhanced traffic monitoring system potentially covering freeways, highways and arterials include individuals and entities that would directly benefit from the more comprehensive traffic characterization data that could be provided by such a system. This group also includes individuals and entities responsible for the collection, processing and storage of data.

Specific stakeholders within MDOT and MDIT would include individuals from the following professional groups:

- System operators
- Transportation system planners
- Asset managers
- Maintenance personnel
- Information system administrators

Additional stakeholders outside MDOT include individuals and entities that may use the enhanced traffic monitoring capabilities to improve their own operations:

- Regional county road commissions
- Transportation planning organizations
- Transit service providers
- Emergency service providers
- U.S. Department of Transportation
- Travelers
- Commercial fleet operators
- Commercial information service providers
- Research community

Vehicle manufacturers, original equipment manufacturers, and communication network operators are also stakeholders as the collection of probe vehicle data only becomes possible if they provide the necessary equipment onboard vehicles and a supporting communication infrastructure to allow vehicles to transmit the data they collect to an application server.

While various stakeholders may have differing needs, all stakeholders would share directly or indirectly the following common high-level common needs from an enhanced traffic flow monitoring system:

- Ability to collect traffic data throughout the entire roadway network, particularly in areas not covered by existing surveillance systems
- Ability to collect traffic data in near real-time
- Ability to discriminate vehicle types
- Ability to determine link travel times along any type of roadway
- Ability to determine turn percentages at intersections, road splits and freeway ramps
- Ability to accurately assess traffic conditions on individual roadways and within an area
- Ability to collect, process and redistribute the data with as little time delay as possible

9.2.3. Assumptions

The ability to use probe vehicle data to develop enhanced traffic information is influenced by the following assumptions:

- Data collected from all probe vehicles will follow a unique standard.
- A certain amount of probe vehicle data is already being collected by private enterprises, thus providing a certain initial level (albeit very low) of market penetration.
- Benefits may be obtained with very low market penetration levels. For instance, only a few observations may be needed to determine whether traffic is flowing normally on a link.
- Data transmission from a vehicle to an application server can occur with a relatively small delay (in the order of a few seconds).
- The anticipated high density of RSEs or ubiquitous cellular phone coverage creates a possibility to collect traffic information from all roadways in urban areas.
- In rural areas, temporary losses of communication capability are compensated by the ability of vehicles to store data on an onboard buffer until communication capability is reestablished.
- To reduce potential data loses, vehicles are assumed to all have an onboard buffer having sufficient storage capacity to store several hundreds of snapshots.
- In addition to standard periodic traffic snapshots, stop/start event snapshots and vehicle event snapshots, vehicles may be allowed to generate additional types of snapshots (for instance, link exit snapshots, stopped periodic snapshots).
- The capability will at least exist to track vehicle movements across individual roadway links. Roadway links will typically correspond to the links used by transportation agencies and information service providers to compile and report transportation system data.
- The capability will exist to track vehicles movements across intersections or junctions. This capability may be provided either by processing standard snapshots (e.g., by matching snapshots with identical PSNs) or by having vehicles generating special event snapshots (e.g., link exit snapshots).
- Individual travelers may allow tracking over longer distances through opt-in data collection agreements.
- Vehicle type may be obtained by allowing vehicles to broadcast VIN parameters defining vehicle make and model. This will allow replacing current indirect procedures using vehicle length, axle sequences, magnetic signature, or vertical profile.
- Transportation agencies will have the opportunity to set or change locally default data collection protocols to meet their data collection needs.
- The increasing reliance on complex communication and data processing technologies will require MDOT to collaborate more closely with other government agencies, notably the Michigan Department of Information Technologies (MDIT), as well as potentially with external service and technology providers.

9.2.4. Potential Constraints

The following constraints have the potential to inhibit or delay the ability to collect enhanced traffic information and process this information to derive data relevant to various applications:

- The rate of growth of probe vehicle data will depend on the rate at which vehicles equipped with the necessary instrumentation will enter the market.
- Data collection will depend on the availability of an adequate communication infrastructure, whether using DSRC or other wireless communication modes.
- Rules implemented to protect the privacy of travelers may limit the capability to track vehicles over moderate to long distances. This may particularly affect the ability to collect trip origin and destination data or to track the movements of vehicles along urban or rural corridors of interest.
- Probe vehicle data collected by private enterprises may primarily consist of data characterizing the movements of commercial trucks, delivery trucks, and business vehicles. These vehicles often have travel patterns significantly different from passenger cars, do not travel on every road, and are often more active during off peak periods than during peak periods, when there is a greater interest in data collection.
- Some functions may require a certain minimum market penetration level to be reached before benefits can be derived from the collection of probe vehicle data. For instance, observations from multiple vehicles may be needed to confirm that lower than normal observed speeds are not just the result of a few vehicles interacting with a temporary road factor.
- Differences in the quality or type of data obtained from various sources may create a need to develop relatively complex algorithms to interpret collected data adequately and effectively assess its usability.
- Data latency may reduce the usability of probe vehicle data, particularly if technical issues or congestion within the communication network results in the collection of data several seconds or minutes old.
- Data losses may occur due to onboard memory buffers becoming full. Losses may occur even if large buffers are provided, particularly in rural networks where vehicles may travel significant distances between RSEs of data communication points. Significant data losses could notably create a need to reach higher market penetration levels before adequate benefits could be obtained from the collected data.
- The ability to store and process data at an application server will depend on the capacity of the server to handle the expected data flows. Since IntelliDrive^{SM} systems are likely to be gradually deployed, data flows will likely start with a trickle and gradually increase to large volumes. This creates a need to review periodically the capacity of the data server to ensure its ability to handle the expected data traffic.
- The expected gradual deployment of IntelliDrive^{SM} systems makes a traffic monitoring system somewhat sensitive to potential changes in data and messaging standards. While initial systems may be designed according to a specific set of standards, changes in technologies and standards, as well as changes in systems operated by external service providers, can result in potential losses of functionalities. This creates a requirement for periodic system revisions to ensure that full functionalities are maintained or achieved.

9.2.5. Desired Operations and Processes

The enhanced traffic monitoring application should support the following operations and processes to address the limitations of existing systems described in Section 9.2.1 and meet the stakeholder needs described in Section 9.2.2:

- Obtain access to all relevant data sources needed to support traffic monitoring needs.
- Store all collected data and derived performance measures in a historical archive to allow the data to be used by other processes.
- Validate all collected data to ensure that erroneous data is not recorded in the historical database or ensure that erroneous data is marked as such.
- Use the latitude and longitude coordinates associated with each snapshot to identify the roadway link and location along the link where the snapshot was recorded.
- Analyze collected probe vehicle data to extract where needed suitable vehicle tracks across individual intersections or roadway links.
- Compile, if available, metadata relevant to the data collected. This may include information about weather conditions, data precision, instrumentation used to generate the data, etc.
- Assess whether collected data can be used in real-time applications based on the time it took to reach the application server.
- For each roadway link, estimate relevant performance metrics supporting various operational, safety, planning and maintenance tasks. At a minimum, this should include information about average link travel times or speeds, as well as data on travel time variability. Information about traffic volumes should also be estimated wherever possible.
- For each intersection, estimate performance measures supporting various operational, safety and maintenance tasks. At a minimum, this should include information on average delays and observed queue lengths. Directional approach volumes should also be compiled if possible.
- Use collected data to identify links or intersections with traffic conditions exceeding specific congestion thresholds.
- Compile performance measures for individual links and intersections at periodic intervals to facilitate time-of-day analyses.
- Produce periodic reports summarizing observed traffic conditions, either for real-time decision making by staff in a traffic operations center or for various off-line applications.
- Produce periodic reports summarizing traffic monitoring operations, such as number of snapshots collected, number of snapshots assessed to be valid, number of links from which snapshots have been collected, etc.

9.3. Concept of Operations

IntelliDrive^{SM} systems are expected to put on the road vehicles that will have the capability to record at periodic intervals the traffic conditions they encounter and to send this information back to an application server via wireless communications. This provides a significant opportunity to expand data collection and to provide a much richer set of data upon which operational, safety, planning, and maintenance decisions could be made.

9.3.1. Application Goals

The ultimate goals of the enhanced traffic flow monitoring application are to:

- Expand data collection from links currently under surveillance to enable more accurate and reliable assessment of prevailing traffic conditions.
- Expand data collection from links from which little or no information is currently collected.
- Enable the collection of all necessary data supporting the execution of a range of operational, planning, safety and network management tasks.

9.3.2. Enhanced Traffic Monitoring Functions

The enhanced traffic flow monitoring system should provide, at a minimum, the following functionalities:

- **Probe vehicle data collection and archival.** The system should attempt to collect and archive snapshots and other relevant vehicle system data from all IntelliDrive^{SM} probe vehicles present within a coverage area.
- **Non-IntelliDrive^{SM} data collection and archival.** Available data supporting network operations, safety evaluations and maintenance activities should be collected and archived. This includes data from traditional point vehicle detectors, weather data, and periodic data collected as part of annual or project-specific surveys.
- **Real-time monitoring of traffic conditions on individual roadway links**. At the most basic level, the system should compile all collected data to assess prevailing travel times on individual roadway links and delays at intersections of interest. Capabilities should then be provided to allow this information to be communicated in real-time, or as soon as possible, to transportation system operators and managers.
- **Data communication to relevant applications.** Information derived from collected probe vehicle data and other data sources should be provided in a timely manner to transportation system operators, planners, and maintenance staff to support their various tasks. This may include the generation of periodic reports summarizing average observed traffic conditions on individual roadway links, corridors, or across a jurisdictional area. At a minimum, the reported data should include vehicle count data and information about average travel speeds or travel times. Information that is more detailed should be provided if available.
- **Archival of assessed network operational parameters.** Assessed network operation parameters, such as travel times or flow rates, should be archived at the end of each operation period to allow the information to be used by other applications.

9.3.3. Key Concepts

Key concepts behind the development of enhanced traffic monitoring capabilities using IntelliDrive^{SM} probe vehicles data include:

- IntelliDrive^{SM} will enable to collect and send information from vehicles equipped with wireless communication devices. Communication will be possible through DSRC roadside communication units, cellular phones, or other wireless technologies.
- IntelliDrive^{SM} will allow using private and commercial fleet vehicles as probes. As the number of equipped vehicles will grow, there will be an increasing ability to monitor continuously traffic conditions on every link and intersection within a network. The collection of data from vehicles operated by ordinary drivers and fleet operators may better reflect true driving behavior than data collected from test vehicles commissioned for a specific purpose.
- IntelliDrive^{SM} systems will allow collecting vast amount of data in near real-time. While this is subject to the capability of the underlying communication infrastructure, it is expected that probe vehicle data will reach an application server in a reasonable interval to support real-time or near real-time operations.
- Probe vehicles cannot only be used to obtain traffic conditions surrounding the vehicle but also information about the status of onboard systems, such as wipers or headlights. Such information, which was not readily available in the past, could be used in many situations to help assess traffic and roadway conditions.
- It is expected that GPS positioning instruments are precise enough to allow the placement of vehicles on correct roadway links. While such a feature is not currently available with low-cost GPS instruments, it is expected that GPS devices with lane-precision accuracy will eventually become affordable for general use.
- While probe vehicle data collection systems are generally described with respect to envisioned default data collection protocols, transportation system managers will have the opportunity to set or change local data collection protocols to meet their specific data collection needs.
- Depending on operational set up, vehicle tracks may be obtained from probe vehicles. While currently recommended protocols impose some strict limits on the ability to track vehicles, full trip information may be obtained from travelers who opt-in on the data collection capability.
- While IntelliDrive^{SM} systems will initially act as a supplement to traditional traffic monitoring systems, increasing proportions of probe vehicles may gradually reduce, and even eliminate, the need to install and maintain fixed vehicle detectors.

9.4. Network Monitoring Data Sources

Until a full market penetration is reached, it can be expected that an enhanced traffic flow monitoring system will rely on a range of both traditional and emerging input data sources to assess network conditions. Typical data sources that may be considered include:

- Traffic snapshots and vehicle status data generated by probe vehicles, whether periodically, following stop and start events, or after the occurrence of special events.
- Vehicle-specific positioning data from Automatic Vehicle Location (AVL) systems used by transit agencies and commercial truck operators to track the movements of their fleets of vehicles.
- Vehicle detections from point detectors, whether from traditional loop detectors embedded in the pavement, roadside sensors, or video imaging processing systems.
- Truck detection and weight data from fixed and mobile weight stations.

- Weather data provided by RWIS and other weather information sources.
- Signal phasing and timing (SPAT) parameters from signalized intersections.

9.5. Network Evaluation Output Parameters

The enhanced traffic monitoring system should be able to provide basic network operational performance parameters to support MDOT's operations, safety, planning, and maintenance activities. As demonstrated in Section 7.7, many of the performance metrics used by MDOT applications can be derived from a relatively small set of key traffic flow monitoring parameters. The enhanced data monitoring system could therefore be tailored to produce at periodic intervals performance measures supporting various applications of interest. Aggregate measures should be produced at intervals correspond to analysis periods commonly used by system operators and traffic monitoring applications, such as every 5 min, 15 min and 60 min, as well as for each day. Estimated parameters should further be stored in a database to allow later uses by other processes and applications.

Typical evaluation parameters that should be produced by the traffic monitoring system for each analysis interval include:

- For each roadway link:
    - Average volume, by vehicle type
    - Average traffic speed, by vehicle type
    - Average travel time, by vehicle type
    - Link travel time variability (minimum, maximum, standard deviation)
    - Average speed profile, by vehicle type
    - Average flow density
    - Number of unusual events reported for the link (incidents, slippery road conditions, etc.)
- For each intersection/junction approach:
    - Average total approach volume, by vehicle type
    - Turn percentages, by vehicle type
    - Average number of stops, by turning movement
    - Average incurred delay per vehicle, by turning movement
    - Average queue length, by turning movement
    - Maximum queue reach
    - Average green signal saturation flow rate, if signalized intersection
    - Number of unusual events reported on the intersection approaches (incidents, slippery road conditions, etc.)
- For each intersection:
    - Average hourly volume, by vehicle type
    - Average number of stops
    - Average incurred delay per vehicle
    - Total number of unusual events reported around the intersection (incidents, slippery road conditions, etc.)
- For the overall network:
    - Vehicle-miles traveled (VMT), by vehicle type
    - Total reported delay
    - Total number of unusual events reported (incidents, slippery road conditions, etc.)

9.6. Traffic Monitoring Performance Metrics

Performance metrics for the enhanced traffic monitoring system are measures used to assess the efficiency of data collection and extent of network coverage. Similar to the output parameters characterizing network operations, these metrics should be compiled for all relevant intervals of interest and subsequently stored in a database to allow later retrieval.

Key performance metrics regarding the collection of IntelliDrive^{SM} data should include:

- Number of snapshots collected, by type and vehicle type
- Number of snapshots collected from each link, by type and vehicle type
- Proportion of snapshots rejected due to erroneous or incomplete data
- Number of links and intersections from which probe vehicle data were collected
- Number of usable vehicle traces successfully collected
- Average latency of snapshots collected, for each RSE and each link
- Proportion of IntelliDrive^{SM} vehicles in network, in an area or specific link

Key performance metrics regarding the operations of point vehicle detectors should include:

- Number of point detectors providing data, possibly characterized by type (for instance, inductive loop, roadside sensors, video imaging system)
- Number of detectors reporting malfunctions or reported to be not operational
- Number of links with data collection equipment

The proportion of IntelliDrive^{SM} vehicles can be used to assess the reliability of the information derived from probe vehicles. Performance measures derived from only a few snapshots will obviously carry much less reliability that measures based upon hundreds or thousands of snapshots. Since the proportion of IntelliDrive^{SM} vehicles on a specific link is likely to fluctuate from one moment to the next, particularly in early deployments, the primarily intent is to assess an average proportion of IntelliDrive^{SM} vehicles within an area, unless reliable estimates can be obtained on a link-by-link basis. Such a proportion can be obtained by comparing the number of vehicle detections made by point detectors at specific locations to the number of vehicles that are estimated to have passed the same locations using probe vehicle data. Since counts provided by point detectors or derived from probe vehicle data can both carry some errors, the goal is only to obtain a reasonable estimate that can be used to assess the overall reliability of the probe vehicle data.

The ability to obtain vehicle tracks directly affects the ability to estimate traffic movements at intersections, junctions and freeway ramps. Similar to the collection snapshots, the reliability of turn proportions and other statistics derived from vehicle tracks will increase with the ability to analyze a larger number of tracks. As outlined in Chapter 8, one of the main constraints for obtaining usable vehicle tracks are the rules imposed to safeguard the privacy of travelers, notably those requiring vehicles to change frequently their PSN. While these rules can be bypassed through opt-in services offered to travelers, they can significantly affect overall data collection. To evaluate data usability, usable vehicle tracks can be quantified by compiling the number of tracks including more than *n* snapshots. For the monitoring of traffic movements at intersections and junctions, a more relevant quantification may be the number of tracks including at least one snapshot upstream of the intersection and one snapshot downstream of the intersection.

Data latency is another important performance metric. In an ideal system, data should arrive at an application server with very little delay. However, as demonstrated in Section 6.8, probe vehicle data could arrive at an application server in an interval varying from a few seconds to several minutes. Furthermore, there could be significant variations in average latency from one RSE to next, also within the data collected by a given RSE. Other data sources may also exhibit some latency. Data with greater latency will obviously have reduced usefulness for real-time applications. However, such data may retain their full usefulness for applications relying only on offline analyses. Since latency may vary from one source to the next, from one location to the next within a given data source, as well as from one period to the next, it is therefore important to assess latency for all collected data supporting real-time and near real-time applications. This information will not only help assess the usability of each data, but also help determine whether operational improvements are warranted and where such improvements should be made.

9.7. General Data Processing Needs

A key feature of the envisioned enhanced traffic flow system is the ability to collect and process data from various sources to derive useful information supporting MDOT's operations, safety, planning and maintenance needs. As indicated in Section 9.5, many MDOT applications rely on performance metrics that can be derived from a relatively small set of key traffic monitoring parameters. To support these applications, the monitoring system could be tailored to calculate automatically the basic traffic performance metrics listed in Section 9.6 and to store the resulting metrics in a database accessible by applications and individuals who may need the information.

Figure 9-1 provides a high-level view of the basic data processing tasks that would be required to process data streaming in to a probe data server from various sources. While some differences exist depending on the source of data, most of the data stream processing needs involve the following tasks:

- **Data validation.** All collected data should be validated before being used to ensure that they are not the result of erroneous sensor readings. Data deemed invalid could be either discarded or stored in the database with an indication of its erroneous status. Any erroneous data should obviously not be used in the calculation of performance metrics.
- **Roadway link association.** The roadway links from which data has been collected should be identified to facilitate analyses focusing on specific roads or corridors. While data collected from point detectors can usually be traced to sensors installed on specific links, data provided by probe vehicles or AVL systems may only provide positioning data in the form of latitude and longitude coordinates. For these data, mapping software will need to be used to convert the coordinates into a specific link location. For links leading to or away from an intersection, the data processing could also include the identification of the intersection served by the link to facilitate intersection-based analyses.
- **Time binning.** To enable time-based analyses and the development of historical trends, all collected data need to be organized according to the time-of-day, day-of-week, day-of-month, month, and year it was collected.
- **Identification of usable vehicle traces.** Enhanced captured data can be processed and used to extract usable vehicle traces. This will most likely only apply to probe vehicle data, as data obtained from AVL sources are usually associated with specific vehicles.

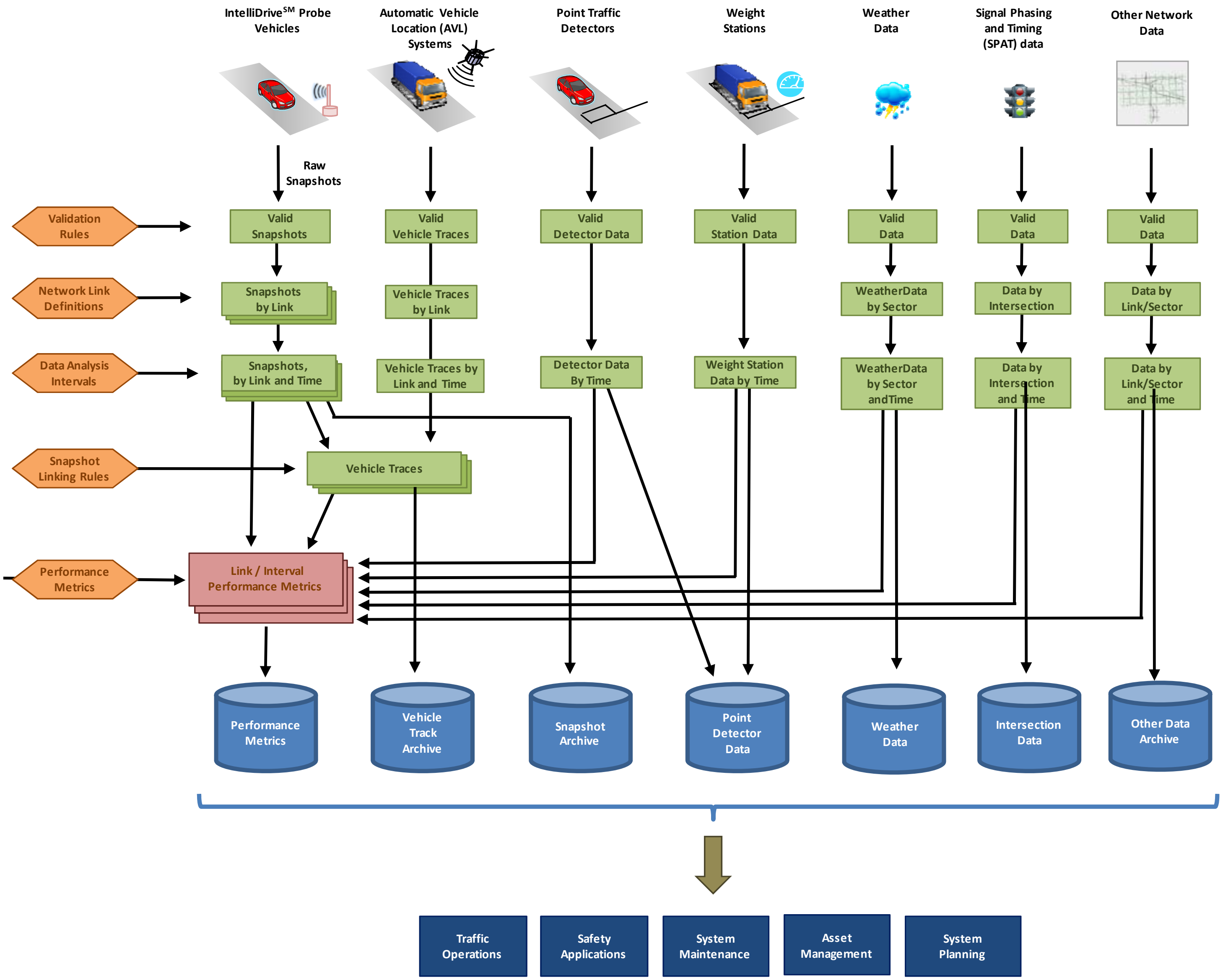


Figure 9-1 – Basic IntelliDrive^{SM} Probe Vehicle Data Processes

- **Calculation of basic performance metrics.** Following data validation, roadway link association, time binning and the identification of vehicle traces, various algorithms can be applied to the available data to extract basic traffic performance metrics and other metrics relevant to specific applications.
- **Data archival.** All collected data should be archived to enable later uses. This includes not only the archiving of the data supplied by the various sources connected to the data server, but also the archiving of the performance metrics derived from the data. To facilitate data usage, and to account for the fact that data from various sources may exhibit different attributes, attributes should be appended to each group of data to characterize its source.

9.8. Operational Scenarios

This section presents various operational scenarios demonstrating the value provided by an enhanced traffic monitoring system and illustrates how traffic-related information supporting various applications could be extracted from the raw data collected. The example scenarios presented include:

- Peak-hour Traffic Management
- Identification of incidents
- Identification of hazardous roadway conditions
- Monitoring of traffic conditions around work zones
- Annual highway performance reporting
- Evaluation of traffic flow patterns along a corridor

A few of these scenarios reprise and update examples that were initially presented in Mixon/Hill's DUAP Concept of Operations document (Mixon/Hill, 2007a).

9.8.1. Peak Hour Traffic Management

Every weekday, the traffic monitoring system at the Michigan ITS Center in Detroit monitors traffic conditions on freeways and primary trunk lines within the Metropolitan Detroit area and develops statistics to characterize the level of congestion on the roadways under surveillance. These statistics are then used by system operators to evaluate in real time unusual traffic conditions, the location of potential problems, and determine whether corrective actions are warranted. Transportation planners may later use the collected and derived data to assess the impacts of congestion on mobility, traffic demand patterns and trends. Finally, decision-makers may use information about congestion to prioritize projects, allocate funds, and develop pitches for additional funding.

The characterization of traffic congestion typically involves assessing travel speeds or travel times along specific roadway links. To derive this information, valid traffic snapshots are merged with speed measurements from traditional loop detectors and roadside sensors. Where available, data from commercial AVL vehicle tracking systems may also be used as supplementary sources. All collected information is compiled to produce an estimate of the observed average travel speed or travel time along each monitored roadway link. For links with observed average speeds are greater than the posted speed limit, the speed limit is used as the reference speed for the observed conditions. Travel delay estimates may also be estimated by comparing the observed travel time to a reference travel time, usually taken to correspond to travel at speed limit. Aggregate statistics covering major travel corridors, such as travel between major freeway interchanges or between a given location to the city center or airport, may also be produced by compiling traffic performance measures from a series of roadway links.

To characterize traffic conditions around signalized intersections under MDOT jurisdiction, the collected data is also processed to assess the average delay incurred by the vehicles traveling on each approach to the intersection and determine current queue reach.

Following the estimation of parameters characterizing current traffic flow conditions, this information is then compared to traffic conditions normally observed in periods of low traffic demand. Links with an average speed or travel time significantly lower than the speed-limit travel conditions, or with an estimated travel delay exceeding a given threshold, are then marked as experiencing congestion. A color-scheme or congestion level grading scale may be used to help visualize the location and severity of congestion hotspots. Links with significant congestion are then flagged on a map or displayed on a list to bring them to the attention of system operators on duty at the traffic operations center. The same information may also be displayed on the MI Drive website or forwarded to individuals responsible for the operation of changeable message signs to inform travelers about observed traffic conditions.

To further help identify unusual traffic conditions, i.e., conditions that are not expected given the time of day, the measured travel speeds or travel times within each sampling interval are also compared to travel speeds or travel times that were observed over the same interval on the same weekday during previous weeks. To help assess whether the observed patterns maybe be due to short-term or long-term effects, comparisons are made for data sampled every 5 min, 15 min, 30 min, or every hour. Travel speeds or travel times falling outside a typical variability range based on traffic conditions observed in the past few weeks would then be flagged and displayed on a screen with a special color or symbol to attract the attention of traffic system operators on duty.

At the end of each interval, all of the estimated traffic flow parameters are stored in a historical database, together with traffic flow counts, vehicle classification and other performance measures that may have been collected or derived to support system operations. All collected probe vehicle snapshots would also be archived. To facilitate data retrieval and use, all collected information is stored with a reference to the specific roadway link it pertains.

To assess the performance of the traffic monitoring system, various statistics are finally produced to enable system health checks and efficiency assessments. Examples of statistics produced include the number of snapshots collected, the average observed latency of data, the estimated proportion of probe vehicles within the network coverage area, and the number of operational or malfunctioning traffic detectors.

9.8.2. Identification of Incidents

This scenario involves a crash occurring during normal rush hour conditions with clear weather conditions. The incident occurs on the southbound segment of I-275/I-96 just north of 10 Mile, where a lane drops normally reduces the number of available lanes from five to four. It is assumed that the freeway segment is not being monitored by video surveillance but is equipped with traditional point traffic sensors sending speed data in real time to the MITS Center. The closest sensors are located about 0.5 mi upstream and 1.5 mi downstream of the incident.

The incident consists of a vehicle rear-ending another one following a sudden traffic slowdown, causing the air bags to deploy in the second vehicle. This incident results in the left two lanes of the freeway being blocked, leaving only two open lanes through which traffic from the five approaching lanes must go through. Immediately after the collisions, the vehicles traveling behind the two colliding vehicles initiate harsh braking maneuvers that causes the Antilock Brake Systems (ABS) of some vehicles to be activated. All approaching vehicles then gradually reduce their speed and attempt to merge to the right two lanes still open, resulting in turn signal activations, changes in steering wheel angle, wheel angle, heading, and further reduction in speed. The lane blockage and resulting merging behavior eventually creates a queue of slow moving vehicles that reaches the location of the upstream traffic sensor 50 seconds after the incident has occurred.

During the incident, the probe vehicles within the traffic stream acquire a mix of periodic snapshots and vehicle event data. The collected data include the position of each vehicle, its current speed, its heading, the steering wheel angle, and the vehicle's longitudinal acceleration. Information indicating brake, ABS and turn signal activations may also be included in the periodic snapshots collected or recorded within special vehicle event snapshots. This data reaches on average the DUAP application server at the MITSC 60 seconds after being generated.

In addition to the snapshot and sensor data, numerous individuals call 911 shortly after the incident occurs. This allows a general description of the event and its location to be picked up by local emergency services. An incident notification from emergency services is then received at the MITSC approximately 60 seconds after the incident is first called in.

While the above events occur, the enhanced DUAP traffic monitoring system would keep processing snapshots and sensor data streaming as it normally does. The data would be sorted by link and time and used to calculate various traffic performance measures. Various possibilities then exist for the system to determine that an incident may have occurred. An incident could be assumed to exist based on the following observations:

- Observation of specific change patterns in the speed and flow data reported by the traffic sensors located immediately upstream and downstream of the incident.
- Snapshots recording vehicle speeds significantly lower than the speeds typically observed in normal traffic conditions over the same period.
- Snapshots indicating usual patterns of deceleration and acceleration.
- Snapshots indicating a high frequency of brake activations in a narrow section of freeway.
- Snapshots indicating ABS activations.
- Usual frequency of lane changes, as evidenced by a higher than usual number of snapshots reporting turn signal activations or steering wheel angles and headings consistent with lane-changing behavior.

Following the detection of a possible incident, the information would be reported to system operators to allow its verification and to initiate response measures if necessary. To help with the verification and the development of an adequate response, the following information could be provided:

- Incident location. Changes in data reported by point vehicle sensors may allow locating the incident between two specific sensors. ABS and brake activations, steering wheel angle, vehicle heading, and vehicle position data recorded within probe vehicle snapshots could further be used to pinpoint a more exact incident location.

- Number of lanes closed / significance of incident. If lane-precision position accuracy is available, the number of lanes closed could be determined by determining the number of lanes from which vehicles still generate snapshots with speeds above a certain threshold around the incident.

- Queue length. The extent of the congestion generated by the incident could be determined by tracking where stop event snapshots are generated. The location of periodic snapshots recording brake application, ABS activation, or an observed vehicle speed below a certain threshold could also be monitored.
- Traffic delay. The average time required to pass the incident could be estimated by using the vehicle speeds recorded within individual snapshots to construct a speed profile from which a typical travel time could be estimated. If probe vehicles have the capability of generating sequences of snapshots with an identical vehicle identifier for periods of several minutes, inquiries could also be made to determine if some vehicles have generated sequences of snapshots covering travel through the incident location. If such traces exist, they could be used to determine the time taken by individual vehicles to reach the incident from a given location and to estimate travel time variability through the incident area. If available, link exit snapshots recording the time taken by vehicles to travel along individual roadway links could also be used to assess the time to reach and pass the incident.

After an incident has been verified, the information characterizing the incident would be distributed to relevant system operators, law enforcement, and emergency services. Operators would also create messages to display on variable signs at strategic locations within the roadway network. Request to deploy portable changeable message signs may also be issued to provide critical information to motorists at locations without permanent signs. Information characterizing the incident would also be inputted into the MI Drive website and be made available for use by private information service providers.

The event would be deemed resolved after emergency services would have cleared the incident from all traffic lanes and reopened them. From a traffic management perspective, the event would be closed when performance conditions reported by data streaming from vehicle sensors and probe vehicles would indicate that traffic flows have been restored to pre-incident levels.

After closing the incident, a record of the incident would be logged in the DUAP archive. Information characterizing the time, location and duration of the incident would be recorded. Information characterizing the surrounding traffic conditions immediately before and during the incident would also be stored, if available, as well as records of decisions taken to resolve the incident and to manage traffic around the incident. The incident information would finally be sent to the individuals responsible for producing the Michigan State Police's UD-10 Incident Form that is to be logged in MDOT's Traffic Management System.

9.8.3. Detection of Hazardous Roadway Conditions

An unexpected early spring storm has brought a mix of rain, sleet, and snow over southeast Michigan. The ground is still largely frozen from winter, and air temperatures are hovering just above freezing. Conditions worsen through the day, and forecasts are now predicting intense precipitations to occur during the evening rush hour. Pretreatment options are limited because of the rain, as any chemicals applied to the road surface would be wasted. In addition, forecasts are not clear on what form the precipitation will take (rain, sleet, or snow) at any particular location. Conditions are particularly problematic on road segments near any of the larger lakes as lake effect could intensify quickly snow precipitations. From an operational standpoint, MDOT and county maintenance crews will have to depend on near real-time data routed through the maintenance dispatcher to prioritize treatment beyond their planned routes.

In this scenario, probe vehicles could provide valuable operational support by providing direct and indirect indications of weather and pavement surface conditions across the road network. These observations could be obtained from weather-related sensors installed on vehicles. Since some of this information is available on the vehicle's control network, it could easily be packaged into probe vehicle snapshots or recorded in weather-specific event messages and sent to the DUAP data server. Weather-related parameters that are potentially available include:

- Ambient air temperature
- Atmospheric pressure
- Windshield wiper setting
- Rain sensor status
- Fog light status
- Headlight status
- Sun sensor status
- Brake status
- ABS actuation
- Traction control system actuation
- Stability control system actuation

In addition to data from probe vehicles, the DUAP server collects data from SEMSIM-equipped maintenance vehicles that have been sent out throughout the area to monitoring road conditions. Sensors installed onboard these vehicles typically include a GPS tracking device, an air temperature sensor, an infrared pavement temperature sensor, sensors indicating whether the front and underbelly plows are up or down, and sensors monitoring the operation of salt spreading equipment. Data is collected by accessing the SEMSIM operational server, where it is streaming in real time.

In addition to probe vehicle data, weather data from fixed environmental stations deployed throughout the region are also collected. Some of these stations were deployed to address local weather related issues, such as bridge icing, low visibility due to fog or intense precipitation, flooding, with some stations providing direct road surface condition monitoring. Others were mainly installed to supplement regional atmospheric observations from the National Oceanic & Atmospheric Administration (NOAA), the Michigan Department of Natural Resources (DNR), and other agencies concerned with generalized weather observation and forecasting. All the data collected from weather stations is aggregated by the DUAP system and used to create a consistent set of weather observations. Impacts on traffic conditions are then assessed by correlating the weather observations with traffic observations from probe vehicles and traffic sensors. As an example, air temperature change and relative humidity, headlight state, and observed vehicle speed changes might indicate fog development In another example, headlight state (off/low beam/high beam), windshield wiper settings, and vehicle speed changes could be used to indicate the presence of precipitation.

Once these direct and correlated observations are available, watch points and thresholds on key weather condition measures can be set to notify traffic operations and maintenance personnel when specific conditions develop. Weather information messages may also be created for posting on changeable message signs and traveler information outlets. Real-time weather risk maps could further be generated to support the dispatch of traffic control personnel, emergency management services, and courtesy patrols to the highest priority locations. Based on the developed correlations, the DUAP system may also send notices to traffic information subscribers via email, pager, or instant messaging whenever particular watch parameters are exceeding certain thresholds.

Among automated system interfaces, traffic management systems across the region could be provided with weather and road condition reports to overlay on network maps. SEMSIM could use the information to develop faster and more granular updates on the condition of specific road segments and combine this information with a maintenance decision support system to dynamically update and optimize treatment plans. In response to these notifications, the MITS Center would be enabled to provide information on specific weather hazards (e.g., icing, flooding) just as it provides information on other traffic events. SEMSIM could then improve deployment of vehicles to prioritized maintenance needs, change treatment and plowing routes dynamically, monitor segments that are temporarily inaccessible or cannot otherwise be monitored, and allow for more accurate treatment analysis and deployment, thereby reducing costs.

RCOC's FAST-TRAC system could further get requests for altering traffic signal timing plans at intersection under its control to facilitate mobility on snow routes or to try to alleviate the congestion resulting from the weather event. The information could be used to create true emergency snow routes, reroute traffic to predetermined high-priority roadways, or dynamically adjust signal timings to redistribute traffic flows based on real-time roadway conditions.

9.8.4. Monitoring of Traffic Conditions around Work Zones

A work zone is going up along I-96 in Lansing. This work zone is scheduled to close one lane in the eastbound direction and to impose a speed of 45 mph when workers are present instead of the normal 70 mph posted speed limit. To minimize impacts on the morning peak-hour traffic, it is required that the work zone becomes active only after 9:00 AM. However, it is also suggested that adjustments to the proposed work schedule could be altered depending on observed traffic conditions. For instance, work could be allowed to start earlier if traffic is unusually light. Conversely, the start of work authorization could be delayed if a significant traffic buildup develops. Temporary work stop orders could further be issued if significant traffic delays occur due to the work zone activities.

To monitor traffic conditions around the work zone, MDOT staff monitors in real time the traffic snapshots streaming in from probe vehicles. Of particular interest are the recorded speeds and the location where these speeds were observed. This information could help determine when the construction activities start and end each day, traffic behavior within and upstream of the work zone, the effectiveness of traffic management plans, whether the implemented traffic management plans should be modified, and help support speed limit enforcement.

The start of construction activities could be determined by monitoring when vehicle speeds drop around the work zone. As activity starts, many vehicles will slow down is direct response to the lower posted speed limit. Other vehicles may also slow down due to the distractions introduced by the construction work. Conversely, the time that construction activities cease could be determined by monitoring when traffic speeds start to increase near the scheduled end of the work zone.

To support speed enforcement, the collected snapshots could be processed to determine the proportion of vehicles traveling at speeds significantly greater than 45 mph. If this proportion exceeds a given threshold, a notification message could then be sent to the Michigan State Police to request that a police cruiser be sent upstream of the work zone to entice motorists to slow down and issue citations if necessary. If the observed speeds remain too high after a few attempts, alternative traffic control measures could then be implemented to entice drivers to slow down. If the ability exists to identify vehicle types from the collected snapshot, it would be further possible to assess whether passenger cars and trucks travel at different speeds within the work zone when not constrained by other vehicles. This information could then be used to develop targeted speed reduction solutions, such as instructing police officers to pay particular attention to trucks or passenger cars only.

The vehicle speed recorded within individual snapshots would also allow monitoring the queue that may develop upstream of the work zone. Vehicles slowing down to join a queue could be identified by flagging snapshots with recorded speeds below a certain threshold. The presence of a queue forcing vehicles to stop could further be determined by looking for stop and start event snapshots. The extent of the queue would correspond to the farthest upstream location where consistent speed reductions, stop/start event snapshots, or snapshots recording brake applications are observed. If very long queues develop during the scheduled work period, a temporary work suspension could then be ordered to allow the congestion to reduce. Similarly, if shorter than expected queues are produced, an authorization could then be granted to start work earlier or to end it later in the day.

In addition to locating the upstream end of a queue, the probe vehicle data could help assess traffic behavior on the approach to the work zone. If the snapshot positioning data is accurate enough to place vehicles on specific lanes, the collected snapshots could be used to determine where traffic typically merges ahead of the work zone. Data recording brake application or turn signal activation could also indicate intent to change lane. The behavioral information derived from the collected snapshots could then be used to assess whether the approach plan should be modified, for instance, to entice merging closer to the work zone and reduce the potential reach of queues developing because of the work zone.

Finally, to help inform travelers about traffic conditions around the work zone, efforts would be made to assess typical travel times across the work zone. Average travel times could be derived from the vehicle speeds recorded within snapshots generated within and upstream of the work zone. Inquiries could also be made if vehicle traces covering the entire length of the work zone exist, or whether traces covering either the approach zone or the work zone itself exist. If such traces exist, they could then be used to determine the time taken by individual vehicles to travel from a given upstream point to the end of the work zone, assess average travel times, and determine travel time reliability.

9.8.5. Annual Highway Performance Reporting

Every year, state departments of transportation must submit a report to the federal government reflecting the extent, condition, performance, use, and operating characteristics of the primary road network within their jursidiction. This report, known as the Highway Performance Monitoring System (HPMS) report, is used for determining the amount of federal funding that each state will receive. Information contained within this report includes the number of road segments within the state and detailed segment attributes for a sample of road segments. For each segment, the Annual Average Daily Traffic (AADT) volume must be provided. The AADT is then converted into Vehicle-Miles Traveled (VMT) by multiplying it by the length of the corresponding road segment. The VMT for all the sample links are then summed up to obtain an estimate of the total amount of traffic occurring in the state.

Various techniques currently exist to estimate the AADT of a given link. For links where a permanent traffic detection station is located, the AADT can be estimated by compiling the number of vehicles detected throughout the year and dividing this total by 365 days (FHWA, 2001). However, this method only works if traffic sensors operate continuously and normally throughout the year. Another approach consists in averaging the daily traffic counts for each of the 12 months of the year and reporting the AADT as the average of all the monthly averages.

For links without permanent traffic counters, AADT are typically estimated using short traffic counts. These counts use portable traffic sensors, typically pneumatic tube sensors, temporarily attached to the road to record the number of vehicles passing at a given location over a period of 2-3 days covering typical weekday traffic patterns. Within Michigan, this data is collected by county road commissions and local transportation agencies in collaboration with MDOT. After completion of the short counts, the vehicle detections are compiled to produce an Average Daily Traffic (ADT) flow measure. This measure is then assumed to correspond to the average traffic that would be observed on the link for the month during which the data collection took place. To account for the fact that traffic volumes vary from month to month due to seasonal effects, adjustment factors are then applied to convert the monthly ADT to an average annual ADT, or AADT.

Due to the efforts involved in collecting traffic data from all roadway links in a state, short traffic counts are typically conducted once every three years for each link. For years during which a traffic count is not executed, the AADT is estimated by applying a growth factor to the latest available count. This growth factor is determined either by analyzing historical data from the same segment or by comparing changes in traffic volumes on nearby roadway links with permanent traffic detectors.

To supplement traditional data collection activities, the database storing probe vehicle data could be accessed to obtain some of the information required for the HPMS report. A key enabling element will be the ability to estimate proportion of probe vehicles within the overall traffic. This proportion could be estimated by comparing vehicle counts derived from collected snapshots to counts provided by traffic sensors. From a statistical standard, the accuracy of the statistics derived from probe vehicle data will increase with greater proportions of reporting vehicles. For links with a sufficient proportion of probe vehicles, the following analyses could be executed to support HPMS reporting activities:

- The monthly adjustment factors used to convert the ADTs derived from short traffic counts into AADTs can be estimated by compiling the number of snapshots collected for each day of the year. If the proportion of probe vehicles remains constant or only gradually change over the year, higher traffic volumes would then normally translate into higher numbers of collected snapshots. For links which adequate data sampling, approximate monthly adjustment factors could then be estimated by comparing the number of snapshots collected during each month. These calculations could be done for each link, which would allow replacing the regional average monthly adjustment factors that are currently commonly used.
- Traffic count estimates could be obtained for links without permanent traffic sensors by determining the number of probe vehicles sending information from the link and then adjusting this number to account for proportion of probe vehicles traveling on the link or in its area. Since this estimation approach carries some uncertainty, particularly with very low market penetration, it can initially only be used to validate or verify AADTs obtained through other approximation methods, such as through the application of growth factors. With increasing proportions of probe vehicles, the increased reliability of the estimates would eventually allow statistics derived from probe vehicle data to replace short traffic counts.
- VMT estimates could be produced by using the assumed snapshot interval to calculate an equivalent traveled distance for each collected snapshot. For instance, if snapshots are typically generated every 4 s, the vehicle speed recorded within each snapshot could then be used to approximate the distance traveled by the generating vehicle during 4 s. The total traveled distance obtained by processing all collected snapshots could then be adjusted by the assumed

proportion of probe vehicles to obtain an overall VMT. As with other probe-based statistics, the accuracy of estimations will typically increase with increasing proportions of probe vehicles.

- Passenger car and truck AADTS could finally be obtained by repeating the above analyses using only snapshots generated by specific vehicle types. .

In this scenario, the enhanced traffic data monitoring system will provide an opportunity to obtain information from every link in a network on a continuous basis. As the number of probe vehicles increases, statistics from an increasing number of links could be derived remotely, thus gradually decreasing need to send crews to conduct short-term traffic counts or other data collection activities. Some counts may, however, still be executed to use as control or validation samples.

9.8.6. Evaluation of Traffic Flow Patterns along a Corridor

To evaluate a proposed expansion of I-75 in Detroit, it was decided to build a simulation model of the section of freeway to be expanded. To build an accurate representation of local traffic patterns, information where vehicles enter and exit the freeway is needed to produce origin-destination flow matrices for a typical weekday morning peak period. Two matrices must be produced, one to characterize passenger car traffic and one for truck traffic. To represent adequately potential congestion buildup, it is also desired to develop 5-min traffic release patterns that would reflect the gradual rise and decrease of traffic demand that normally occurs in the morning.

To develop the traffic demand model, MDOT staff first collects traffic counts from permanent traffic detection stations within or near the corridor. The counts are then aggregated into 5-min intervals to produce a temporal traffic demand profile. The staff then accesses the database storing vehicle traces extracted from collected probe vehicle data to see if usable traces are available. In this case, usable traces are be those allowing determining the points of entry and exit of a particular vehicle along the freeway. The availability of such traces will depend on the protocols imposed to protect traveler privacy and whether individual travelers have allowed their vehicle to be tracked beyond what is allowed by the default protocols through opt-in agreements. If the vehicle traces are not automatically extracted, the individual snapshots stored could also be processed. In this case, trip origins and destinations will be determined by attempting to match snapshots with identical Probe Segment Numbers (PSNs) or other vehicle identification attributes, if available.

To develop accurate representations of flow rates across each pair of origin and destination data, MDOT staff would then compare the number of vehicles that produced snapshots from locations where vehicle counts from traffic sensors or short-counts efforts are available. From these comparisons, an average proportion of probe vehicles along the freeway would be determined and used to convert the origin-destination flow rates derived from probe vehicle data into overall origin-destination flow rates. To produce truck-specific flow rates, the above analysis would then be repeated by considering only information supplied by or pertaining to trucks..

9.9. Deployment Strategy

Unlike many IntelliDrive^{SM} applications, an enhanced traffic monitoring system does not require a large market penetration level before benefits can be obtained. While higher proportions of probe vehicles are expected to generate greater benefits, small market penetrations may still generate noticeable benefits. This is in great part because probe vehicle data can be used to complement existing traffic monitoring capabilities. This allows building a DUAP application server that could initially only processes data from exist monitoring system but that will have the capability to absorb data supplied by an ever increasing number of probe vehicles.

A critical factor that will affect an eventual deployment strategy is the type of communication used to retrieve data from probe vehicles. While the initial Vehicle-Infrastructure Integration concepts focused on the use of roadside communication units implementing DSRC standards, the currently envisioned IntelliDrive^{SM} system opens the field to any type of wireless technology. Following the rapid development of cellular communication capabilities, an increasingly discussed possibility is to use cellular phones to collect data that may not be time critical, such as traffic snapshots, and restrict the use of DSRC roadside units to support safety applications. Cellular phones may for instance be used to collect vehicle speed and position without additional instrumentation. However, connection with vehicle systems is required to collect data characterizing the status of onboard vehicle systems. Ideally, the methods of communication associated with each application should be established before initiating their development. However, because these methods are likely to keep evolving, it may still be best to try to deploy data collection systems that will have the capability to handle data streaming in from various communication modes.

To ensure success, initial deployment activities should focus on the development of an application server capable of handing the data processing loads and storage needs expected to be produced by early applications. As new data sources would become available, the server would then be updated to allow it to process the increased data processing and storage needs. Periodic system updates should also be made as the proportion of probe vehicles increases to allow it to process adequately the increased volume of data streaming in. Periodic revisions may also be made to the data processing algorithms and supporting software to ensure that they remain efficient, retain a capability to extract accurate and reliable information from collected data, and remain compatible with the latest technologies.

9.10. Summary of Impacts

The introduction of IntelliDrive^{SM} systems will not require the replacement of existing traffic monitoring systems. Since the provided data will initially be complementary to data provided by existing traffic monitoring systems, this will allow IntelliDrive^{SM} data collection and processing capabilities to be gradually built in parallel to existing systems. However, the availability of new data collection capabilities could have the following general impacts on MDOT operations:

- Probe vehicle data will expand significantly traffic and roadway monitoring capability. Instead of relying only on a relatively limited number of point detectors and periodic data collection efforts, data could eventually be collected on a continuous basis from every road in a network without requiring the installation of sensing equipment on each road.
- Increased data collection will enable better assessments of traffic and network conditions. These improved assessments may in turn lead to better allocations of available resources to support transportation system operations and management activities.
- The availability of a richer dataset will expand system analysis capabilities. For instance, the ability to collect trip origin-destination data may allow MDOT personnel to develop improved regional travel demand patterns. The ability to track vehicles over certain distances may also allow better characterizations of traffic flow patterns along corridors or around intersections. Data characterizing various vehicle system events will further provide additional analysis

capability to determine the causes of recurrent or unexpected congestion and help determining potential solutions to these problems.

- The ability to collect data in near real-time will allow personnel in traffic operation centers to better manage day-to-day traffic and other operations, as well as better respond to unexpected events, such as incidents and weather storms. The combined ability to track network conditions in near real-time and to access historical data may further enable the development of more proactive event management strategies.
- Until a full IntelliDrive^{SM} deployment is achieved, a need will still exist to install temporary traffic detectors or send survey crews to locations from where large samplings of vehicles are needed. However, probe vehicle data may reduce the need for such data collection efforts or reduce their extent, particularly for studies only requiring relatively small samples. This could reduce data collection staffing needs and translate into significant cost savings.
- The reliance on a multitude of vehicles and a variety of data sources to collect needed information will reduce problems caused by sensor malfunction. At most locations, traffic information is currently only available as long as the pavement or roadside sensors remain operational. However, these sensors, particularly those installed in the pavement, have a high occurrence of failure. When a detector fails, there is no data collected, resulting in a blind spot that could last for days, weeks or months. By allowing individual vehicles and other sensor networks to collect data, the likelihood that data pertaining to a certain link be completely lost is significantly reduced. Even if a roadside communication unit fails, the data could still be collected by other units or sent through alternate wireless communication methods.
- The collection of data from probe vehicles operated by private individuals and commercial fleet operators, as well as from alternate sources, can increase data collection significantly at a relatively low cost.
- The expanded monitoring capabilities will not require all existing MDOT operating procedures to change. While some enhancements could lead to some procedural changes, others could simply result in extending the geographical or operational reach of existing operations.
- Because of the expected large amount of data to be collected on a continuous basis, a greater emphasis will need to be put on data management to avoid overloading the data collection system and to ensure that all collected data is properly handled. This includes the development of appropriate data validation and storage protocols.
- New data retrieval and processing systems will likely need to be developed to allow the merging of data streaming from different sources and to allow applications to access and use data stored in various archival systems, particularly if the data is to support real-time operations.
- Contrary to existing systems, which typically handle the same volumes of data throughout their life, IntelliDrive^{SM} are likely to provide an increasing amount of data as system deployment progresses. This will require the development of strategies to review periodically the adequacy and effectiveness of existing data processing algorithms.
- The increasing reliance on complex communication and data processing technologies will require MDOT to collaborate more closely with other government agencies, notably the Michigan Department of Information Technologies (MDIT), as well as potentially with external service and technology providers.

- The reliance on data collected by external private enterprise will require the development of close working collaborations with these enterprises, particularly if it is eventually desired that these enterprises address potential data quality concerns.

Below is a summary of the potential benefits that can be expected from the above impacts:

- Improved ability to monitor travel speeds and queues along roadways
- Ability to collect various data in near real-time
- Ability to collect data from every road vehicles travel
- New ability to collect data characterizing the operations of various onboard vehicle systems
- Improved ability to assess traffic volumes and traffic density along roadways
- Improved ability to detect incidents, identify their cause, and monitor their impacts on traffic
- New ability to collect information about lane changes and vehicle movements along roadways and at intersections
- Improved ability to monitor truck flows and truck weights across the network
- Improved ability to monitor traffic conditions at intersections and to collect data that may be used to develop signal-timing plans
- Improved ability to monitor traffic conditions around work zones
- Improved ability to collect data to assess the useful life of pavement and bridges
- Improved ability to obtain trip origin-destination data, if travelers allow this information to be collected, and develop regional and local travel demand patterns
- Improved ability to communicate detailed travel information to travelers and support trip routing applications
- Improve ability to respond to incidents and emergency events
- Improve ability to monitor weather events and plan responses to such events
- Potential ability to reduce incidents through improved network condition assessment
- Reduced data collection costs

Potential factors that could affect the impacts and benefits derived from an enhanced traffic monitoring system include:

- **Limited data collection**, particularly in early deployment stages.
- **Data collection restrictions** imposed by regulations designed to protect traveler privacy.
- **Insufficient data processing and storage capacity.** Capacity problems can develop as IntelliDrive^{SM} systems are deployed. While initial design may consider some expected data processing loads, these needs can change as new technologies and applications are developed. Similarly, vehicles with inadequate data storage capacity may cause significant data losses.
- **Inadequate communication system.** The ability to use collected data to support real-time operations depends heavily on the ability to carry data effectively from their source to the application server.
- **Outdated data processing algorithms.** As the quantity of data collected increases, some of the algorithms used to process the data may need to be recalibrated to account for the availability of new or more reliable information. Some algorithms may also become irrelevant, while new issues may create a need to develop new algorithms.

- **Outdated interfaces.** Standards or external systems may change over time. If the data processing systems are not updated following some changes, some system functionality could be lost.
- **Inadequate staff.** The heavy reliance of the system on data processing, communication and archiving creates a need for using staff having appropriate knowledge of communication functions, computer operations, and data handling procedures. Operational delays and inefficiencies could then ensue if staff with proper training is not available.

10. Deployment Issues

This chapter discusses issues that may impact the deployment of new applications and when such applications may start to yield benefits. The discussions include:

- Market penetration constraints
- Data latency constraints
- Privacy constraints
- Need for onboard equipment
- Requirement for viable application business models

10.1. Market Penetration Constraints

All envisioned IntelliDrive^{SM} applications rely on the eventual ability to communicate with a large number of vehicles, either to retrieve information from them or send data back to them. For many applications, appropriate instrumentation must be deployed onboard a sufficiently large fleet of vehicles before they could become effective and beneficial.

How many vehicles need to be equipped depends on the application considered. For instance, an application aiming to use data collected from probe vehicles to detect cracks and potholes on the roadway surface will not require that all vehicles traveling on the segments of road of interest be equipped with data collection and communication instruments. Benefits could be obtained by with only a few vehicles providing data, such as specially instrumented service vehicles owned by a transportation agency. On the other hand, applications aiming to characterize travel speeds along road segments will require collecting data from a sufficiently large number of vehicles to ensure that statistically valid estimates of average travel conditions can be obtained. While data collected from a few vehicles could help assess prevailing traffic conditions, small data samples offer no guarantee than the captured data truly represent average traffic behavior and create a potential to provide applications with faulty information.

Most applications will not require collecting data from all vehicles. As an example, the investigations reported in Chapter 8 indicated that reasonably reliable average travel time estimates along signalized urban arterial segments could be produced by sampling only 5 to 10 % of vehicles traveling along the arterial when traffic conditions are relatively stable. Parameters exhibiting higher underlying variability, such as estimates of the average control delay incurred or number of stops made by vehicles on an intersection approach, may however require higher sampling requirements to reach certain statistical accuracy.

Table 10-1 lists the applications of interest to departments of transportation and the estimated level of market penetration required for them to be effective. Given the difficulty of estimating precisely the fleet requirements, the penetration requirements are only categorized in terms of "low", "medium" and "high. Applications with low requirements are those expected to require just a few equipped vehicles. Medium-level applications are those requiring between 10 and 50% of all vehicles to be equipped to operate properly, while high-level applications are those assumed to require more than half of vehicles to be equipped.

Table 10-1 – Application Maximum Data Latency Constraints

No.	Application	Description	Market share requirement for initial benefits	Acceptable latency
Network flow monitoring				
1	General traffic flow monitoring	Monitor traffic on freeway and arterials to measure flow efficiency; use of collected data to profile normal and abnormal traffic patterns and bottlenecks; analysis of archived data to identify	**Low** - Valuable data may be collected from small fleets	1-5 min / Not time critical is used for offline analysis
2	Detection of unusual congestion	Monitor traffic flow and report abnormal situations and disruptions.	**Low** - Valuable data may be collected from small fleets	1-2 min / Not time critical is used for offline analysis
3	Incident detection and response monitoring	Monitor and detect incident formation, duration and clearance intervals, capturing causal factors (via visual data) where possible.	**Low** - Valuable data may be collected from small fleets	10-60 sec / Not time critical is used for offline analysis
4	Monitoring of traffic around work zones	Evaluate work zone traffic flows and identify differences from planned flow.	**Low** - Valuable data may be collected from small fleets	1-5 min / Not time critical is used for offline analysis
5	Monitoring of weather impacts on traffic	Monitor weather conditions and detect impact on road conditions and traffic flows. Report current situation and abnormalities to	**Low** - Valuable data may be collected from small fleets	1-2 min / Not time critical is used for offline analysis
	Detection of icy/snowy/wet roads	Monitor weather conditions and correlate to vehicle data to determine if slippery roads conditions exist; Clarus, SEMSIM and MDSS are example programs.	**Low** - Valuable data may be collected from small fleets	1-2 min
Network operations				
6	Special event planning and management	Plan and schedule special actions necessary to minimize impact on traffic of special events.	**Medium** - Requires fairly detailed traffic demand information	1-2 min / Not time critical is used for offline analysis
7	Management of arterial / freeway corridors	Optimize traffic flow on freeway and arterial corridors by monitoring flow and adjusting signals and VMS messages as required.	**Medium** - Requires reasonably accurate information about traffic	1-5 min / Not time critical is used for offline analysis
8	Traffic signal operations	Use traffic flow data to assess adequacy of existing signal timing plans and develop new plans when necessary	**High** - Requires collecting data from most vehicles	1 - 2 sec if used for online control/ Not time critical is used
9	Priority traffic signal phasing to transit and emergency vehicles	Use vehicle presence/tracking data to provide preferential treatment to transit and/or emergency vehicles at signalized intersections.	**Low** - Only requires communication from transit and emergency vehicles	1 - 2 sec
10	Operation of ramp meters	Use information about gap between vehicles on freeway to optimize the release of entering vehicle from ramps.	**High** - Requires monitoring gaps between vehicles	1 - 2 sec
11	VMT-based fee collection	Use vehicle tracking data to assess mile-based usage fees along DOT-controlled roads.	**High** - Requires data collection from all vehicles	Not time critical
12	Toll collection	Use vehicle tracking data to assess and collect tolls from toll roads, toll bridges and high-occupancy toll (HOT) lanes.	**High** - Requires data collection from all vehicles using toll road	1 -2 sec / Not time critical if post-payment is allowed
13	Congestion pricing	Use vehicle tracking data to assess fees associated with traveling on a congested link or area	**Medium** - Requires accurate information about traffic conditions	1-60 sec / Not time critical if post-payment is allowed
14	Evacuation planning and management	Emergency evacuation policies, practices and procedures designed to maximize quick evacuations where needed.	**Medium** - Requires fairly detailed traffic demand information	1-2 min
Traveler information services				
15	Management of variable message signs	Management of messages given to the driving public through roadside variable message signs.	**Low** - Valuable data may be collected from small fleets	1-2 min
	Traffic flow information to websites	Aggregated traffic flow information provided to web servers and 511 services to inform drivers of traffic flow conditions.	**Low** - Valuable data may be collected from small fleets	1-5 min
System Planning				
16	Estimation of traffic flow patterns	Collect O-D for transportation planning purposes and congestion management optimization applications.	**Medium** - Requires information from sufficient trip samples	Not time critical
17	Transportation system modeling	Development of models to simulate traffic flows and execute traffic demand studies using collected and archived traffic data to evaluate network system performance and needs.	**Low to medium** - Requires information from sufficient trip samples	Not time critical
18	System needs assessment	Use of traffic flow and vehicle data to identify location of recurring bottlenecks and roadways with possible safety issues	**Medium** - Requires information from sufficient trip samples	Not time critical
19	Air quality assessment	Collect air quality data from vehicles and traffic volume to monitor and assess air quality changes.	**Medium** - Requires information from sufficient trip samples	Not time critical
Truck				
20	Hazardous cargo notification	Monitor and track hazardous material movements through a road network.	**Low** - Only requires hazmat trucks to be tracked	1-5 min
21	Commercial vehicle safety Inspection	Monitor heavy truck safety conditions by inspections using non-intrusive wireless technologies.	**Low** - Does not require all trucks to be initally equipped	1-2 sec
22	Commercial vehicle electronic weight inspection	Weigh-in-motion roadside equipment to monitor vehicles for excessive axle loading.	**Low** - Does not require all trucks to be initially equipped	1-2 sec
Asset Management				
23	Management of salt and snow plow equipment	Salt and snow plow equipment scheduling by monitoring road conditions and deploying appropriately; e.g., MDSS, SEMSIM.	**Low** - Only requires service vehicles	1-5 min
24	DOT vehicle tracking and work-order management	Track maintenance equipment to manage logistics and use scheduling.	**Low** - Only requires vehicles to be tracked	5-60 min
25	Pavement pothole/crack detection and mapping	Monitor and report road surface conditions using vehicle sensing while traversing road network.	**Low** - Only requires survey vehicles	Not time critical
26	Bridge deck monitoring	Instrumentation of bridge structutures to monitor loading, stress and deteriotion.	**Low** - Only requires survey vehicles	Not time critical
27	Sign inventory	Monitor roadside signage conditions and placement by special vehicle mounted cameras.	**Low** - Only requires survey vehicles	Not time critical

When this report was written, there was still significant uncertainty regarding how IntelliDrive^{SM} systems would be deployed. Approaches ranged from mandating that all new vehicles starting with a given model year be equipped with IntelliDrive^{SM} units to simply allowing individuals to purchasing after-market devices or options on new vehicles. These various approaches result in a wide range of potential deployment scenarios that make it difficult to predict exactly when specific market penetration levels would be reached. As an example, Figure 10-1 illustrates projections from a recent study by Noblis that was conducted to support the deployment of IntelliDrive^{SM} vehicle safety applications (Chang, 2010). This study assumes that OBEs would become available in 2015 and explores various deployment alternatives. As can be observed, a wide of variety of outcomes result from scenarios considered. The most aggressive scenario, which involves mandated OBE deployment in new vehicles starting in 2017 and the concurrent ability to retrofit older vehicles, results in attaining a 10% penetration based on vehicle miles traveled in 2018, a 50% penetration in 2022, and a full deployment in 2030. The least aggressive scenario, which involves a weak consumer market in which individuals either purchase the OBEs as options on new vehicles or as retrofit for older vehicles, only reaches a 10% penetration in 2031, a 50% penetration in 2042, and never reaches full deployment over the 40-year analysis period.

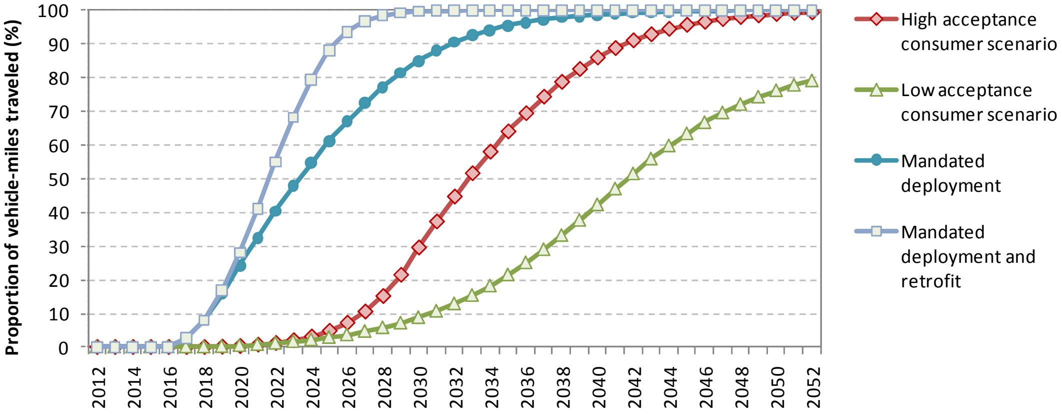


Figure 10-1 – Onboard Vehicle Deployment Scenarios
(Adapted from a Noblis study by Chang, 2010)

Acceptance of new technologies by the traveling public and commercial fleet operators is not a concern for applications only requiring the instrumentation of service vehicles owned by the transportation agency. However, such acceptance is a critical element for any application relying heavily on the ability to collect information from vehicles being driven by ordinary travelers or commercial fleet drivers. A low acceptance would likely result in slow deployments and in reduced data collection capabilities that may hinder application operations for long periods. This suggests potential benefits in rolling out in early deployment stages applications demonstrating clear benefits to the traveling public or fleet operators, such as applications using the collected data to provide real-time traffic information on changeable message signs or websites. Government mandates, such as the anticipated 2013 decision by NHTSA regarding the installation of equipment supporting safety application onboard vehicles, may also significantly contribute to accelerated deployments, as is illustrated in the scenarios of Figure 10-1. However, while the demonstration of potential benefits could increase interest in the technology and lead to accelerated deployments, perceived problems may on the contrary result in lower acceptance and slower deployments. There is therefore a requirement not to roll out applications too quickly.

10.2. Latency Constraints

In addition to market penetration needs, data latency constraints may affect the ability of specific applications to benefit from collected probe vehicle data. Whether the data reaches an application server a few seconds or a few minutes after being generated will generally not affect offline applications but can have significant impacts on applications meant to support real-time operations.

The last column of Table 10-1 indicates typical tolerable latencies for IntelliDrive^{SM} applications of interest. These are not specific requirements but general assessments based on the time scale of decisions associated with each application. Vehicle based safety applications have the lowest tolerance for information delays due to their critical nature. These applications typically require the use of data with latency of less than one second due to the need to map precisely the movements of surrounding vehicles. While the use of probe vehicle data to support dynamic traffic signal control, transit signal priority or ramp metering also requires collecting relatively precise information about vehicle movements, latencies of a few seconds are tolerable in this case. Data supporting incident detection applications or the operations of variable message signs may exhibit latencies of a minute or two as these applications often rely on the analysis of several minutes of data to smooth out random fluctuations and confirm observed trends. Delays of several minutes are finally acceptable for data supporting weather response applications where the focus is on determining where maintenance vehicles should go and what they should do after having completed their current task.

Latency requirements may have a particularly important influence on the method used to retrieve data from individual vehicles. As an example, Figure 10-2 illustrates typical transmission delays imposed by current communication technologies. As can be observed, DSRC communication is expected to be the method with the lowest latency, with typical transmission delays of less than one second between DSRC units. In comparison, cellular and WiMax communication technologies may impose latencies of 1.5 to 3.5 s, while Bluetooth and WiFi devices may impose latencies varying between 3 and 5 s. The expected low-latency performance of DSRC technology largely explains current system design envisioning the use of this technology by most, if not all, safety applications. For applications that are not safety critical, more options are available.

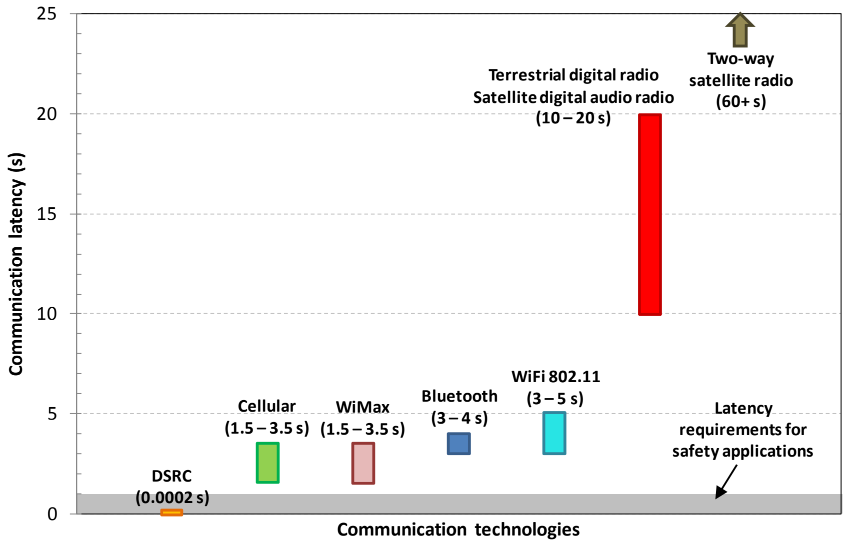


Figure 10-2 – Typical Latency of Communication Technologies
(Adapted from Schagrin, 2010)

While latency associated with the use of a particular communication technology is important, overall data latency is as critical. Overall latency refers to the total time that elapses between the moment a piece of information is captured and the moment it becomes available for use by specific applications. As demonstrated in earlier chapters, probe vehicles may take a few minutes to reach an RSE. Data collected by an RSE may also take a few seconds to reach an application server located in a traffic operations center or elsewhere via a backhaul communication system. Even if DSRC technology is used, latencies of at least several seconds can be expected. This leads to the need to design an overall data collection system minimizing potential sources of data latency to ensure that all applications of interest are adequately supported.

In addition to affecting design, latency constraints may affect when applications can be deployed, particularly if they impose a need to deploy new communication equipment. If the installation of supporting communication equipment is required, an application can only become active after the necessary equipment has been installed and tested. This requirement may not impose significant delays if an application requires only a few RSEs, such as to provide specific functionalities at specific intersections or to monitor traffic along a particular freeway corridor. However, important delays may be incurred if a large number of RSEs must be deployed. For large deployments, the best approach may be to develop a staged deployment. An application would first be rolled out in a specific area of the network. This would allow conducting initial operational tests. Once the operational tests are concluded, the application coverage could then gradually be expanded based on need or as permitted by available funds.

10.3. Equipment Vehicle Needs

Data collection from vehicles requires that each be equipped with suitable instrumentation. Vehicle equipment configurations can take many forms. Potential configurations are heavily influenced by initial applications and the sponsors of these applications. Ideally, a configuration allowing new applications to be added or existing applications to be upgraded with relative ease is needed. However, a consensus on system configuration has not yet been reached by the IntelliDrive^{SM} community as initial application sets are still being discussed and potential business plans being researched. Automobile manufacturers have not yet embraced an IntelliDrive^{SM} deployment plan either.

Regardless of how ITS applications may evolve over the next 20 years, several basic elements are likely to be part of proposed vehicle system configurations:

- Integrated OEM devices built in the vehicle.
- Ability to download software upgrades to existing equipment.
- Travelers carrying smart phones and other personal devices capable of running custom applications downloaded from various service providers.
- Utilization of personal devices featuring hardware specifically developed for ITS applications, such as wireless communicators capable of broadcasting “Here-I-Am” or other application data using DSRC or WiFi standards.
- Dedicated vehicle devices such as onboard navigation systems capable of interfacing with vehicle resources to provide dedicated and contextual content.
- Aftermarket devices that could be easily swapped for existing components, such as existing DIN audio components, and which could allow, for instance, changing existing AM/FM radio module for a combination system featuring a hard drive, a media entertainment system, a built-in navigation systems, and IntelliDrive^{SM} application support.

It is expected that most of these approaches will come onto the market over the next several years as the ITS markets develop commercially.

10.4. Traveler Privacy Policies

Current privacy safeguards have significant constraining impacts on data collection capabilities. Current IntelliDrive^{SM} system design principles call for the ability to collect data from vehicles while maintaining the anonymity of drivers and passengers. These privacy requirements are being the current snapshot generation protocols restricting the tracking of vehicles to relatively short distances and constraining snapshot retrieval by RSEs. These privacy safeguards further prevent collecting origin-destination and other trip data that may allow the characterization of travel patterns. Unfortunately, the very information that is excluded by current policies is the same information that is highly sought by transportation system planners and transportation system analysts.

Current privacy rules do not necessarily prevent the tracking of vehicles over long distances or the collection of data characterizing trips. Collection is usually permitted with the consent of the traveler, as long as there are appropriate safeguards to ensure that any private information collected will not be shared with third parties or law enforcement agencies. For example, travel surveys have been executed for decades. At the center of the deployment problem is the need for travelers to perceive that any information is being collected to support applications that may ultimately enhance their mobility or safety, and that there is no misuse of information. This requires the development of appropriate data handling protocols before any application aiming to collect potentially sensitive data could be rolled out.

10.5. Requirement for Viable Application Business Models

Original IntelliDrive^{SM} deployment scenarios were based on the concept that the USDOT would finance and contract the ongoing operation and maintenance of a nationwide wireless data communications network using DSRC technology. It was originally assumed that DSRC roadside units would be installed at 150,000 to 250,000 locations throughout the United States in order to provide sufficient coverage to motivate motor vehicle manufacturers to produce DSRC-equipped vehicles. Another assumption was that the US DOT would be able to acquire the requisite authority to deploy, operate, and maintain a national communications network. However, the validity of this particular business model has come under question due to limitations on transportation funding, increasing infrastructure construction and rehabilitation needs, and rising construction costs.

The absence of clear business models supporting the deployment and operation of specific applications can be a significant impediment to the deployment of applications. Without a clear definition of who pays for the deployment and operations of the application and how supporting funds are to be obtained, an application may never pass the stage of conceptual design. Recognizing the importance of clear business models, the USDOT launched in 2008 an effort to define a set of alternative business models for achieving deployment that would, meet the public sector technical and policy requirements, offer opportunities to the private sector for delivering, operating and maintaining IntelliDrive^{SM} infrastructure, and create services generating economic growth (Volpe National Transportation Systems Center, 2009). Far from resolving the issue, this effort produced a variety of potential business models involving the federal government, state and local governments, private information and communication providers, and travelers. The variability of proposed business models illustrates both the scope of the current debate and the remaining need to define viable business models for envisioned applications.

11. Summary of Findings

Section 1 of the report provides a general description of the DUAP project, its initial purpose and scope, and the events that led to a significant re-scoping of project activities midway through it and to the activities that are now documented herein.

Section 2 provides a general review of the envisioned IntelliDrive^{SM} probe vehicle data system. This review reflects the data collection system that was deployed on the USDOT's Vehicle Infrastructure Integration (VII) Proof-of-Concept (POC) test bed near Detroit, Michigan, in 2008. The chapter starts with a brief overview of the POC system architecture, onboard vehicle units (OBEs), and roadside communication equipments (RSEs). It then successively describes the types of snapshots generated, the protocols used to generate snapshots, how snapshots are stored onboard vehicles, how vehicles interact with RSEs, the process by which snapshots are transmitted to RSEs, and the rules that were implemented to safeguard traveler privacy. A detailed description of the data elements that are expected to be included as standard data items in probe vehicle snapshots is also provided. For each item, the description includes information about default measurement units, expected precision level, and potential parameter values for items that could only take a finite set of values.

Section 3 evaluates the general usability of the USDOT POC probe vehicle data that had been collected by Booz Allen Hamilton during the main POC evaluation phase in late summer 2008. The chapter starts with a brief overview of the data collection tests conducted, quantity of snapshots collected, and type of information collected from the various test vehicles. Findings from the POC test program reports relevant to the DUAP evaluations are then summarized. This is followed by a summary of analyses that were conducted at UMTRI to determine the time that each snapshot typically took to travel from a vehicle to an RSE and then from an RSE to a Service Delivery Node (SDN). These evaluations led to the following general findings:

- The POC tests successfully demonstrated the ability for individual vehicles to generate snapshots and upload these to RSEs along their route using prevailing DSRC standards.
- Not all vehicles will report the same set of parameters. While all vehicles can be expected to provide GPS position data, information about vehicle systems, such as wipers, brakes or lights, will depend on the reporting capability of each vehicle.
- Vehicles can potentially communicate with an RSE at a distance of up to 3600 ft (1100 m). However, communication effects may limit the effective range to a much shorter value.
- Some data losses may occur due communication effects. During the POC tests, 88% of all generated snapshots were received by an RSE. Data losses were attributed to privacy rules, vehicles moving out of range of an RSE before completing data transmission, and unexpected termination of communication while a vehicle was still within range of an RSE.
- The largest expected source of data latencies in an RSE-based system is the time required by vehicles to reach an RSE. This interval may result in data latencies ranging from a few seconds to a few minutes, depending on the RSE. Long latencies can notably be expected from RSEs at the edge of a coverage area or where the RSEs are relatively far apart.
- Snapshots collected by RSEs can take an additional 0.5 to 3.0 s to reach a Service Delivery Node (SDN) or application server, depending on the type of backhaul system used to transfer the data.

The last subsection finally assesses the usability of the collected POC data for evaluating applications of interest to MDOT. The general conclusion is that the available data was insufficient to support planned evaluations. While data were collected from 27 test vehicles, the test activities primarily resulted in single vehicles attempting to communicate with an RSE at any given time and in the production of probe vehicle data mainly characterizing vehicles traveling relatively far apart. While some opportunities exist to use the collected data to estimate vehicle-specific trip statistics, there are very limited capabilities for exploring how probe data collected from multiple vehicles could be used to estimate aggregate traffic performance measures characterizing average flow behavior, such as traffic volumes, flow density, or travel time variability.

Section 4 frames the DUAP operating environment. The chapter starts with a summary of IntelliDrive^{SM} data processes of interests to the DUAP program, a description of how the envisioned DUAP system relates to various data sources and data uses, and a brief overview of proposed system services. A list of potential system stakeholders and a review of available vehicle sensing technologies follows. The framework description then continues with a presentation of potential data sources within and outside MDOT that could complement probe vehicle data, a list of applications that could benefit from the data collected by a DUAP system, and a description of operational constraints that may affect the development of applications and benefits that could be obtained from the applications. The chapter concludes with a justification of the need to conduct some evaluations using simulated data, primarily to enable evaluations not feasible with current probe vehicle datasets from field experiments.

Section 5 describes UMTRI's Paramics IntelliDrive^{SM} probe vehicle simulator that has been used to enable evaluations not feasible with existing field data sets. While this simulator has primarily been developed as part of other projects, a description of its functional elements is provided herein to establish the relevancy and validity of the simulation results presented later. Elements described include a justification for using the simulator; the road network and traffic demand used as a case study; and descriptions of the probe vehicle data generation, onboard storage, and collection processes that have been introduced within the simulation environment through the software's Application Programming Interface.

Section 6 presents evaluations that were conducted to assess the efficiency of prevailing probe data generation protocols and determine the usability of the data that could be collected through these protocols. Most of the reported findings are based on evaluations using UMTRI's Paramics IntelliDrive^{SM} probe vehicle simulator. The primary findings are as follows:

- Significant data losses could occur if vehicles are allowed to operate with a small memory buffer, such as the 30-snapshot buffer currently recommended in general system design standards. Both simulation tests and POC evaluations indicate that a 300-snapshot buffer may be required to reduce the risk of completely filling onboard memory buffers and losing data.
- Simply collecting snapshots every 4 s instead of at intervals varying between 4 and 20 s based on the speed of the vehicle could more than double the amount of data collected when holding all other system parameters fixed.
- All snapshot generation protocols have a potential sampling bias, particularly on roads on which traffic speeds are not constant. Allowing the interval between snapshots to vary based on vehicle speed can result in an over-representation of low-speed traffic conditions. Generating snapshots at fixed interval provide a more representative sampling of traffic conditions but could still produce a slight bias towards low speed conditions, as slower vehicles would still generate more snapshots per unit distance than faster ones. Finally, while using a fixed spacing

based on distance traveled would theoretically provide a more uniform sampling, it would also prevent collecting data while stopped. While there is no ideal sampling approach, the best option appears to generate of snapshots at short, fixed time intervals.

- The requirement that vehicles stop recording snapshots for a short interval following a change of PSN can result in a loss of approximately 10% of all generated snapshots.
- Rules forcing frequent changes in PSN have significant limiting effects on the ability to track vehicle movements. Current system design forces a change after a vehicle has traveled 3280 ft (1000 m) or 120 s, when a memory buffer is emptied, and when an RSE connection is terminated. Simulation results indicate that these frequent changes result in practice in much shorter tracking capabilities than the expected 3280 ft or 120 s.
- Rules forcing frequent PSN changes have a particularly limiting effect on the ability to track vehicle movements across intersections. Simulations indicated an ability to track less than 30% of all vehicles traveling across the POC test network under current variable speed-based snapshot spacing protocols in a full market penetration situation. Generating snapshots every four seconds improves tracking capabilities, but still only allows tracking about 50% of all vehicles. One of the main limiting factors is the imposition of a mandatory gap in data collection following each PSN change, which results in a potential inability to track vehicles changing their PSN up to 820 ft upstream from an intersection.
- The largest potential source of data latency in RSE-based data collection systems is the time needed for probe vehicles to reach an RSE, particularly if vehicles are restricted to communicate only once with it. Other elements that may affect latency include wireless communication effects, the data priority level, and data losses due to a full onboard memory buffer.
- Restricting vehicles to communicate only once with an RSE can significantly increase data latency. Simulation experiments indicated a potential ability to reduce the average latency of snapshots collected over the POC test network from 61 to 30 s by simply allowing vehicles to communicate more than once with each RSE.
- Because of local effects, data collected at each RSE may exhibit relatively different latencies. These differences could reach several minutes depending on network configuration. This introduces additional complexity when considering merging data from various RSEs to support real-time applications.

Section 7 looks at the processing needs to convert raw probe vehicle data into usable data for public transportation applications. The evaluation conducted in this chapter identified seven basic data processing needs:

- Data validation – Removal or flagging of erroneous data from collected datasets.
- Time binning – Binning of collected data into 1-min, 5-min, 15-min, 1-hour or other analysis intervals based on the time the data was generated, as dictated by network evaluation needs.
- Roadway link association – Association of collected snapshots to specific roadway links to enable link-based analyses.
- Identification of vehicle tracks – Linkage of snapshots with identical vehicle identification parameters to enable the extraction of available vehicle tracks.
- Data fusion – Fusing of IntelliDrive^{SM} probe vehicle data with data from other sources.
- Statistical sampling – Determination of data sampling requirements to enable the estimation of statistically valid averages from collected data based on observed variability.

- Calculation of performance measures – Extracting performance measures supporting public transportation agency operations from collected data.
- Data archiving – Storing of raw data and derived information in a user-friendly archival system for later uses.

The chapter also provides a detailed listing of performance metrics frequently associated with DOT applications and a description of basic parameters typically required to evaluate each of the identified performance metrics. This evaluation indicates that a large fraction of performance metrics can be estimated from a relatively small set of basic parameters characterizing traffic volumes, travel times, speed profiles, queue locations, and turn percentages.

Section 8 looks at how various key traffic performance measures could be estimated using probe vehicle data collected by RSE-based systems implementing currently envisioned traffic snapshot generation and retrieval protocols. To highlight potential problems with current protocols, the evaluations focus on data collected under full IntelliDrive^{SM} system deployment, i.e., with all vehicles acting as probes. Where relevant, partial market penetrations effects are also discussed following the main evaluations.

The analyses indicate that parameters characterizing traffic flow rate, flow density, speed profiles, link travel times, incurred delays, number of stops, the location of vehicle queues, and turning counts at intersections can be estimated within certain accuracy using standard periodic and stop/start event snapshots. However, various data processing complexities are introduced by the requirements that vehicles frequently change their PSN and temporarily discard snapshots generated following a PSN change. Vehicle classification data could further be obtained by simply requiring each vehicle to record the first nine digits of their Vehicle Identification Number (VIN). Collecting vehicle occupancy data is finally not possible with sensors currently installed onboard vehicles.

The evaluations conducted in this chapter identified significant benefits that could be obtained from the use of specific snapshot generation protocols:

- While the default approach is to generate snapshots at intervals based on the speed of the vehicle, this approach results in biased data samples on links on which vehicles do not travel at constant speed, particularly near intersections. Generating snapshots at fixed intervals would provide a better sampling strategy as it reduces the differential amount of data collected by fast and slow moving vehicles.

- Current protocols instruct vehicles to discard all periodic snapshots generated while stopped. While this protocol was likely instituted to keep the size of the required onboard memory buffer as small as possible, benefits could be obtained by retaining these snapshots. Potential benefits include better tracking of vehicle movements across an intersection, improved travel time and delay estimations, and better tracking of vehicle queues.

- Frequently changing the PSN tagged to snapshots can result in a significant overestimation or underestimation of the number of vehicles traveling on a link if the probe vehicle data are not handled adequately. These frequent changes also restrict the ability to track vehicle movements across individual links or intersections. Allowing vehicles to retain their identification number for longer periods would allow vehicles to be tracked over longer distances and could expand data analysis capabilities, in addition to the accuracy and reliability of the performance measures derived from the collected data.

- While vehicles are not currently instructed to generate snapshots every time they exit/enter a link, such snapshots could allow collecting reliable travel time estimates within the current privacy framework. Vehicles could record the times at which they enter and exit each link and use this information to generate anonymous link entry/exit snapshots recording observed travel times. Such snapshots could also facilitate directional flow analyses at intersections if information about both the link being exited and the link being entered are recorded.

Evaluations also indicate that many of the traffic flow performance metrics could be estimated, albeit with a somewhat reduced accuracy, with data being collected from only a fraction of vehicles. For instance, estimating average travel times between two points only requires collecting a sample of travel times sufficiently large to allow a certain accuracy to be reached based on the observed variability of the collected data. Estimating link flow rates or density is also possible, but only if a method exists to determine the average proportion of probe vehicles in the traffic stream. This may be achieved by comparing counts of vehicles derived from probe data to counts provided by traditional point detectors. However, the accuracy of the estimate will greatly depend in this case on the proportion of IntelliDrive^{SM} vehicles, with greater accuracy expected with increasing proportions of probe vehicles.

Section 9 provides a concept of operations for an enhanced DUAP traffic flow monitoring application integrating the collection of IntelliDrive^{SM} probe vehicle data to data provided by traditional sources. This concept evolved from the observation that many DOT operations rely on the capability to characterize traffic flow conditions across a network, whether in real-time or offline. The main expectation is that probe vehicles will offer an opportunity to collect much detailed information than what is currently allowed. The concept of operations details various constraints, operational requirements and stakeholder needs that will have to be considered to collect probe vehicle data and convert successfully this data into usable information.

Unlike many IntelliDrive^{SM} applications, an enhanced traffic monitoring system will not require a large market penetration level before benefits could be obtained since probe vehicles and other IntelliDrive^{SM} data will initially operate concurrently. As probe vehicle data collection ramps up or new data sources become available, the application server could be periodically updated to allow the processing of the new data. If necessary, periodic system updates may also be made following significantly increases in the proportion of probe vehicles to adjust the algorithms used to derived reliable performance metrics from the collected data.

The following impacts on MDOT operations can be expected from the successful deployment of an enhanced DUAP traffic monitoring system:

- The collection of probe vehicle and other IntelliDrive^{SM} data will expand significantly traffic and roadway monitoring capability. Instead of relying on a limited number of point detectors and on periodic data collection efforts, data could eventually be collected on a continuous basic from every road or street in a network. This will improve assessments of current traffic conditions and historical trends and lead to better allocations of resources to support transportation system operations and management.
- The availability of a richer dataset will expand system analysis capabilities. For instance, the ability to collect trip origin-destination data may allow MDOT personnel to develop improved regional travel demand patterns. The ability to track vehicles over certain distances may also allow better characterizations of traffic flow patterns along corridors and around intersections. Data characterizing various vehicle system events will further provide additional capabilities to

determine the causes of recurrent or unexpected congestion and help determining potential solutions to these problems.

- The ability to collect data in near real-time will allow personnel in traffic operation centers to better manage day-to-day traffic and other operations, as well as better respond to unexpected events, such as incidents and weather storms. The combined ability to track network conditions in real-time and access historical data may further enable the development of more proactive event management strategies.
- Until a full IntelliDrive^{SM} deployment is achieved, a need will remain to install temporary traffic detectors or send survey crews to collect data from specific roadway links, particularly from links from which it is desired to collect data from a large proportion of vehicles. However, the availability of probe vehicle data may reduce the extent of these efforts and even eliminate some of them. This could translate into reduced data collection staffing needs and provide significant cost savings.
- The reliance on a variety of data sources will reduce the risk of system failure resulting from sensor malfunction. For instance, the malfunction of an RSE may not create blind spots if the generated data could be sent to the application server through other RSEs or other communication paths. Failure of a sensor could further only results in minor losses if complementary data could be collected through other sources.
- The collection of data from probe vehicles operated by private individuals and commercial fleet operators offers the potential to increase data collection significantly at a relatively low cost. While roadside sensors and communication units may still need to be installed, their number should be far less than what would be required to obtain the same level of coverage if traditional pavement and roadside detectors were to be installed. The use of cellular communication to retrieve data that is not time critical may further significantly reduce the need for installing roadside devices.
- The expanded monitoring capabilities provided by IntelliDrive^{SM} systems will not necessarily require all existing MDOT operating procedures to change. While some enhancements could lead to procedural changes, others could simply result in extending the geographical or operational reach of existing operations without requiring modifications to underlying processes.
- Because of the expected large amount of data to be collected on a continuous basis, a greater emphasis will need to be put on data management to avoid overloading data collection systems and ensure that all collected data is properly handled. This includes the development of appropriate data validation and storage protocols.
- New data retrieval and processing systems will likely need to be developed to allow the merging of data streaming from different sources and allow applications to access and use data stored in various archival systems, particularly if the data is to support real-time operations.
- Contrary to existing systems, which typically handle the same volumes of data throughout their life, IntelliDrive^{SM} are likely to handke an increasing amount of data as deployment progresses. This will require the development of strategies to review periodically the adequacy and effectiveness of existing data processing algorithms.
- The increasing reliance on complex communication and data processing technologies will require MDOT to collaborate more closely with other government agencies, notably the

Michigan Department of Information Technologies (MDIT), as well as potentially with external service and technology providers.

- The reliance on data collected by external private enterprises will require the development of close working collaborations with these enterprises, particularly if it is eventually desired that these enterprises address identified data quality concerns.

Potential factors that could affect the impacts and benefits derived from an enhanced traffic monitoring system include:

- Limited data collection, particularly in early deployment stages.
- Data collection restrictions imposed by regulations designed to protect traveler privacy.
- Insufficient data processing and storage capacity. Capacity problems can develop as IntelliDrive^{SM} systems are deployed. While initial design may consider certain expected data processing loads, these needs can change as new technologies and applications are developed. Similarly, vehicles with inadequate data storage capacity may cause significant data losses.
- Inadequate communication system. The ability to use collected data to support real-time operations depends heavily on the ability to carry data effectively from their source to the application server.
- Outdated data processing algorithms. As the quantity of data collected increases, some of the algorithms used to process the data may need to be recalibrated to account for the availability of new or more reliable information. Some algorithms may also become irrelevant, while new issues may create a need to develop new algorithms.
- Outdated interfaces. Standards or external systems may change over time. If the data processing systems are not updated following some changes, some system functionality could be lost.
- Inadequate staff. The heavy reliance of the system on data processing, communication and archiving creates a need for using staff having appropriate knowledge of communication functions, computer operations, and data handling procedures. Operational delays and inefficiencies could then ensue if staff with proper training is not available.

Section 10 finally addresses some general issues that may affect the deployment of IntelliDrive^{SM} applications. Issues discussed include market penetration requirements and the uncertainty regarding the pace at which new probe vehicles may be introduced; effects of data latency on data processing requirements and application deployment; the current absence of a definite vehicle equipment configuration; the impacts of current traveler privacy policies; and the need to develop viable business models supporting envisioned applications.

12. Lessons Learned

The following lessons were learned through the execution of this project regarding the generation, collection, and use of probe vehicle data:

1. Current snapshot generation protocols do not allow individual vehicles to be tracked over distances exceeding 3280 ft or for more than 120 s. This restriction corresponds to what an observer standing on the side of the road can currently do.

2. The inability to track vehicles over long distances significantly restricts the ability of using probe vehicle data to support network operational evaluations and transportation system planning activities. Unless travelers agree to more extensive vehicle tracking options, no information about the origin or destination of trips can be collected. This will for instance prevent using collected probe vehicle data to determine regional trip patterns or directional flows along a corridor. Network operators and system planners will thus have to continue to rely on periodic travel surveys and trip forecasting models if the privacy framework is not modified or if a way is not developed to allow such information to be collected within the framework.

3. While it is theoretically possible to track vehicles over 3280 ft or 120 s, the imposition of various events causing a change of PSN can result in a much shorter effective tracking capability. This can have significant implications on the ability to use collected probe vehicle data to analyze traffic behavior at intersections and at freeway merges, diverges and weaving areas. Simulation results indicate for instance that frequent PSN changes may result in an ability to collect usable vehicle tracks for as low as one fourth of the vehicles going through an intersection. While the collected data may still be used to help characterize traffic movements across intersections and decision points, the low sampling rate may create a need to reach a higher market penetration level before reliable estimates of traffic movements could be obtained from the collected data.

4. Current privacy rules affect the ability to extract reliable vehicle counts from probe vehicle data. The requirement that vehicles frequently change their PSN can lead to assuming that sequences of snapshots with different PSNs are generated by different vehicles while they are not in reality. Rules requiring the mandatory discarding of snapshots generated for a short interval following a change of PSN, as well as the discarding of all snapshots remaining in a vehicle's onboard memory buffer following the termination of an RSE connection, can further result in vehicles traversing a section of road without generating snapshots. Special data processing algorithms are thus required to minimize the potential for over-counting or under-counting vehicles and for biasing the evaluation of performance metrics relying on vehicle counts.

5. Current snapshot generation protocols may introduce some sampling biases that may affect the accuracy of the traffic conditions estimated from the collected probe data. For instance, varying the interval between snapshots based on the speed of the vehicle, as currently defined in the default protocols, results in an oversampling of low-speed traffic conditions on links with varying conditions. This effect can particularly affect data collection on approaches to signalized and stop-controlled intersections. The oversampling can result in a systematic underestimation of average travel speeds and an overestimation of link travel times. Using a fixed snapshot interval reduces the biases but does not eliminate them, as slow moving vehicles will still generate more snapshots while traversing a link that faster vehicles. Generating snapshots based on distance traveled would remove all sampling biases associated with moving vehicles, but will not allow an

adequate sampling of stopped traffic conditions. An ideal approach may be to generate snapshots based on distance traveled while moving and based on elapsed time when stopped.

6. There are significant benefits in allowing vehicles to keep generating snapshots while stopped. While such a protocol would increase the amount of data to be processed, the additional snapshots would facilitate the tracking of vehicle queues and improve the estimation of stopped delays, particularly in stop-and-go situations.

7. The simplest way of estimating link travel times is to allow vehicles to generate an event snapshot each time they exit a link. Each snapshot would record the link entry time, link exit time, and thus, the actual time taken by the vehicle to traverse the link. These snapshots would not need to include a vehicle identification number and would therefore allow travel time data to be collected without compromising current privacy rules.

8. A database of pre-defined links will be required to associate each snapshot to a specific road segment and enable link-based analyses. Such a database will further need to be carried by vehicles if vehicles are expected to generate link exit snapshots or other link-based data.

9. Roadway links defined in any database should correspond to links used by MDOT and other stakeholder agencies to conduct network evaluations.

10. Estimating link travel times and speed profiles does not require collecting data from all passing vehicles. All that is required to is to collect data from a sufficiently large number of vehicles to allow statistically valid estimates to be calculated. The minimum number of data to collect can be determined using standard statistical data sampling formulas. These formulas determine the number of data samples to collect based on observed variability, a given confidence level, and a tolerable error.

11. Flow rates, numbers of stops, turn percentages and traffic density can be estimated under partial system deployments only if an estimate of the proportion of probe vehicles in the area of interest allows converting the partial counts derived from the collected probe vehicle data into overall traffic measures. Simulation results indicate for instance that reasonable estimates may be produced when sampling only 5 or 10% of vehicles for parameters exhibiting relatively moderate variability. However, a high potential of error may remain until a reasonably high proportion of probe vehicles is reached.

12. Parameters exhibiting large variability are likely to require higher data sampling rates, and thus higher probe vehicle market penetration levels, than those with smaller variability. Examples of such parameters include estimates of the number of stops made by vehicle or average incurred delay at signalized intersections, as not all vehicles will stop and then remain immobilized for the same duration during a signal cycle. In particular, parameters exhibiting very high variability may not be reliably estimated from collected probe data until high market penetration levels are reached.

13. The proportion of probe vehicles traveling on a link or in a given network can be estimated by comparing counts of vehicles derived from probe data to counts provided by traditional point detectors. The accuracy of the estimated counts will depend on the proportion of IntelliDrive^{SM} vehicles, with greater accuracy expected with increasing proportions.

14. Snapshots generated by probe vehicles will likely arrive at an application server with a delay that can range from a few seconds to a few minutes. The delay will be function of the density of RSEs, rules governing how vehicles interact with RSEs, the type of wireless communications used, and transmission delays due to congestion within the wireless communication network.

15. The largest potential source of data latency in RSE-based collection systems is likely to be the need for vehicles to reach an RSE before starting to transmit the snapshots they have generated. Over the POC test network, the average data latency due to the need to reach an RSE was estimated to be about one minute, which latency at some RSEs reaching a few minutes.

16. Restricting vehicles to communicate more than once with an RSE can significantly increase data latency. For the POC network, simulation tests indicate that simply allowing vehicles to keep uploading to an RSE any new snapshot generated while within its range could reduce average data latency from 61 to 30 s.

17. Transmitting data through a cellular phone connection rather than through an RSE could significantly lower data latency in networks where RSEs are relatively far apart. This mode of communication may be particularly useful in rural areas.

18. Probe vehicle data collected by different RSEs may reach an application server with varying delays. While these differing latencies may not affect the compilation of data associated with a specific RSE, it imposes a need to wait for all data pertaining to a certain time interval to reach an application server before attempting to compile data from multiple RSEs and to derive network-based performance measures supporting various operations or applications.

The following additional lessons were learned regarding the effectiveness of field experiments and simulation studies to evaluate data collection capabilities and data uses:

1. Field experiments have proven valuable at testing the capability of wirelessly transmitting data to and from a vehicle. However, the amounts of data that can be generated by such experiments often impose limits on the ability to evaluate fully applications, particularly those requiring high levels of market penetration to achieve full benefits.

2. While simulation models cannot fully replicate the complexity of real systems, they can provide reasonable approximations of real systems. Simulators may be used to perform system performance evaluations and interaction analyses before hardware and software component designs are completed. Simulations may also be used to confirm functional requirements, design specifications and test procedures as part of the design process of prototype hardware and software.

3. System simulation studies can be done many years before a full system deployment may occur. This allows exploring how an envisioned system may eventually operate under various market penetration levels and scenarios, as well as evaluating deployment strategies and application business models.

4. A simulator's ability to control the movement and placement of individual vehicles (a few or many) facilitates the design of test scenarios. This provides a capability to create and repeat specific test conditions that may not be available through field experiments or only possible through costly re-builds..

13. Recommendations for Future Work

One of MDOT's major goals is to maintain its position as a national leader in the deployment of ITS applications. In the last four years, MDOT has already championed the deployment of the USDOT's IntelliDrive^{SM} Test Bed near Novi, Michigan, to support the research needs of the USDOT, as well as the deployment of equipment at various intersections to support the development of safety applications by automobile manufacturers of the Crash Avoidance Metrics Partnership (CAMP). Building on these past efforts, MDOT is currently supporting both the development of applications relying on vehicle-infrastructure communications and the development of safety applications attempting to leverage emerging vehicle-to-vehicle communications. MDOT's interests in vehicle-infrastructure applications are linked to the opportunities offered to support the operation, planning, and management of transportation systems. Particularly strong interests are placed on applications that may enhance transportation system monitoring capabilities, expand management opportunities, reduce operational and staffing costs, provide benefits to the traveling public, support commercial fleet operations, and further promote the deployment and use of IntelliDrive^{SM} systems across Michigan and the United States. While vehicle-to-vehicle applications may not directly support MDOT operations, interest in their development is based on the expectation that they may contribute to improving network operations by reducing the number of accidents and the congestion that often results from them.

Most of the analyses contained in this report focus on wireless data communications protocols that were developed based on the Vehicle-Infrastructure Integration (VII) architecture that was defined five years ago. This architecture was predicated on a solution that only involved the use of DSRC technology for supporting both safety and mobility applications. Since then, significant changes in the communication technology landscape have resulted in a broadening of its scope to include also cellular phones, WiFi, WiMax and other wireless communication methods, and in the definition of the current IntelliDrive^{SM} architecture. In parallel to this change, there has been a significant shift of interest towards vehicle-to-vehicle safety applications. Since the aim is to make these applications as stand-alone as possible, they are expected to involve only limited interactions with roadway infrastructure. Interactions are mainly expected for the distribution of security certificates, GPS differential corrections, and a few other critical elements. This shift, however, does not reduce interest in vehicle-infrastructure communications, whether using DSRC or other communication technology, as this will be the primary means of collecting probe vehicle data supporting public transportation agency operations.

Despite the change in scope, the envisioned IntelliDrive^{SM} system still has many issues that need to be resolved before a national launch is viable. This includes, among other things, the development of viable business cases, the adjustment of data collection protocols to support envisioned applications efficiently, adequately addressing issues surrounding the privacy of travelers, the development of mature DSRC technology, and resolving compatibility issues among the various possible communication modes. These various tasks clearly indicate that significant research and development needs remain. However, the magnitude of these tasks should not prevent early application deployments, as opportunities exist to draw benefits from partial deployments that could easily be upgraded later as IntelliDrive^{SM} technologies mature. This approach allows starting to test various operational elements and to assess potential benefits without having to wait for 5, 10, 20 or 40 years before a sufficiently high market penetration of IntelliDrive^{SM} probe vehicles is reached. These early deployments could notably become de facto standards and influence the development of future applications. They may also affect the definition of the future generations of the IntelliDrive^{SM} architecture that will likely emerge from continuing developments in communication and data processing technologies.

Moving Past Demonstration Projects

It is recommended that MDOT moves past IntelliDrive^{SM} demonstrations and test beds and initiates the development and deployment of a real IntelliDrive^{SM} system. For instance, a data collection system using commercial off-the-shelf (COTS) components can be deployed across the state without requiring significant new infrastructure. With the proper incentives, participants from across the state could join the effort, particularly if there are perceived benefits from using the applications being deployed. In addition to directly supporting MDOT's and possibly other stakeholder's data collection needs, the proposed data collection system would provide a unique environment to address data collection issues and refine proposed applications. While there are risks associated with being the first at attempting such a development, this effort, combined with other on-going research activities being executed in the Detroit area, would assure that MDOT and Michigan would remain the nation-wide leaders in IntelliDrive^{SM} application development.

To assure maximum compatibility with other development efforts and facilitate later upgrades, it is further recommended that any new system or application respect the design objectives and standards defined within the envisioned nationwide IntelliDrive^{SM} architecture. The needs for potential system upgrades should also be included in the proposed business plans. Over the next 20 to 40 years, many architecture and system design changes will likely be made on the road to full market penetration. It should therefore be assumed that the first deployed applications would likely require some changes at some point in the future to accommodate new functions not currently possible with today's technology.

Data Collection System Needs

Data collection from vehicles is the primary function that supports and creates value for all of the envisioned mobility and asset management applications. Future work on the development of IntelliDrive^{SM} systems should therefore not only look at individual applications but at the need to develop a robust and reliable underlying data collection system potentially serving the needs of multiple applications. It is recommended that MDOT include plans to design, deploy and implement a data collection system supporting its applications of interest, as well as those of potential system stakeholders.

As described below, many of the building blocks supporting the development of such a data collection system are already in place or available:

- Ability to retrieve data from built-in vehicle systems through hardwired or Bluetooth CAN interface devices
- Smart phones equipped with GPS receptors; cellular, WiFi or Bluetooth communication capabilities; USB connectors; and accelerometers
- Mixon-Hill DUAP data server
- Backhaul data communication system

Generally, there are two kinds of raw data available from vehicles: data that can be collected by devices independent of the vehicle and data from embedded sensors in the vehicle. The first type of data includes information collected by brought-in devices, such as smart phones. Most of these devices now come equipped with GPS sensors allowing them to collect location, heading and speed, in addition to time. Some devices also have built-in accelerometers allowing them to measure vibrations caused by road roughness. The second type of data includes information from embedded vehicle systems such as throttle position, acceleration, deceleration, ABS brakes, traction control, wipers, lights, etc. Many of these data can already be obtained using low cost interfaces to the vehicle CAN bus.

Once data is captured by an onboard device, it must be transferred to a backend data server located at a transportation operation center or elsewhere via a backhaul system. This does not require a large deployment of DSRC RSEs as was originally planned in the initial VII architecture. Effective data collection could be done using cellular technology available in smart phones and PDAs. This option would be viable for any application tolerating data latencies of several seconds. Protocols could further be used to minimize the transfer of non-critical data in situations in which large payloads may overload the communication network. If cellular cost becomes important, non-critical data can be retained onboard the vehicle or in the device and transferred using a different media (WiFi, Bluetooth) when the vehicle reaches a given location (for instance, a fleet garage or specific communication hotspots). A number of possibilities can be evaluated with the intent of adopting a low cost solution featuring the use of COTS hardware and IntelliDrive^{SM} compatible software.

A backend data server suitable to aggregate data from vehicle devices and other ITS sources has already been developed by Mixon-Hill as part of the DUAP program. This server is already capable of supporting various applications of interest, including *road surface weather monitoring* with *slippery road detection*, *road surface condition monitoring* (pothole detection), *traffic incident detection*, and *monitoring of traffic conditions* (estimation of average travel times, identification of congestion hotspots, etc.).

An important issue at the server level that will eventually need to be addressed is how to merge data from various sources. Data streaming in from various sources may be collected using sensors having different accuracy. Another potential problem is how to address apparent discrepancies between data sources. Finally, as new IntelliDrive^{SM} applications are introduced, there may be a potential for data pertaining to a specific vehicle to be collected by different systems and for duplicate data to reach the server. In such a situation, the issue is then how such data would be detected and handled.

Additional studies regarding the collection and use of data provided by IntelliDrive^{SM} vehicles that will eventually need to be executed include:

- For each application selected for deployment, there is a need to define exactly what data should be collected, what are appropriate sampling rates, and which performance metrics must be calculated to support adequately the application's operational needs
- What volume of data will initially need to be processed by the server to satisfy the aggregate application needs and how these volumes are expected to grow over the years
- How collected data will be validated
- Development of data collection methods enabling the collection of origin-destination trip data or the tracking of vehicles over sufficiently long distances to support various system needs

Deployment Approach

To promote the development of IntelliDrive^{SM} systems supporting MDOT operations, the recommendation is to design and build a system supporting the following four key applications:

- Road surface condition monitoring
- Road surface weather monitoring with slippery road detection
- Traffic incident detection
- Road traffic condition monitoring

While all of the above applications attempt to provide data supporting various DOT needs, many of them also cater to the needs of travelers.

While the road surface condition monitoring application could be deployed by equipping only MDOT service vehicles, all other applications will typically seek to collect data from a fleet of probe vehicles as large as possible. To promote participation from other governmental agencies and the public, a program to incentivize installation of the appropriate equipment in vehicles will need to be developed. MDOT may for instance target individuals who already have a wireless data service plan on their cellular phone or portable device. MDOT may also work with potential application providers to develop a catalog of applications that would be available free of charge. As an exchange for agreeing to have data collection software installed on their cellular phone or hardware installed on their vehicle, MDOT may further offer program participants:

- Free upgrade for their smart phone
- Rewards to those who call in travel problems (incidents, flooding, etc.)
- Free access to state parks
- Priority reservations at state sponsored events, like the Labor Day Mackinaw Bridge Walk
- Reward points based on the quantity of data provided that can be exchanged for goods or services
- Lotto tickets when reaching specific levels of data provided

All the above applications could be developed by collaborating with a telecom service provider such as Verizon or AT&T to get the wireless resources needed while minimizing infrastructure investments. MDOT may initially subsidize the cost of equipment or service fees to help launch the system and build some market penetration, but most of the cost burden should eventually be assigned to drivers and travelers, unless alternate financing means are developed. In all cases, care would need to be exercised to ensure that drivers perceive that they are obtaining something of value in return for the data they are providing. This may be the only approach to ensure win-win outcomes for MDOT, its customers, and the IntelliDrive^{SM} initiative.

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