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16. Abstract

Vehicle-Infrastructure Integration (VII) is an initiative of the U.S. Department of Transportation with participation by automobile manufacturers and other organizations. VII seeks to create a network of communications and shared applications within the U.S. among all vehicles and countless roadside and infrastructure-based elements. This would enable or improve vehicle safety applications, transportation management functions, and other public- and private-sector applications, such as real-time traffic information. An area that highlights the potential of VII is emergency transportation operations, which are activities by public agencies to manage the movement of vehicles in response to everyday accidents and emergency needs, as well as in response to extraordinary events such as large-scale natural disasters or man-made catastrophes.

This paper provides a framework for considering potential uses of the VII network. Three basic types of communication are described: vehicle-to-vehicle, vehicle-to-infrastructure, and infrastructure-to-vehicle. For emergency transportation operations, an additional distinction between emergency vehicles and private vehicles is added. With this in mind, potential applications can be classified according to the communication paths.

A set of VII applications is described in the context of emergency transportation operations. The challenges of deploying VII and creating applications for emergency transportation applications are considered. Gaps in technology and knowledge are identified, with suggestions for research to close the gaps. Gaps considered include technology gaps, techno-social issues, algorithmic and modeling gaps, and human-machine interface gaps. By providing a conceptual framework for the possible functions that VII can enable, and by examining key functions and their challenges, this paper serves to both highlight the potential of VII and address the challenges of bringing VII to full deployment.

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EMERGING TECHNOLOGIES FOR VEHICLE INFRASTRUCTURE COOPERATION TO SUPPORT EMERGENCY TRANSPORTATION OPERATIONS

A Synthesis and Extrapolation of the VII Concept and Its Potential Applications

FINAL PROJECT REPORT
Submitted to the

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1.0 INTRODUCTION AND BACKGROUND

Although the rate of motor vehicle fatalities per unit distance traveled in the U.S. is declining, the rate of decline has recently been decreasing. This reduction of safety gains is sometimes attributed to the maturation of successful programs to improve crashworthiness, as well as driver awareness and compliance with alcohol and seat belt regulations, which may be reaching asymptotic limits of benefit. Meanwhile, congestion and congestion-related delays in the U.S. are increasing as the population and the distance-traveled-per-capita increases.

To meet these challenges, the U.S. DOT has established the Vehicle-Infrastructure Integration (VII) initiative as part of its Intelligent Transportation Systems program (FHWA, 2005). The initiative proposes using new wireless communications technologies to build a networked transportation system to improve safety and reduce congestion. Each new vehicle would be manufactured with a wireless radio and numerous roadside units would be installed, so that vehicles and the roadside would be linked into a widespread, high-speed, and low-latency network. These roadside units would be part of a large computer network to service both public and private sector applications.

Several automakers and other private and public sector groups have joined the effort to explore the potential of VII. The U.S. Federal Communications Commission has allocated bandwidth near 5.9 GHz for this cause and standards are nearing completion for dedicated short-range communications (DSRC) using this spectrum. Since highway management in the U.S. is highly decentralized, a separate private-public partnership has been proposed as the way to construct and manage the roadside network across the country. The current exploration phase for the VII concept will culminate in a decision by automakers and transportation officials about whether to proceed with equipping vehicles and roadsides with the necessary equipment. This exploration includes consideration of the technical, legal, and financial issues involved in deploying and operating this network. This final report addresses an element within this exploration – the consideration of potential applications and benefits of VII for emergency transportation operations (ETO).

VII is focused on defining and prototyping a communications system and sets of standards that would use wireless technologies to enable vehicle-to-infrastructure communications and also provide a land-based network system that would support public and private sector applications. These applications would have access to selected data from all vehicles and would have the ability to communicate to vehicles. VII is not focused on the creation of the applications themselves, although there are related programs such as the Cooperative Intersection Crash Avoidance System (CICAS) program that will develop and field test examples of cooperative systems consistent with the VII program.

VII also supports the development of standards for consistent vehicle-infrastructure elements (such as intersection crash warnings) and perhaps novel uses of dynamic messaging systems. Standards development is essential to provide for a scalable and interoperable system, and will accelerate development.

The current chapter lays the foundation for this investigation by presenting frameworks for considering emergency transportations and VII, respectively. Section 1.1 presents the domain of application considered in this report for the use of VII, specifically the definition and components of emergency transportation operations. Section 1.2 describes a framework developed to consider VII itself for the purposes of this project. Finally, Section 1.3 states some of the sources used to gather information about the technology and the possible applications of VII to emergency transportation operations.

The remainder of the report presents the results of a three-stage investigation into the potential benefits and challenges associated with developing and applying VII to support emergency transportation operations. Section 2 covers the first stage, an assessment of technology that describes the tools available for developing cooperative vehicle-infrastructure systems for emergency transportation operations. Section 3 describes the second stage of exploring the potential benefits of VII. Section 4 presents the final stage, a critical analysis of the key gaps that may arise in developing and applying VII in the context of emergency transportation operations. Together, these chapters present an overview of the potentials and challenges of this pursuit.

1.1 Emergency transportation operations

This report takes a wide view of emergency operations and considers two broad categories:

- Operations involving primarily emergency vehicles, such as incident response
- Operations involving all vehicles, such as evacuation

Research on intelligent transportation systems (ITS) can improve emergency transportation operations. For example, the U.S. DOT's ITS Joint Program Office announced 11 initiatives in April 2004 to apply ITS to all forms of transportation emergencies with the goal of faster and better-prepared responses to major incidents, shorter incident duration, reduced impact, and more rapid restoration of normal travel conditions. FHWA Emergency Transportation Operations has nine projects (as of July 2004) that build on ITS technologies. Thus, it is vital to determine how improved communication ability will facilitate the application of ITS technologies to emergency transportation operations.

The National Response Plan describes five related components of treatment of emergencies (SAIC, 2004):

- Prevention – avoidance or mitigation of an event
- Preparedness – prior measures taken to minimize potential harm
- Awareness – detection, verification, and monitoring of an event
- Response – actions immediately after or during an event to safeguard life and property
- Recovery – restoration of normal service and conditions

The latter four components are relevant to treatment by emergency transportation operations (Pearce, 2004). Vehicle-infrastructure cooperation technologies can play a role in these components, with the most significant roles possible in the awareness and response components that involve the periods of time immediately surrounding the emergency event. VII can also support the awareness, detection, and verification categories and has potential for improving recovery and traffic management activities.

Similarly, traffic incident management has been partitioned into seven categories (Bunn & Savage, 2003):

- Detection – discovering an event and informing salient agencies
- Verification – confirming an event and obtaining relevant information
- Motorist Information – disseminating event-related information to affected motorists
- Response – dispatching vehicles and activating communication links
- Site Management – coordinating on-scene activities
- Traffic Management – applying traffic control measures to affected areas
- Clearance – removing wreckage and restoring roadway capacity

The first National Response Plan component of interest is preparedness, which involves planning and coordination activities as well as implementation steps. An example of planning and coordinating activities is creating emergency plans among several agencies. Implementation steps could include installation of technology such as purchasing and deploying mobile radio services or highway surveillance systems. Preparedness will involve setting up some of the technologies to be identified in the other three components, but the use of the technologies, per se, is not central to this preparatory phase. The preparedness component is also assisted by the ongoing development of standards, such as incident management standards (e.g., IEEE 1512-200 (see Kowalenko 2002)), communications standards, and NTCIP standards (NTCIP, 2000).

The awareness component addresses data collection and interpretation activities that allow transportation managers to identify the occurrence of an event, understand its nature, monitor the event, and understand transportation-related information throughout the event and the response to the event. Table 1 lists capabilities that could contribute to the awareness component. Vehicle-infrastructure cooperation can provide significantly to the awareness component, as will be shown later.

Table 1. Emergency transportation operations awareness activities – Examples

Examples of Emergency Transportation Operations Awareness Activities
Detecting possible indications of emergencies
Verifying or disproving the occurrence of an event
Identifying the nature and scope of the event
Alerting relevant agencies
Detecting the state of the emergency response activities of relevant agencies
Identifying the state of lifeline routes (e.g., congestion or obstructions)
Identifying the state of evacuation routes
Communicating status among relevant agencies and emergency response facilities

The third component of interest includes response activities. Vehicle-infrastructure cooperation can contribute significantly to response activities. Table 2 below lists some possible examples of response activities (Paniati, 2005) and (Pearce, 2004).

Table 2. Emergency transportation operations response activities - Examples

Examples of Emergency Transportation Operations Response Activities
Identifying and managing lifeline (first responder) routes
Managing evacuation, including route selection, traffic control, and responding to capacity reductions
Managing freight such as that necessary to support emergency personnel
Managing public transit
Communicating with the public during disasters, e.g. evacuees in personal highway vehicles
Directing first response transportation
Assisting first responders with information (e.g., telemedicine, or improving awareness of other first responders)
Identifying secondary response needs (e.g., Hazmat containment, towing) and directing responders
Managing traffic demand in affected areas
Closing or re-configuring transportation assets
Identifying damage in the transportation system
Coordinating assessments and decisions among agencies/governments

The final component of interest is the recovery phase which may involve activities that occur over longer time scales, and therefore the criticality of vehicle-infrastructure cooperation will be lower than for activities conducted during or immediately following the event. Nevertheless, one area where vehicle-infrastructure cooperation can be useful is in the provision of information to professionals and the public on re-entry or reconstruction activities. Technologies for this support are similar to those supporting the management and communications during the response phase, and therefore it is not necessary to treat the recovery component separately.

1.2 Framework for VII

In order to better organize current information and to provide a convenient framework for future research evaluations, VII efforts are, like Caesar's Gaul, in three parts divided:

- Vehicle to vehicle (V2V) communication
- Vehicle to infrastructure (V2I) communication
- Infrastructure to vehicle (I2V) communication

V2V communication assumes direct information flow between nearby vehicles. While it may be possible to implement such communication by routing information (indirectly) through the infrastructure, this report assumes that either (a) this routing is transparent and very fast, or (b) vehicles communicate directly without depending upon the infrastructure. Section 2 of this report discusses the technologies that might enable V2V communication. An example of V2V communication would be an ambulance approaching an intersection and broadcasting a warning message to other vehicles near the intersection.

V2I communication allows the vehicle to send messages to the infrastructure about the state of the vehicle, and to a limited extent using onboard radar and other sensors, about the immediate roadway environment. An example of V2I communication would be using the vehicle as a traffic probe, such as was done in the Florida Travtek IVI studies, to determine highway congestion.

I2V communication allows the vehicle to receive information from the infrastructure. Highway advisory radio is an example of I2V communication.

Figure 1 shows the conceptual space used to organize this report. It reveals an orthogonal combination of the three VII components crossed with the two classes of emergency operations. Thus, the three-dimensional cube displayed in Figure 1 has six cells.

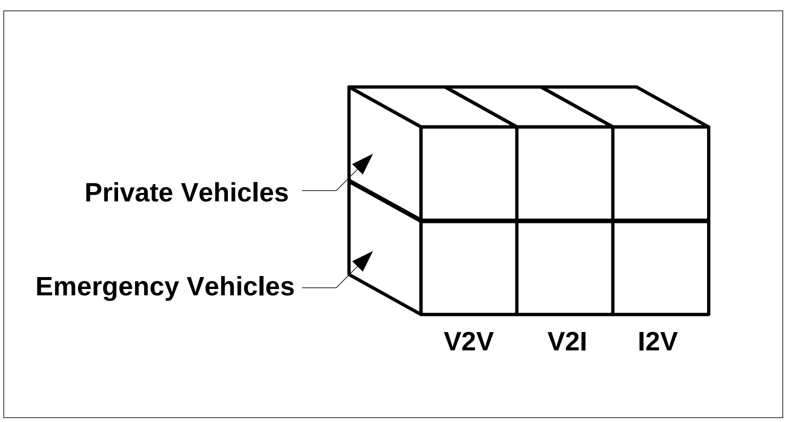

Figure 1. State space for VII components

1.3 Information sources

Information was gathered for this report in several ways:

- Review of transportation databases conducted by the UMTRI Library
- Coordination with Booz-Allen-Hamilton on a related project concerning service concepts
- Attendance at public workshops on VII
- Searches of the TRB database of research in progress and contacting investigators by e-mail and telephone
- Contact with researchers working on relevant VII projects, such as those at the Crash Avoidance Metrics Partnership (CAMP)
- Review of IEEE standard development efforts for possible application to VII
- Website searches and monitoring to assess the state of wireless systems development

Several literature database searches were conducted by the UMTRI Library for this project. The most productive search, on vehicle-infrastructure cooperation/ communication, found a list of 258 citations, most of which were not directly relevant to emergency operations. Another search of the UC Berkeley PATH database, on DSRC, produced 22 citations, most of which, again, were not directly relevant to the needs of this project. Approximately 35 articles were obtained from these databases. Results from the few useful articles are contained in Sections 2 and 3 of this report. It is likely that this topic is so new that very little research has appeared in the published literature, including technical reports that are generally available. Similarly, personal contact with researchers conducting current projects yielded only some verbal anecdotes since their final results are not yet ready for public dissemination.

2.0 TECHNOLOGY ASSESSMENT

This section identifies vehicle-infrastructure cooperative technologies that may impact emergency transportation operations. The technologies are described as existing or emerging, and the nature of the role they may play is described, relative to specific components of emergency transportation operations. A few examples of these technologies include automatic collision notification, automatic vehicle location, wireless communications between vehicles (including emergency vehicles as well as other vehicles), and telemedicine. A series of tables is used to associate technologies with emergency transportation functions.

2.1 Identifying technologies to support emergency transportation operations

This section identifies many technologies that are related to vehicle-infrastructure cooperation and may play a role in enabling or enhancing emergency transportation operations. There is emphasis on technologies related to the Vehicle-Infrastructure Initiative (VII), although other cooperative technologies (involving vehicle and infrastructure elements) are also covered.

A discussion of technologies begins by presenting a table of many function-level technologies relevant to emergency transportation operations. The function-level technology supplies a high-order function (Table 3). It must be supported by lower-level technologies that enable the high-order function (Figure 2). Examples of these enabling technologies are presented in Table 4, Table 5, and Table 6; they directly support either private vehicles, emergency vehicles, or infrastructure. All lower-level technologies in turn must be realized in specific physical devices operated by people. Thus, the human-machine interface (HMI, as described in Section 4.5) will be essential. It uses allocation of function to support the physical displays and controls used in each device.

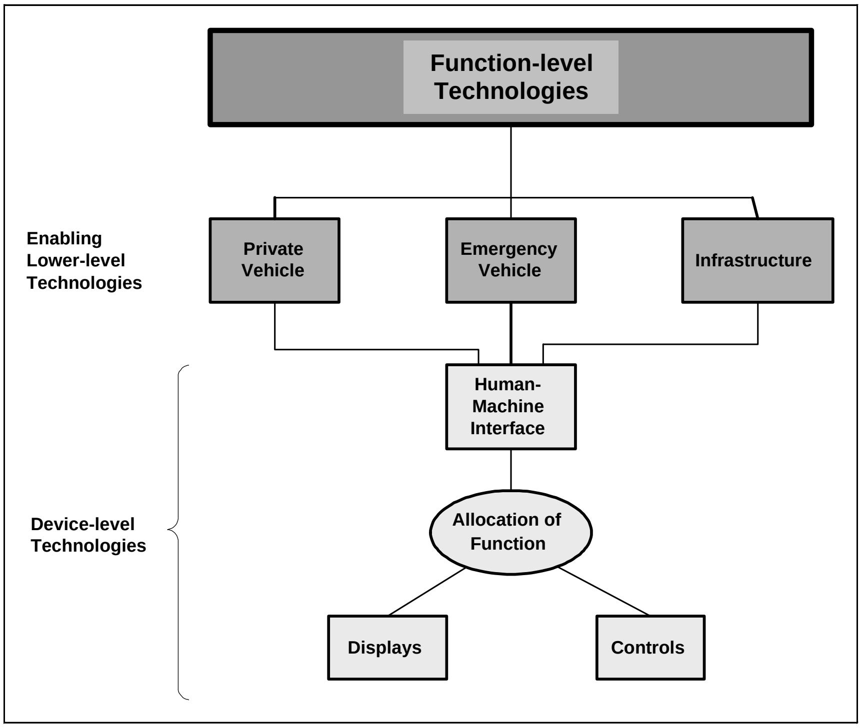

Figure 2. Levels of VII technology

A function-level technology may be composed of several hardware, software, or activity elements that together deliver a cohesive function or service. This list is shown in Table 3. The table also assigns a maturity level to the technology, including:

- Deployed – for technologies already deployed commercially
- Developed – for technologies that have been demonstrated to function in operational or near-operational settings
- In development – for technologies that are the subject of R&D
- Conceptual – for technologies that are envisioned but not yet in development

All technologies listed in Table 3, will use, or may use, wireless technologies, so these technologies are critical to support cooperative capabilities. This is natural, of course, since the exchange of information from land-based facilities such as transportation management centers (TMCs) or roadside field equipment to vehicles, both emergency vehicles and other vehicles, is the defining characteristic of cooperative vehicle-infrastructure elements.

Short descriptions of the function-level technologies listed in Table 3 are now provided:

Automatic collision notification (ACN) systems –
ACN systems are onboard systems that sense that the host vehicle has been involved in a crash and automatically contact a commercial service or a public safety answering point. GPS coordinates are sent; voice, crash pulse information, and even video may be delivered as well. ACN is available commercially, e.g., as a feature of the OnStar service provided by GM.

Wireless 911 –
Wireless 911 (or E911) involves the use of cell phones for contacting public safety answering points (PSAP), and the progress toward allowing PSAPs to identify the phone number and the geographic location of the call. The cellular industry, public agencies, and the FCC have been involved for several years in developing viable approaches to this, with some success.

Automatic vehicle location (AVL) –
AVL refers to existing technology that allows fleet dispatchers to track the location of vehicles. This is usually done by periodic transmissions of the vehicle GPS location in the sidebands of voice channels.

Traffic control device pre-emption by emergency vehicles –
Current technology has been implemented in several markets that allows emergency vehicles to broadcast their approach to traffic signals during emergency activities. The signal controller then adjusts the signal phase to allow the vehicle to pass safely through the intersection.

"Static" route guidance –
Without real-time traffic or conditions information, static route guidance involves developing a turn-by-turn plan for reaching a destination using a digital map. This often uses estimates of speed limits, road classification, and the number of intersections to compute a recommended route.

"Dynamic" route guidance –
The improvement of dynamic route guidance over static route selection is that quasi real-time information about traffic and weather and/or road conditions, such as congestion-related measurements from the field, can be factored into the route selection.

Emergency vehicle proximity warning for nearby vehicles –
Vehicle-to-vehicle communications would allow a signal from an emergency vehicle to trigger in-vehicle displays in surrounding traffic, alerting other vehicles of the emergency vehicle's approach.

Telemedicine –
In the emergency transportation context, telemedicine refers to the use of high bandwidth data (perhaps including video) to connect a mobile medical responder to nearby medical facilities for the purpose of providing improved patient care, as well as identifying the most appropriate emergency facility to which the patient should be transported.

Regional medical facility coordination –
During major incidents, nearby medical facilities coordinate the distribution of persons in need of medical care.

Transportation management center (TMC) access to real-time data from infrastructure sensors –
Most metropolitan TMCs have quasi real-time access to loop detectors and/or camera-based vehicle counters to monitor flow and average speed on major throughways. Emerging technologies will create new options for collecting and managing this information.

TMC access to real-time data from probe vehicles –
R&D groups from several automotive manufacturers, as well as digital map suppliers, have pushed for the development of a capability to equip vehicles with transponders that relay information about their recent travel to roadside units or base stations. This would allow TMCs access to more detailed information about traffic, including coverage of more of the roadway system.

TMC environmental sensing systems –
These systems collect information about the region's weather conditions that may affect traffic management.

Crash avoidance and pre-crash sensing aided by vehicle-to-vehicle communication –
Low-latency communication between vehicles would significantly improve the performance of some crash warning, crash mitigation, and pre-crash sensing systems, as described in CAMP, 2005.

Crash avoidance aided by cooperative vehicle-infrastructure communication –
Some crash avoidance systems target crash types that are best suited to cooperative communications with the infrastructure. Intersection crash prevention is the most obvious example, but many others are possible (CAMP 2005).

Human-machine interfaces for all technologies –
Suitable displays and controls are critical to the human-machine exchange of information that is intended to improve emergency transportation operations.

Many of the technologies listed above require lower-level technologies. Many existing and emerging enabling technologies are now presented in Table 4, Table 5, and Table 6 for private vehicles, emergency vehicles, and the infrastructure, respectively. Wireless communications are treated separately in following subsections. These tables are not exhaustive and include technologies that are currently available, emerging, or envisioned.

Table 3. Function-level technologies supporting vehicle-infrastructure cooperation (Multiple maturity levels indicate ongoing technology innovation and deployment)

Technology	**Maturity Level**	**Wireless Involvement**
Wireless technologies suitable for vehicle-to-vehicle or vehicle-to-infrastructure applications	Conceptual, In Development, Developed, Deployed	Yes
Automatic collision notification (ACN) systems	Developed	Yes
Wireless 911	Developed, Deployed	Yes
Automatic vehicle location (AVL)	Deployed	Yes
Traffic control device pre-emption by emergency vehicles	Conceptual, Deployed	Maybe
Route guidance – "static," i.e., without real-time traffic or conditions information	Deployed	Yes
Route guidance – "dynamic," i.e., with real-time traffic information and weather/conditions information	Developed	Yes
Emergency vehicle proximity warning for general public vehicles	Conceptual	Yes
Telemedicine	Conceptual, In Development, Developed, Deployed	Yes
TMC access to real-time data from infrastructure sensors e.g., congestion	Deployed	Maybe
TMC access to real-time data from probe vehicles	Conceptual	Yes
TMC Environmental sensing systems	Conceptual, Deployed	Maybe
Crash avoidance and pre-crash sensing aided by vehicle-to-vehicle communication	In Development	Yes
Crash avoidance aided by cooperative vehicle-infrastructure communication	In Development	Yes
Human-machine interfaces for all technologies	Concept, In Development, Developed, Deployed	Maybe

Table 4. Lower-level technologies that may be needed in private vehicles (partial list)

Likely Lower-Level Technologies for Private Vehicles
GPS
Digital maps (and associated use of GPS to locate the vehicle on the map)
Wireless communications equipment (e.g., cellular, DSRC)
Vehicle data buses carrying vehicle sensor and driver activity messages
Driver-vehicle interfaces, including audio, video, and/or haptic displays
FM/AM radio, satellite radio
Crash avoidance technologies
Pre-crash sensing and response technologies
Active brake systems
Onboard navigation (route computation)

Table 5. Lower-level technologies that may be needed onboard emergency vehicles (partial list)

Likely Lower-Level Technologies for Emergency Vehicles
All capabilities listed in Table 4 for private vehicles, plus those below:
Radio units for agency communications
Data communications service
Video cameras and frame-grabbers to provide video data
Mobile data terminal
Advanced data entry devices (e.g., fingerprint digitizers)
Telemedicine video and data systems
Signal priority request broadcast
Additional driver-vehicle interfaces

Table 6. Lower-level technologies that may be needed within the infrastructure (partial list)

Likely Lower-Level Technologies for the Infrastructure
Driver-infrastructure interface (e.g., active signs at intersections)
Sensors for traffic volume, speed (e.g., pavement loops, camera systems)
Roadside wireless communications units
Active traffic control devices (traffic signals, ramp meters), including links from those devices to transportation management centers
Dynamic messaging systems
Highway advisory radio
Reconfigurable lanes
Weather and road condition monitoring stations

2.2 Wireless communications: Candidate technologies for cooperative vehicle-infrastructure systems

Below is a list of communications technologies that may be candidates for vehicle-infrastructure communication to support emergency transportation operations. The maturity of these technologies in the transportation domain varies greatly, with some systems in use in applications for years and other systems still in the R&D phase. All technologies involve transmission of electromagnetic waves between the infrastructure and the vehicle. There are basic physical laws that strongly influence which technologies are suited for various applications. Higher carrier frequencies (such as WiFi) support higher data rates, but require more power for a given transmission range. Antenna size shrinks with higher frequencies. In addition, many other characteristics of a technology influence its applications to cooperative capabilities, including security concerns, latency, and quality of service levels. The list below introduces the technologies, while Table 7 summarizes some characteristics of these technologies.

Land mobile radio (LMR) –
Traditionally, communications among public safety, fire, and medical response agencies and their field units have been accomplished through land mobile radio systems set up in frequencies dedicated to that agency. A set of broadcast sites is used to span the necessary coverage area. Up through the mid 1990s, the frequencies of these LMRs have been in two areas of FCC allocation for public agencies: less than 512 MHz or in the 800 MHz region. These communications have been simple radio systems, trunked radio systems, or some modest integration of voice and data capabilities. As the desire for data transfer has increased over the past few decades, the agencies have sometimes been forced to trade voice for data, with the result that the data capabilities within these spectrums are limited to basics such as automatic vehicle location (AVL) and some support for mobile data terminals. The agencies have compensated for this by leasing commercial mobile radio services, such as data services using cellular technology (e.g., CDPD), or obtaining commercial services such as specialized mobile radio (e.g., Nextel).

As described in Kain (2003), these agencies are undergoing a sea of change in their communications between dispatch centers and their fleets. This is being driven by two forces, the first of which is the changes in FCC spectrum allotments that are forcing migration of public agency communications from the traditional systems into newer narrowband radio systems. The second force is the fast-moving changes in the commercial cellular technology industry. The cellular communications service providers are relevant because of the data services that were mentioned. Recent changes by the FCC are motivated in part by the desire to make more efficient use of the spectrum and to provide public agencies with more data capabilities. The frequencies below 512 MHz are being phased out and the 800 MHz region is being re-assigned to reduce interference effects, and as the effects of the FCC's rule changes that are associated with migration of TV to digital signals takes effect, some of the freed-up spectrum (700 MHz) is being allocated to public safety.

The newer narrowband land mobile radio systems will have the ability to support integrated voice and data systems. One advantage of this is the ability of agencies to retain control over their communications systems, whereas the use of commercial cellular system providers brings with it the need to make wise technical and organizational decisions to minimize the risk of consequences associated with the fast-moving and slightly unpredictable cellular service industry. The disadvantage of a dedicated communications system is that although the systems may be more tailored to the agency's needs, the supporting communications system providers do not have the same economic base to improve data capabilities as the cellular provider industry.

Commercial mobile radio services (CMRS), including cellular networks and specialized mobile radio –
U.S. public agencies have been leasing data services from cellular system providers for years, in addition to using existing mobile radio systems. These services, such as CDPD and Cellemetry, have been successful. Cellular networks operate in the 400 MHz to 1.9 GHz range, and have the advantage of requiring fewer infrastructure receivers/ transponders than some other technologies, such as DSRC. The disadvantages of cellular networks include some added latency and a lower data rate than that achievable by higher-frequency technologies. Cellular technology is developing so rapidly that specific technologies and commercial services have lifespans of only several years, providing challenges to public agencies' planning and implementations. An example is CDPD, a popular option for public safety data services, which was introduced in the late 1990s and is now being phased out. As agencies migrate to newer technologies, there can be substantial costs associated with updating hardware. One possible solution to this is a recent move toward creating standards for software-defined radios (SDR), so that SDR units are not dedicated to a particular wireless technology, but can be converted on the fly from one to the other, as the need arises (Mohney, 2005). Coverage for cellular data services may also be an issue for some rural locations.

For passenger vehicles, cellular communications have been used in the U.S. and Japan to augment onboard vehicle navigation systems with additional information such as traffic congestion or weather conditions. These make use of data packet-based cell protocols to boost data throughput. Examples of these are General Motor's OnStar system in the U.S. and Toyota's G-Book telematic service in Japan.

The cellular industry has been transitioning carrier services along a path defined by a set of "generations" that correspond to increasing capabilities and usability. Currently 2G (second generation), 2.5G, and 3G services are available, with 4G capabilities being developed. The transition paths through 3G are described in Kain 2003.

RFID or IR tags (sometimes called DSRC, but different from the 5.9GHz DSRC) –
Existing applications on four continents makes use of dedicated short-range communication (DSRC) links that are based on communications using the lower ends of the radio frequency (RF) or the infrared (IR) portion of the spectrum. Many of these are in the 915 MHz frequency range. Note that these DSRC systems are different from DSRC 802.11p systems, which are described later. (DSRC 802.11p has been a focus of recent research using the

higher 5.9 GHz band that has recently been allotted by the FCC for vehicle safety and commercial purposes.) Radio frequency identification (RFID) tags and infrared (IR) tags are used in electronic toll and traffic management systems on four continents. There are several standards (mostly proprietary and non-interoperable) that cover these, which are well summarized in Klein, 2002. RFID and IR tags may have different levels of functionality, but essentially a roadside or overhead unit transmits radio frequency or infrared energy in the vehicle's direction, and an onboard transponder or tag transmits information back to the roadside unit. In typical uses, the information returned is fairly simple, such as the tag's ID number for toll collection, or the vehicle number and loading information for commercial vehicle operations uses. It is possible to use this technology to transmit other vehicle-based data, such as vehicle speed or brake lamp status, but no significant projects have been identified that have tested this approach.

WiFi –
WiFi is a term created by a special industry group to address three separate communications standards that currently dominate the wireless local area network (LAN) domain. WiFi addresses 2.4 GHz and 5 GHz protocols, each of which has different range and data rate capabilities. The standards are IEEE 802.11a, b, and g. While these are widely used in business and home computer local area networks (LANs), there has been little use in communication between highway vehicles or between those vehicles and the roadside. Two groups of R&D activities have used these, however. First, in the U.S., the Vehicle Safety Communications Consortium that operates under the Crash Avoidance Metrics Partnership (CAMP) has been involved with Virginia Tech Transportation Institute and California-PATH with experiments using 802.11a radios for investigating countermeasures to traffic signal violation crashes via infrastructure-to-vehicle communications. In Europe, the Car to Car Communications Consortium (C2C CC) is investigating the use of 802.11a for ad hoc vehicle-vehicle communications. One drawback of WiFi is latency that will be important for some applications (crash avoidance) but may not be significant for others. Another key disadvantage for use in emergency transportation operations is that WiFi transponders are not licensed, so that there are significant security issues for sensitive applications.

DSRC (802.11p) –
In the past few years the FCC has allotted spectrum near 5.9 GHz for use in vehicle-infrastructure communications for safety and commercial applications. The IEEE has also pursued an associated standard, denoted 802.11p, under the wireless LAN umbrella. Some communities, particularly the crash avoidance community, refer to this as "DSRC," but it is noted again that the term DSRC has been used for years for many types of short-range dedicated links carried on various frequencies. For this reason, the technology will be called 802.11p DSRC in this report. The advantage of 802.11p DSRC over other technologies is a relatively high data rate system with small time latency, which can support a range up to a few hundred meters. Security and the ability to prioritize messages are also important features. At this time, however, DSRC has been implemented only in R&D projects to demonstrate feasibility. Still, the automakers such as the seven that participate in the Vehicle Safety Communications Consortium (VSCC) appear to treat this technology as a prime candidate in their R&D groups for vehicle-to-vehicle or vehicle-

infrastructure communications. The key reasons for this include (1) the standard is built on the ubiquitous 802.11a chipsets, providing cost savings, (2) 802.11p DSRC is being developed with suitable security, (3) privacy issues are being treated carefully so that individual vehicles cannot be identified, (4) small latency for high priority messages is a centerpiece of the standards, with demonstrated latencies of less than 50 ms, and (5) 802.11p DSRC is expected to have minimal problems with multiple senders (CAMP, 2004). One issue with this technology is that there may be poor communications between users separated by a “hard” obstruction, as demonstrated by the VSCC projects. This includes attempts to communicate over the crest of a hill or between vehicles that are separated by dense vegetation or other obscuration without an alternate path.

The DSRC 802.11p standard from IEEE actually addresses a subset of the necessary issues for standards, and there are several other standards addressing security, etc. As of July 2005, not all standards associated with this technology had been finalized, although lower levels of the protocols appear to be virtually defined.

Infrared beacons –

Infrared beacons can be used to communicate between vehicles and the infrastructure using optical transmissions in the infrared region. An existing example of this is traffic signal priority systems used by some first responder and public transit agencies. The vehicle broadcasts a request for signal preemption, often along with a code that identifies the vehicle. The signal that initiates transmissions is sometimes mated with the warning lights on the vehicle. The infrastructure antenna is typically located on the signal mast arm. Current optical preemption systems require that the traffic control system be equipped with an add-on module that validates and passes the request to the controller module.

One characteristic of infrared systems is the requirement for line-of-sight – that is, there must be no obstacles between the transponder and receiver. Therefore infrared is not suitable for V2V applications. Another characteristic is some sensitivity to severe weather conditions, such as snow or heavy rain, which scatters the transmission.

WiMax –

WiMax is a broadband wireless wide area network (WAN) technology that will emerge in the next few years. WiMax stations would be located within a metropolitan area, and communicate to subscribers within a range up to 30 miles. A WiMax approach could provide partial coverage of a metropolitan area. Bandwidth is not supportive of streaming video, however data rates are significant – estimates vary widely, with the upper end around 20 Mbps. Recently Intel has released alpha versions of chips for use in receiving units, which would be analogous in purpose and similar in data rate to cable or DSL modems, with products expected in 2008. There are two types of WiMax – line of sight and non-line of sight. WiMax will initially occupy an unlicensed spectrum, although there may soon be licensed spectrums available. However, emergency transportation operations require mobility, which is still a theoretical capability of WiMax.

Bluetooth –
Bluetooth is a wireless technology for personal area networks, that is, for communications within a relatively small region (1 – 10 m). Bluetooth is a trademark of the Bluetooth Special Industry Group. The first international standard based on Bluetooth has been adopted by IEEE (802.15.1) and describes the use of 2.4GHz for PAN communications. There are additional standards being drafted to achieve variations in the performance, including one that increases the data rate and another that reduces the power requirements. Bluetooth is typically used for communications between personal computers and peripherals, including cellular phones and personal data assistants. An automotive example of a Bluetooth application is the use by GM in current automotive products to allow synchronization of hands-free phones, PDAs, and so on. As an unlicensed entity, Bluetooth is also vulnerable to security issues, as illustrated by the current issues with viruses on Bluetooth-enabled cell phones. Wireless PAN technologies are most suited to within-vehicle communications or for synchronizing portable devices that emergency personnel may carry to the equipment in their vehicle.

Zigbee –
Zigbee is the name given to another personal area network standard that is characterized by its simplicity and low power needs. Zigbee is aimed at connecting nearby sensors or simple devices, such as thermostats. Zigbee will not likely play a significant role in emergency transportation operations.

Ultra Wide Band and Wireless USB –
Ultrawide band is another wireless personal area network technology with higher data rates and low power needs than Bluetooth. There has been an inability, however, of working groups to settle on a standard and, partially in response to this, Intel has recently indicated it will abandon ultrawide band and pursue "wireless USB." Wireless USB would use much the same protocol stack as USB. It is impossible to predict the outcome of the struggles over defining the second generation of wireless PANs, but for the purposes of this report, PANs are not central to the questions of how to harness vehicle-to-infrastructure technologies to further emergency transportation operations.

VICS (*Japan; not listed in Table 7*) –
Japan has deployed the Vehicle Information and Communications System (VICS) in several large cities to provide drivers with real-time information on road and traffic conditions. This system is mentioned here because it is an existing infrastructure-to-vehicle system in daily operation. VICS uses three broadcast technologies for infrastructure-to-vehicle communications, one of which is a multiplexed FM signal that is carried by local radio stations between 88 and 108 MHz. The FM signal provides a one-way communication to the vehicle. FM radio broadcasting covers a large area but has limited data rates and cannot efficiently provide information specific to locales within the broadcast areas. The VICS system also uses one-way broadcasts from infrared transmitters mounted above traffic lanes on major trunklines. These systems have moderately high data rates. The third communication path is radio frequency transmissions from roadside beacons with ranges of 60 – 70 m.

Table 7. Candidate communication technologies for vehicle-infrastructure communication

Technology	Paths	Range (m)	Theoretical Data Rate* (Mbps)	Latency	Off-the-Shelf?	Example	Maturity	Remarks
Land mobile radio	V2V, V2I, I2V	40,000	Various	Moderate	Yes	Emergency dispatch	Currently in use (U.S.)	Transitioning from wide to narrowband
Cellular data services, 2G, 2.5G	I2V, V2I	10,000	0.4 (GPRS) 0.3 (1xRTT)	Moderate	Yes	2G: GSM, CDMA, etc. 2.5G: GPRS 1xRTT	Currently in use	Delays & possible availability issues. Data rates depend on setup.
Cellular wireless – 3G	V2I, I2V	10,000	2.4 (1xEvDO)	Moderate	Yes	WCDMA, 1x-EvDO	Becoming available in U.S.	Delays & possible availability issues
Cellular data, 4G	V2I, I2V	10,000		Moderate	No		In development	
Radio freq id. tags (RFID)	V2I, I2V	< 30m	0.5	Low	Yes	Electronic toll collection, CVO	In use; low interoperability	Low flexibility, low data rate
IEEE 802.11a (WiFi)	V2V, V2I, I2V	100-200	54	High	Yes	CAMP VSCC (U.S. research). C2C CC (Eur.)	Infra-veh experiments by CAMP, C2C CC	Security & latency an issue
IEEE 802.11b and g (WiFi)	V2V, V2I,I2V	10-100	11 (b) 54 (g)	High	Yes	Wireless LAN	802.11g may replace 802.11b	Security & latency issues.
IEEE 802.11p (DSRC)	V2V, I2V,V2I	250	6-27	Low	No	CAMP VSCC (research)	V2V, V2I, I2V experiments	Prototype stage, but promising
Infrared	V2I, I2V	200m	Modest	Low	Yes	3M Opticom signal preemption	Currently in use	Line of sight only
WiMax	I2V, V2I	20,000	0.5 - 20	Moderate	In 2006	Enterprise WAN	Emerging. IEEE 802.16d, e	Coverage & security likely issues in near term
Bluetooth	Within vehicle	1-10+	0.7	Moderate	Yes	General Motors in-vehicle	Currently in use. IEEE 802.15.1	Security & data rates an issue. Max 7 nodes.
Zigbee	Within vehicle	1-75+	0.25	Low	No	Building heating-cooling systems	Builds on IEEE 802.15.4	Low data rates & limited range

* Data rates are for base station to mobile. Application-related data for transmissions in operating environments may be much lower than values provided in the table.

Another key issue in evaluating communications alternatives is the vulnerabilities of particular systems and the compatibility of this with the missions that depend on the system. Vulnerabilities for cooperative communications enabling emergency transportation operations may include:

- Coverage limitations (geographical reach)
- Latency and/or unavailability due to busy networks
- Reliance on the power grid
- Reliance on the Internet
- Security of communications
- Dependence on commercial entities

Figure 3 below illustrates two of these dimensions: coverage and time latency of messages. The ordinate of the graph is related to coverage, so that infrared and RFID techniques are at one extreme, being very localized approaches, and satellite radio and FM/AM broadcasts are at the other extreme due to their broader coverage. The abscissa addresses time delays of messages, including time latency or the difficulty in receiving a connection. FM/AM broadcasts are at one end because of the time needed to broadcast a voice message, but more importantly because drivers may not have their radios on. DSRC has the lowest latency, with high priority messages available within a few tenths of a second, once the message is known and is sent to the DSRC radio transponder. While this figure is approximate, it is included here to indicate a few of the many tradeoffs of these technologies. Clearly different types of messages may be sent through communications channels best suited to those messages.

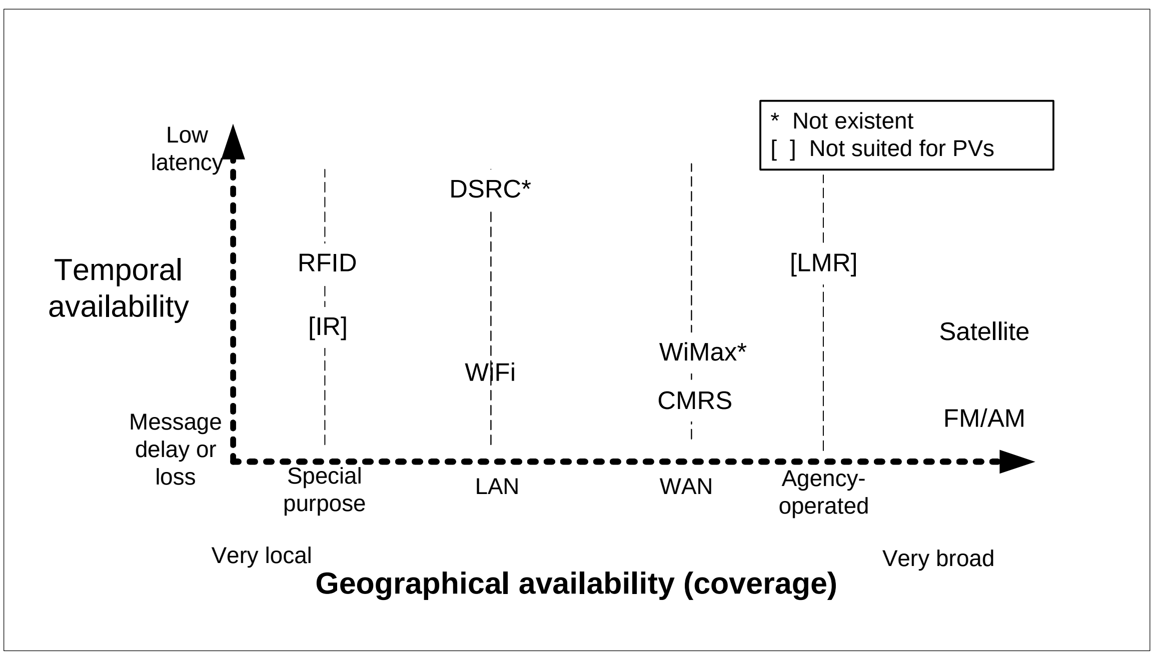

Figure 3. Relative availability for cooperative communications technologies

3.0 VII APPLICATIONS FOR EMERGENCY TRANSPORTATION OPERATIONS

This section first develops a framework for considering VII applications in emergency transportation by elaborating on the general framework introduced in Section 1.2. Sections 3.2 through 3.4 then address applications within that framework.

3.1 Communications modalities in emergency transportation operations

Sixteen different communications modalities are described here, in order to assist with the later description of candidate communication technologies for emergency transportation operations systems. The sixteen modalities result from the definition of four generic types of communications nodes or endpoints, so that the modalities are defined as linking one type of the four communication endpoints with another of the four. In Section 1.2, it was noted that two communications endpoints could be defined – vehicles and infrastructure. This yielded four modalities, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), infrastructure to vehicle (I2V), and another modality that is not directly relevant to a study of cooperative elements, the communication between infrastructure elements (I2I).

For this technology discussion, however, it is useful to further break down the vehicle category into emergency vehicles (EVs) and all other vehicles, denoted as PV (private vehicles), because of the difference in the roles of each and the type of technology that may be installed on each. In addition, for completeness, the infrastructure components can be described as centers (C) and field-based locations (F), as done in NTCIP (2002). Centers are brick-and-mortar facilities, such as transportation management centers, public safety answering points, emergency operation centers, dispatch centers, hospitals, National Guard command centers, etc. Field locations may be dynamic messaging signs, loops, ramp meters, environmental sensing stations, traffic control devices, roadside wireless communications units, and so on. This breakdown into centers and field elements is done here for completeness, since many emergency transportation operations capabilities that involve cooperative elements also lead to wireless communications between these infrastructure elements. As emergency transportation operations systems are conceived and developed, then, the decisions about the communications structures and technologies may be influenced by considerations of these infrastructure-only elements.

Other possible important communications endpoints include transit vehicles, such as buses, subways, trains, etc. These elements must be considered carefully in preparing and executing emergency transportation operations strategies; however, they are not addressed explicitly in this report.

Using the four types of endpoints defined (EV, PV, C, and F), a table of sixteen cells can be created such that each cell relates to communications initiated by one of the four elements and ends at another element. This is shown in Table 8. That table also shows the mapping among elements that indicates that each of the three groups of modalities (V2V, V2I, and I2V) consists of four modalities. Furthermore, there are communications within the infrastructure system that may also be described using four modalities, such as center-to-field. Infrastructure-only modalities are discussed at length in NTCIP (2002), but are outside the scope of this report. By not focusing on I2I communication, this leaves twelve modalities of interest. Recalling Figure 1 that showed the V2V, V2I, and I2V modalities of cooperative information exchange, the blocks in that figure can be rearranged and subdivided, as shown in Figure 4 below.

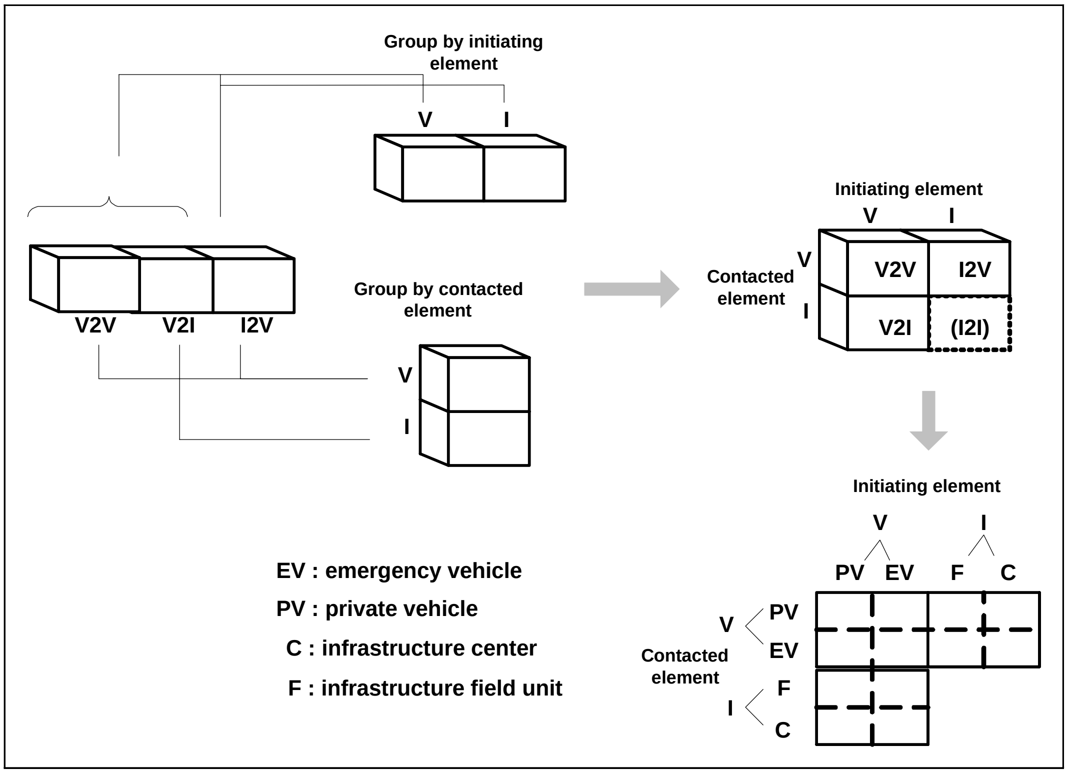

Figure 4. Arranging the VII component state space to highlight communications endpoints

Table 8. Modalities of cooperative communications

Type of Communications	Initiating Element	Contacted Element
V2V: Vehicle-to-vehicle	Private vehicle	Private vehicle
"	"	Emergency vehicle
"	Emergency vehicle	Private vehicle
"	"	Emergency vehicle
V2I: Vehicle-to-infrastructure	Private vehicle	Component(s) of infrastructure
"	Emergency vehicle	Component(s) of infrastructure
I2V: Infrastructure-to-vehicle	Component(s) of infrastructure	Private vehicle
"	"	Emergency vehicle
I2I: Infrastructure-to-infrastructure	Component(s) of infrastructure	Component(s) of infrastructure

For each of the modalities, Table 9 shows an example of communications that might occur within that cell during an emergency transportation operations event.

Table 9. Examples of cooperative emergency transportation operations communications

Type of Communications	Initiating Element	Contacted Element	Example of Communication
V2V	Private vehicle	Private vehicle	V2V data to support crash avoidance
V2V	Private vehicle	Emerg. vehicle	V2V data to support crash avoidance
V2V	Emerg. vehicle	Private vehicle	Warn vehicles that EV is approaching
V2V	Emerg. vehicle	Emerg. vehicle	Mobile radio communication for coordinating
V2I	Private vehicle	Infrastructure	Probe data to assist with congestion or damage estimates
V2I	Emerg. vehicle	Infrastructure	Optical signal from EV to traffic signal for signal priority
I2V	Infrastructure	Private vehicle	Relay evacuation info via hwy advisory radio
I2V	Infrastructure	Emerg. vehicle	Relaying information about incident, e.g., hazardous materials info
I2I	Infrastructure	Infrastructure	Not applicable

3.2 Vehicle-to-vehicle (V2V) communication

Table 10 shows the four possible combinations of V2V communication.

Table 10. Communication across vehicles

Initiating Element	Contacted Element	Type of Communications
EV2EV: Emergency-vehicle-to-emergency-vehicle	Emergency vehicle	Emergency vehicle
EV2PV: Emergency-vehicle-to-private-vehicle	Emergency vehicle	Private vehicle
PV2EV: Private-vehicle-to-emergency-vehicle	Private vehicle	Emergency vehicle
PV2PV: Private-vehicle-to-private-vehicle	Private vehicle	Private vehicle

Only three types of communications, those concerning emergency vehicles, will be discussed. The fourth type, private vehicle to private vehicle, is beyond the scope of this project. However, this category remains important for crash avoidance and other non-emergency vehicle operations, and requirements for those applications will strongly influence the available communications options for those vehicles.

Levels of communications equipment can be expected to vary with the type of vehicle. Emergency vehicles will have the most sophisticated and complex capabilities. Private vehicles, especially passenger cars used by individual drivers, will provide much less communications capability. This distinction is vital since it is the lowest common denominator that will limit communication between emergency and private vehicles. Some of the sophisticated communications equipment in emergency vehicles may not be useful or compatible with equipment in private vehicles.

3.2.1 Communication between emergency vehicles

It is quite common for more than one single emergency vehicle to respond to an event or incident. Sometimes multiple vehicles from the same organization (e.g., two fire department vehicles) respond. Usually multiple vehicles are from separate organizations (e.g., ambulance and police), and often there are responders from more than one jurisdiction. In many cases, there is a need for communication between all emergency vehicles responding.

This communication need is most often met by external dispatchers who coordinate emergency responses. It seems likely that some of this information can be communicated directly among responding vehicles, eliminating some of the workload and possible delay associated with external dispatchers. For example, the first unit responding to an emergency may need to know when the next vehicle will arrive, as well as what type of vehicle it will be. These questions can be answered directly by some forms of communications technology, especially when the vehicles are in proximity. Aviation communications technology offers some insight into this problem. At one time, dispatchers (air traffic controllers) had the sole responsibility for separating airplanes not in visual contact. By the time visual contact was established, it might be too late or too difficult for pilots to take appropriate evasive action. Modern communications technology now has collision warning systems in flight decks that both notify pilots of airspace incursions and command coordinated avoidance responses (Plane A descend- Plane B ascend) much more rapidly than voice commands from air traffic control. Emergency vehicles responding to an incident can announce their estimated time of arrival and vehicle capabilities directly to other emergency vehicles, without having to route information through dispatchers. This can be especially valuable when the vehicles belong to different organizations that may not share the dispatching function in real time.

Another example of the need to communicate directly among emergency vehicles is when the response to incidents involves responders from neighboring agencies. It is often valuable to have on-scene coordination, which involves awareness of asset locations and ongoing communications between responders in their vehicles. Voice is the primary need in this example, although data sharing between vehicles (including video) and with the dispatch centers gives responders more effectiveness. The technology for this interoperable communications is likely to be the next generation of mobile radio that meets the Association of Public Agency Communications Officers (APCO) 25 interoperability standards (see Section 2). Public agencies also use commercial radio services based on cellular technology, but the use of these across agencies requires the agencies to share providers.

3.2.2 Communication from emergency vehicles to private vehicles

At present, EV2PV communication is limited by the direct sensory perception and awareness of the private vehicle driver. Emergency vehicles signal their presence first by auditory alarms, such as sirens and horns, and then by visual warnings, such as flashing lights. Even when an approaching emergency vehicle is correctly detected by a private driver, it is quite difficult for the driver to determine the direction from which the emergency vehicle is approaching; it has been known for some time that auditory localization of warning alarms is not readily accomplished within a closed vehicle (Caelli & Porter, 1980).

VII technology could be used to provide in-vehicle warning and location direction that would alert the driver and also specify the direction of approaching emergency vehicles. Direct communication between the vehicles using DSRC is likely to be the most effective path, given the VII vision for DSRC implementation in the U.S. passenger vehicle fleet, as well as its low latency capabilities.

3.2.3 Communication from private vehicles to emergency vehicles

At present, PV2EV communication does not exist, unless there is a crash between an emergency vehicle and a private vehicle. However, the same benefits that are being forecast (e.g., CAMP Task 3 report) for PV2PV communication can also help avoid crashes between private and emergency vehicles. Since emergency vehicles will have more sophisticated communication equipment, with greater computing power, it might be possible to create a crash-potential map to aid the emergency vehicle driver. However, great care will be required to prevent high false-alarm rates which will cause the emergency-vehicle driver to ignore such map information.

Automatic incident location might be another benefit of PV2EV communication. Currently, emergency vehicles depend on dispatcher information to locate incidents. The disabled vehicle, in turn, may be located by the public safety answering point (PSAP) and provided to the dispatcher using various technologies. Existing technology for this includes the caller's description of the location, estimates of a cell phone caller's location using cellular technology (E911), and automatic crash notification (ACN) devices (Butler, 2002). E911 is still emerging, as discussed in Section 3.1. It is conceivable that in certain circumstances DSRC communications could play a role as well. Although the range of DSRC is only 200-500 meters, and the survivability of the onboard DSRC unit is not yet defined, such a capability may be useful when a disabled vehicle is not easily spotted from the highway, e.g., road departure underneath a bridge.

3.3 Vehicle-to-infrastructure (V2I) communication

Safety and mobility can be improved by having emergency vehicles send information to the roadway infrastructure. This section discusses two examples of V2I communication:

- Traffic signal preemption
- Vehicle probe information

The simplest form of traffic signal preemption has the emergency vehicle send a message to each traffic signal as the vehicle approaches. Current hardware for this technology, such as the 3M Opticom, uses line-of-sight signals from emitters mounted on the emergency vehicle. Hence, optical preemption does not work around curves and when obstructions, such as trees in a median, block the traffic signal. The high setting of this device activates the traffic signal from 0.5 miles away and holds it on green for 15 seconds after the preemption signal goes off. Fire and rescue vehicles typically have the emitter either mounted on the warning light bar and controlled by the warning lights or mounted and controlled independently of the warning lights (FEMA, 2004). Controlling the emitter automatically, when the warning lights are turned on or off, works well. However, there have been some problems with older independent systems when operators fail to manually deactivate the system. This results in nearby signals holding on green and tying up traffic (FEMA, 2004).

There is a serious safety problem with optical preemption when two vehicles approach a traffic signal from perpendicular directions. The first vehicle to reach the signal is in control. The driver of the second vehicle thinks he or she is in control and often trusts the device to change the signal. Such misplaced confidence is termed automation complacency by human factors experts. Operators assume equipment will automatically produce the desired state of the environment and fail to monitor events carefully. This is not an abstract theoretical construct: In 1990 the Plano Texas Fire Department had a serious collision between an engine and a ladder truck. The ladder truck had preempted the signal and was struck by the engine. The driver of the engine suffered from automation complacency, since in his experience traffic lights had been captured as expected, and so he failed to monitor the intersection properly for vehicle conflicts. This problem can be solved by I2V message capability (see Section 3.4) that allows each signal to automatically announce its presence and condition to an approaching emergency vehicle. Approaching emergency vehicles would be notified when a signal was already preempted.

The technology that appears best suited for this scenario is two-way DSRC communication between the individual emergency vehicles and a roadside unit at the intersection. The application is localized and requires low latency, which are both natural fits with DSRC. The VII vision includes the installation of DSRC units at major intersections – which would include most intersections with preemption capabilities. The Cooperative Intersection Collision Avoidance System (CICAS) program currently being developed by the ITS JPO envisions intersection-based DSRC units that broadcast signal state and possible approaching vehicle information to nearby traffic. The coordination of emergency vehicles approaching on a possible collision path is a natural extension of the CICAS type of system.

A more sophisticated form of traffic signal preemption allows the emergency vehicle to set up its entire route in advance, rather than waiting to approach each signal. This is in some ways similar to the waypoint navigation systems used in airplanes where the entire route is programmed before the plane departs. If the communications system in the emergency vehicle can receive real-time traffic I2V information (see Section 3.4), an optimal route can be established. The vehicle can also use V2I messages to continually update its destination about projected arrival time.

A theoretical study of a route-based preemption strategy was conducted by Kwon and Kim (2003). The goal was to provide the most efficient and safe route for an emergency vehicle by using dynamic route clearance and online route selection. Using Dijkstra's algorithm, the system computes the least congested route and the safest signal phase for each intersection. Then the dynamic preemption module controls the signals on the selected emergency route. The sub-goal is to minimize or clear the traffic queue for the approaching emergency vehicle. Results showed a potential benefit of 10-16% in reduction of travel time for the emergency vehicle. There were some limitations in the study that the authors have noted: (1) the online route selection method could not be tested, and (2) more field testing is needed. Nevertheless, this is a promising beginning and indicates a potentially useful application of V2I technology.

The strategy of Kwon and Kim could be implemented using a combination of communications technologies:

- Direct communications between the emergency vehicle and the dispatch center to locate the vehicle's initial point (using the agency's AVL system)
- Use of DSRC-collected data from a vehicle in traffic to understand the existing traffic congestion state, to support the route selection computation
- Transmission of the selected route to the emergency vehicle, again using the agency's basic data technology (land mobile radios, typically)
- Use of infrastructure communications to dictate to traffic control devices the necessary adjustments to signal phase (existing infrastructure systems commonly use fiber optic, radio, or even optics for some links)

- Use of DSRC-based vehicle-to-vehicle and vehicle-roadside communications to warn other traffic of the emergency vehicle's approach, as well as to alert traffic control devices at upcoming intersections of the vehicle's approach

The second application of V2I technology uses the emergency vehicle as a probe. The probe vehicle sends information about its local roadway environment (e.g., congestion, ice on the road, etc.) to the infrastructure. The utility of vehicle probes has been a long-term theme of intelligent transportation systems going back at least as far as the Florida field tests of TravTek. Since emergency vehicles are likely to have more communications equipment than private vehicles, and since it will be easier to implement such equipment updates in the emergency vehicle fleet relative to the much larger private vehicle fleet, it makes sense to plan for probe communications ability in emergency vehicles. For example, if the first responding emergency vehicle has probe capability, such information could be utilized by later responders to minimize their travel time to an incident. The first generation of emergency-vehicle-as-probe would use the agency's existing automatic vehicle location (AVL) capabilities, which are typically supported on the mobile radio system. Future applications could use upgraded AVL functions that may reside on the agency's wireless data system (mobile radio or leased commercial cellular technology services).

3.4 Infrastructure-to-vehicle (I2V) communication

The basic concept of the infrastructure sending information to the vehicle is far from new in highway transportation. Variable message signs inform the driver about roadway events. Highway advisory radio accomplishes this same goal with the additional advantage of being presented inside the vehicle. However, both of these technologies have the limitation of being available only at point sources where signs or transmitters are placed on the roadway. Modern I2V technology may be able to present information inside the vehicle continuously (see Figure 3 on page 21). In urban areas where roadside units may become commonplace, LAN technologies (DSRC, WiFi) may provide adequate coverage. In areas with fewer roadside units, technologies with broad coverage zones would be required – such as cellular systems, WiMax, or satellite-based communications.

This section considers four examples of I2V communication:

- Congestion information
- Work zone information
- Emergency vehicle ahead
- Evacuation

The presentation of congestion information has been a staple in using intelligent transportation systems to improve vehicle mobility. While the Orlando TravTek study validated the proof of concept for this, the overall system did not work well because the number of probe vehicles was quite limited. Congestion displayed on the vehicle navigation map had often disbursed by the time the subject vehicle arrived. Technical improvements since then have been substantial and you can now purchase a private vehicle that supplies more accurate congestion information. The human factors principles of how to best display this information in a navigation system are well understood and solid guidelines are available to the designer (Campbell, Carney & Kantowitz, 1998). Accurate congestion information is particularly vital for emergency vehicles where time saved translates directly into lives saved.

Work zones are a priority area for all vehicles. While much of the focus of this research has been on improving the safety of highway workers, there are important safety issues that are salient for emergency vehicles as well. One critical work zone problem is the great variability associated with the queue that can build up approaching a work zone. A project in progress at UMTRI sponsored by FHWA is finding solutions to warning drivers about work zone queues using smart barrels that detect the tail of the queue and issue warning signals to approaching vehicles. This is particularly valuable when the queue is unusually long since it provides early warning to the approaching emergency vehicle. While the current version of smart barrels uses a visual signal to communicate with drivers, future developments could include DSRC links directly to approaching vehicles. It will also be possible to alert the driver that an active work zone is located ahead, even before the tail of the queue and any smart barrels are reached.

In a similar manner, a private vehicle could be notified that an emergency vehicle is located ahead. This would be similar to information currently provided by variable message signs and highway advisory radio. However, such information, as already noted, would have the advantage of both being presented continuously and within the vehicle.

Since emergency vehicle operations have a tendency to produce traffic queues, even when the vehicles are located on the side of the road not blocking any lanes, advance warning would assist the approaching driver. Information could also be provided about the nature of the incident and about delays and queue speed. This would increase safety in low visibility road conditions and when geometric features of the highway obscure long sight distances.

One promising area for the application of I2V communications technology is emergency evacuation from an area due to a natural disaster or terrorist incident. A communications technology that can reach large numbers of vehicles quickly is required to manage evacuations. Broadcasting to passenger vehicles could be accomplished using various approaches:

- FM/AM radio broadcasts using existing commercial or public outlets
- Existing fixed or portable dynamic messaging signs (DSM)
- DSRC or other wireless local area network communications from roadside units to vehicles near the roadside units
- Use of any cellular-based in-vehicle systems that might exist

The best-case timeline for DSRC deployment was estimated in Section 2. In the next five years, there is not likely to be a significant portion of the U.S. passenger fleet with DSRC capability (<1%). This is because prototyping research has been going on for only a few years (CAMP, 2004). In the best-case scenario that all manufacturers decided in four years to equip all vehicles sold in the U.S., the penetration in the fleet would reach 25% in 2014 and 50% in 2017. This assumes that the time from the industry decision to the time that vehicles are available is two years, and that 25% of the fleet turns over every three years.

The concept of operations for emergency transportation operations has been recently reviewed for FHWA (SAIC, 2004). Evacuation scenarios for hurricanes, terrorism events, and earthquakes are described in this report. Nine critical transportation functions, similar to those reviewed in Section 2.1 of the present report, were listed. Of these nine, the following three may be excellent candidates for use of I2V technology:

- Traffic control strategies to support emergency response and evacuation
- Management of unexpected capacity reductions on detours and evacuation routes
- Warning and public information/traveler alert requirements

Supporting communications technologies for these capabilities may involve:

- Collecting the state of traffic flow and identifying disabled and active routes using DSRC-enabled vehicle probe data
- Centralizing control of traffic control devices using existing technologies (fiber optics, radio, microwave, etc.), possibly with this capability “networked” for temporary direct control by a regional authority during emergency periods
- Communicating with passenger vehicles to pass along route information, as described above
- Re-routing emergency vehicles based on congestion and road closure information

While several proprietary computer simulations for evacuation exist, they are based upon current conditions and do not estimate network clearance time. Recent work (Radwan et al., 2005) expands this framework. However, such simulations deal with static data, such as estimating evacuation times before a disaster occurs; our review was unable to locate any computer models for dynamic evacuation with real-time data. This may be a key information gap. How will the infrastructure be able to coordinate data it sends to vehicles? A dynamic model would be a great help and might prevent or minimize new congestion that could occur when large numbers of vehicles respond to information sent by the infrastructure.

4.0 ANALYSIS OF GAPS

This section focuses on critical gaps that might retard development and deployment of VII, especially as it applies to emergency transportation operations. This is a moving target since the rapid development of VII concepts both fills old gaps while possibly creating new gaps.

In this paper gaps are organized into the following categories:

- Communication capability and interoperability
- Communication cost structures
- Socio-technical issues
- Vulnerabilities of communications
- Human-machine interface issues
- Public agencies ceding control to individual drivers
- System-level gaps associated with possible service concepts

Introduction of any new technology creates a fundamental gap between the old technology and its newer replacement. This has been widely studied in industry with case examples of successful older companies being unable to respond effectively to the challenge of new competition with newer technology (Foster, 1986). The adoption of new technology when plotted over time yields an S-shaped curve as shown in Figure 5. Initial adoption of new technology is slow while economies of scale and experience are accumulated. Eventually the new technology takes off and provides sharp increases in productivity. But as the technology becomes mature, such gains slow down; this creates an opportunity for a new replacement technology.

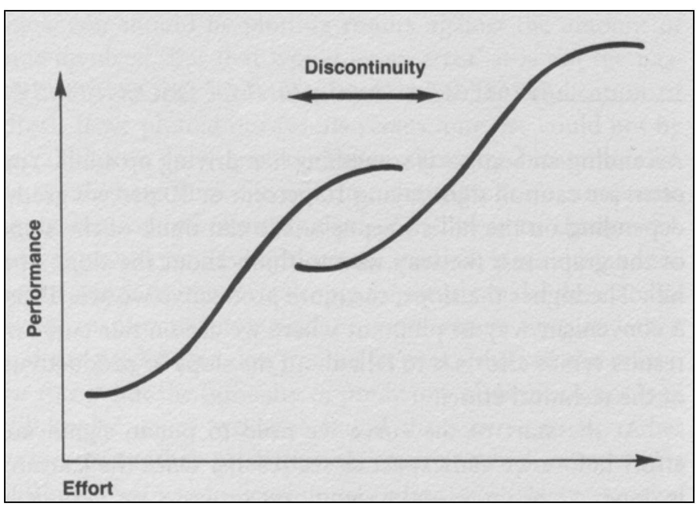

Figure 5. Conceptual illustration of a technology jump (from Foster 1986)

Figure 5 shows S-curves for a mature (left) and a new replacement technology (right). The most salient part of this figure is the gap between the two S-curves. At first, the new technology cannot beat the old technology. But as the new technology improves, it surpasses the old technology. As discussed in Sections 2 and 3, VII represents the new technology and it will eventually replace existing older technologies such as highway advisory radio and roadway variable message signs. For example, if messages can be presented inside the vehicle, why have any roadway message signs that are expensive to build, maintain and operate (e.g., Eby & Kantowitz, 2005).

The gap between S-curves for VII and existing technology is the root cause of the more specific gaps listed above and discussed in this report. Jumping from the old curve to the new curve represents a major discontinuity in transportation operations. As the minor discontinuities represented by specific gaps are removed, the probability of jumping from the old technology curve to the new technology curve increases. As more adopters join the new technology, considerable effort is put into closing all remaining gaps. Once a critical mass is established for the new technology, there is a stampede away from the old technology. Organizations that refuse to make the jump usually wither and die because they cannot compete with the productivity gains offered by the new technology. Public agencies may initially survive if they do not make the jump since they are immune to some of the creative destruction of capitalism. However, if they choose to ignore progress, eventually they will be regarded as irrelevant by the public with a consequent loss of effectiveness and budget.

Finally, section 4.8 summarizes the gaps identified and possible actions that the DOT might take to help close the gaps.

4.1 Communication capability and interoperability

Section 3 presented several candidate technologies to support cooperative vehicle-infrastructure communications. The VII program has focused on the deployment of dedicated short-range communications (DSRC) in the 5.9 GHz band as the basis for cooperative communications between vehicles and the roadside. In the specific context of emergency transportation operations, however, DSRC will be one component of wireless communications. Emergency vehicles will have more capability than private vehicles. This is because emergency transportation operations will need data sets to be rich and flexible, and coverage will need to be seamless. DSRC is not intended to support these requirements by itself. Instead, emergency vehicles are able to support more investment in onboard communications technologies, so that additional technologies are viable and can be expected onboard emergency vehicles.

The technologies discussed in Section 3 that will likely be factors as well include:

- Land mobile radios
- Cellular-based systems (sometimes called commercial mobile radio services)
- WiFi (Wireless Fidelity)
- DSRC
- WiMax (Worldwide Interoperability for Microwave Access)

The authors of this report speculate that the most likely scenario for wireless use in 10 to 15 years will include land mobile radios with DSRC as a backup in certain conditions.

Predicting gaps in communications technologies that may be associated with VII or emergency transportation operations is challenging. One challenge is that the current pace of innovation in wireless communications is very fast, so that the current expectations of technologies will not be able to account for future developments that are not yet on the horizon. In addition, because the planning and execution of emergency transportation operations are primarily done at the local and regional levels, the coming years will probably see many unique and possibly equally effective combinations of communications technologies. This is because local and regional agencies will make choices depending on many factors including legacy systems and the prospective coverage areas and radio traffic. Therefore, a gaps analysis faces the challenge of concluding that one set of communications technologies will be used, while future developments may result in a different set being available. Nevertheless, it is instructive to identify the anticipated gaps in each communications technology, so that the remaining candidates are better understood.

The decision to deploy the public sector of VII is expected to be made in approximately 2008 or 2009, according to automotive manufacturer and U.S. DOT comments at the 2005 annual meeting of the Intelligent Transportation Society of Michigan. At that time, Ford Motor Company provided a best-case estimate of penetration of DSRC-equipped vehicles, showing the penetration within the U.S. private passenger car fleet reaching 10% by approximately 2012, 50% by 2017, and 95% by approximately 2020 or 2025 (Robinson, 2005). This was based on an assumption of the gradual rollout of DSRC in all vehicles, beginning in 2010-2011. The limiting constraint, of course, is that the average life of this class of vehicle is on the order of 11 or 12 years.

This paper assumes a more rapid deployment of infrastructure-based DSRC, so that some capabilities could be widely available within eight years of a deployment decision, or 2017. In any case, the gaps analysis here will assume that the time frame of interest is from the current time until approximately 2012.

The following sections present a relative ranking of communications technologies with regards to several attributes that are relevant to this study. We now address the strengths and weaknesses of individual communication technologies, and then summarize the gaps associated with each technology. Finally, in Section 4.8, a summary of simple actions are suggested to pursue the most important gaps.

Land mobile radio –
Land mobile radio systems are the newer generations of traditional first-responder agency dispatch systems, including trunked radio systems. Section 3 discussed some of the restructuring of the public agency spectrum by the FCC; the bottom line is a forced migration for most agencies to newer narrowband channels during the first 10 to 15 years of the new century. The timing of this is significant for our interests, because most agencies will have made communications upgrades within 10 to 15 years of the time VII begins to roll out. Therefore the capabilities of land mobile radio systems will not be influenced much by current research until approximately 2020, when the next upgrade cycle begins.

A significant advantage of land mobile radios is that the system is under the control of the public agency, so that its vulnerabilities are known and manageable. New generations of land mobile radio will have a higher data rate than the older systems, which had almost no data capabilities. Still, the newer systems may not have data rates comparable with higher frequency technologies such as WiFi. Another drawback of land mobile radio systems is that historically an upgrade involves extensive hardware changes on the vehicles as well as at the dispatch center.

A major gap in land mobile radios has been the general lack of interoperability between agencies or between neighboring jurisdictions. The so-called Project 25 industry standard set should help reduce this impediment. One advisable action seems to be the encouragement of land mobile radio standards to adopt full interoperability as soon as possible.

Cellular technology (also called commercial mobile radio services) –
Cellular technology has been used by first and second responder agencies, as well as law enforcement, through the leasing of data services from commercial service providers. The advantage of these services is that agencies can take advantage of the economies of scale involved with cellular systems, which are of course largely provided by business and consumer customers. Capabilities of cellular systems will continue to grow rapidly. The disadvantage of this, of course, is a lack of control over the infrastructure and the need to keep up with new versions of cellular protocols that arrive. Another related drawback is that signals are subject to delay or could even be locked out of a busy system.

Gaps for cellular capabilities include the stability of hardware and services, coverage gaps, and competition for bandwidth.

WiFi –
The advantage of WiFi is its data rates, as well as the fact that it leverages the economies of scale on hardware elements with this popular wireless standard. WiFi coverage is currently an issue in almost all parts of the U.S.

The disadvantages of WiFi include some data security risks and the lack of an existing and proven WiFi infrastructure. Although there is a significant movement whereby many municipalities have created, or plan to create, WiFi zones that cover their entire communities, additional access points would be required. First responder agencies will not create WiFi coverage for their own purposes – this is not economically viable. Instead, they would piggyback on coverage that is driven by economically-induced initiatives within their own community.

DSRC (802.11p) –
As discussed in the Section 3, DSRC is specifically designed for vehicle-to-vehicle and vehicle-to-infrastructure use. DSRC is more suitable than WiFi in several areas, including low latency, prioritization mechanisms, and security. However, DSRC deployment depends on the outcome of the next few years of investigation by the U.S. DOT, state DOTs, and automobile manufacturers. Assuming that a decision to deploy is made by all parties, the obvious gap will be the actual deployment. In general, deployment of VII will have three aspects: physical installation of infrastructure including roadside units, creation of a backhaul capability to connect

the roadside units with an architecture (FHWA, 2005), and gradual penetration of onboard units into the passenger vehicle market. For emergency transportation operations, there are important steps including installing DSRC onboard units into emergency vehicles as well as interfacing operations with the VII architecture. In summary, capability gaps with DSRC will include deployment within the infrastructure, within the passenger vehicle fleet and the emergency vehicle fleet, and interfacing operational systems with the VII system.

WiMax –
At the time of this project, WiMax is still in the final stages of development, with mobile applications not expected until 2007, according to an Intel presentation at the Intelligent Transportation Society of Michigan (Hoffman, 2005). Therefore, the performance capability of WiMax on moving vehicles is still theoretical and not well documented. There are several other characteristics of WiMax that are not well understood at this time, including the business model of deployment. It is assumed in this report that agencies would lease bandwidth on municipal-wide WiMax systems provided by commercial entities. Sharing bandwidth with other applications may lead to disadvantages discussed earlier with cellular technology.

A final observation is that a basic gap in all of these technologies is that the communications infrastructure evolves faster than the supporting equipment wears out. Therefore periodic upgrades are made, which are expensive and consume many resources. An action to address this would be to investigate the feasibility and benefits that may be offered by a nascent effort to define software-definable radio technology (SDR). SDR would mean that changes in the communications technology (e.g., DSRC to WiMax) would not require hardware changes in vehicles or on the roadside (SDRF, 2005). The SDR radio would be configurable by downloading software. Clearly this is in a time frame that is longer than VII deployment, but the promises are so great that the U.S. DOT may wish to investigate further.

Table 11. Rating the suitability of communication technologies for emergency transportation operations

1 = highly desirable, 2 = adequate, 3 = barely adequate or inadequate, TBD=to be determined

Capability	Land Mobile Radio	Cellular/ CMRS	WiFi	DSRC	WiMax
Data rate	2	2	1	2	1
Security	1	2	3	1	TBD
Low latency	1	3	2	1	TBD
Interoperability	3	1	1	2	1
Upgradable	3	2	3	3	TBD
Coverage	1	2	3	2	1
Controllability of coverage	1	3	3	2	2

4.2 Cost and cost stability

Cost and cost stability are important to consider since they affect both the viability of specific technologies as well as the likelihood that those technologies will remain in the marketplace. It is difficult to estimate cost figures that might apply at the time of VII deployments; however, several observations can be made to support conjectures on relative costs.

Land mobile radio systems –
Since land mobile radio is deployed by the public agencies in a jurisdiction, all deployment, maintenance, and operational charges are borne by those agencies. One advantage of these systems is obviously that it is an integrated package generally supplied by a single vendor. These systems are relatively more expensive than leasing similar bandwidths on commercial networks, such as cellular systems of the future. One advantage of this agency-operating model, however, is that the costs are relatively predictable. The most important factor here is that upgrades are discretionary acts by the agencies, whereas commercial systems often force migrations from one technology to the next.

Cellular system data services –
Cellular services are relatively inexpensive due to the leveraging of development and deployment costs with a wide array of cellular services customers. There is, however, less stability of costs than land mobile radios. This is due to the necessary upgrades that an agency has to perform to keep up with changing cellular technology. An example is that as CDPD is phased out in most areas over the next few years, its entire lifespan will have been less than 10 years. Agencies are now selecting replacement services for CDPD and investing in upgrades in hardware, software, and training. It may be expected that relatively rapid and forced transitions in cellular data technologies will continue to occur, with two migrations often occurring within a 10-year period.

WiFi and DSRC –
The cost of these wireless local area network technologies will include the deployment of roadside units that communicate with passing traffic, but also the backhaul infrastructure that takes these messages and associates them with the appropriate applications, e.g., probe data used to estimate traffic congestion and travel times. Since these systems have ranges on the order of 100 to 1000 m, a cost question is how broadly DSRC will be deployed within jurisdictions, and which services are appropriate for areas of incomplete coverage. The gap in both WiFi and DSRC is the need to deploy roadside units that are capable of supporting VII functions. The DOT could support an analysis of the required deployment coverage (and associated costs) for important emergency transportation operations services that are otherwise well-suited for WiFi or DSRC. In any case, should VII be deployed, it will be important to create and publicize the plan for deployment of roadside units.

WiMax –
The costs of WiMax-based services are not yet known; however, they would presumably be somewhere between those of cellular technology and land mobile radio services.

Table 12. Rating the approximate cost structure of communication technologies for emergency transportation operations

1 = highly desirable, 2 = adequate, 3 = barely adequate or inadequate, TBD=to be determined

Cost	Land Mobile Radio	Cellular/ CMRS	WiFi	DSRC	WiMax
Deployment	3	1	2	3	3
Maintenance & operations	2	1	3	3	TBD
Upgrade costs	3	2	3	2	TBD
Stability of cost	1	3	2	1	3

4.3 Socio-technical issues

For technology to be deployed successfully, it must not only meet the high-level system requirements of VII (e.g., improve safety, reduce congestion, etc.), but it must also satisfy the individual needs of institutions that are stakeholders in the VII process. The notion that a system such as VII depends upon careful coordination between technical systems and social systems is called the socio-technical systems approach (Bunn & Savage, 2003). Figure 6 shows their representation of the dynamic aspects of socio-technical systems.

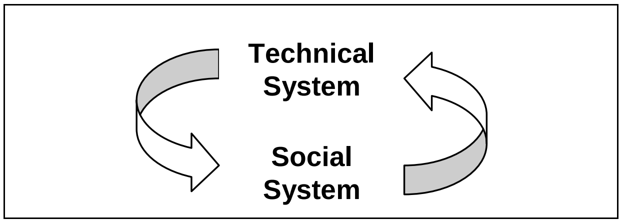

Figure 6. Dynamic representation of socio-technical systems (from Bunn & Savage, 2003)

While Bunn and Savage (2003) have correctly identified a vital topic for VII and ITS, and have proposed useful survey measures to evaluate institutional issues (indeed, we will use some of their measures in our own survey of stakeholders), their treatment can be made less fuzzy and more precise by incorporating some concepts from the discipline of human factors. Textbooks of human factors have long stressed system-wide aspects of interactions between people and technology (e.g., Kantowitz & Sorkin, 1987). For example, when considering the interaction between an operator and a machine, there are two interfaces of interest. Displays inform the operator of the state of the machine and controls inform the machine of the state changes desired by the operator. In a similar fashion, there are two (latent) interfaces in Figure 6. The technical system must somehow display its current state to the social system and the social system must in turn provide inputs to the technical system.

Interfaces can be static or dynamic. Most of the institutional research concerning stakeholders has been static, dealing with general capabilities and responsibilities associated with the coordination of several social systems. But VII is a dynamic system whose properties change in real time. There is a major gap in providing dynamic information exchange between technical and social systems. This critical gap exists on both sides of the interface. For example, VII offers the technical promise of real-time information from hundreds, and perhaps thousands, of vehicles. How will a traffic management center understand and process this vast amount of information in real time? This is an example of the display (technical system to social system) interface problem. Furthermore, even assuming that this information can be properly assimilated, how will the traffic management center communicate desired actions (the control interface problem) to thousands of vehicles in a manner that will not create additional confusion or congestion? Note that this is not a technical problem about how to use standards to carry the information to the vehicles. This is a socio-technical problem about what messages to send will best achieve the desired outcome.

A plan to fill this gap would start from the table of cooperative emergency transportation operations communications (Table 9 on page 24). This table would be expanded to include all the relevant stakeholders and institutions that must initiate and receive messages. Then a functional analysis of the potential message set would be prepared. But such analytic methods will not suffice for a complete solution since the message matrix will likely be complex, and different institutions will place different priorities on particular message subsets. Computer simulations will be required to understand how the messages and institutions interact. Finally, before deployment, additional empirical simulations with emergency vehicle drivers (and possibly also private vehicle drivers) and representatives from institutional stakeholders should be conducted. Only then, after empirical simulations have eliminated many undesirable cases, can expensive field tests be conducted to fully validate the dynamic interfaces.

4.4 Vulnerabilities

This section addresses the susceptibility of communications to power outages and service shutdowns. Approximate rankings of the technologies based on the relative merits for these issues are shown in Table 13. Land mobile radio systems are typically immune to power outages because the public agencies provide backup power sources. As illustrated by the wide-scale power blackout in the northeast in August 2003, cellular systems are not robust in such conditions. It is assumed that WiFi and WiMax networks that are operated by third-parties will also have vulnerability to power outages. Finally, it is not known yet whether the deployment of a DSRC-based network would include failsafe operations in power outage situations. This is a potential gap, and it is suggested that the emergency response community should consider studying the vulnerability and consequences of power outages on DSRC applications. Another technology not considered in detail in this project is satellite communications which obviously is unaffected by power grid outages.

Service shutdowns are also a real possibility in services supported by third-party agents, such as cellular data services, which occasionally have business cases to drop coverage in a region. In this report, we have also assumed that WiFi and WiMax networks would not be operated by emergency response agencies, so that there may be economic or other reasons for service disruptions that could affect emergency response agencies depending on that communications path. For that reason, it is suggested that a technical gap may be the reliance of critical operations on commercial service providers unless special agreements are possible to mitigate the vulnerabilities. Land mobile radio and DSRC are the two technologies that are assumed to be operated with philosophies that would prevent shutdown without consultation of emergency response agencies.

Table 13. Rating vulnerability characteristics of communication technologies for emergency transportation operations

1 = highly desirable, 2 = adequate, 3 = barely adequate or inadequate, TBD=to be determined

Vulnerabilities	Land Mobile Radio	Cellular/ CMRS	WiFi	DSRC	WiMax
Power grid influence	1	3	3	2	TBD
Operations dependent on other institutions	1	3	2	1	TBD

4.5 Human-machine interface issues

The engineering and science of constructing interfaces between people and systems are well understood. Human-machine interfaces (HMI) are discussed in many human factors and ergonomics textbooks. For VII emergency operations there are two key HMI loci: inside the emergency vehicle and at the infrastructure site communicating with the vehicle.

4.5.1 Allocation of function

Figure 2 on page 10 shows the relations between HMI, enabling lower-level technologies, and device-level technologies. The gap to be filled is bridging between enabling and device-level technologies. Allocation of function will be a key concept to help fill this gap. Allocation of function is defined (Kantowitz & Sorkin, 1987) as the mapping of system functions to either the operator or to the machine. For example, a driver turning on automated cruise control (ACC) is making an allocation of function decision that the vehicle will be responsible for maintaining a set speed. Similarly, a vehicle turning off ACC because rain interferes with the system radar sensors is also making an allocation of function decision that the human driver will be responsible for maintaining vehicle speed.

Thus, allocation of function technology works both ways. At one time, allocation of function decisions were hard-wired into systems. Later developments in computer technology permitted dynamic allocation of function, whereby the operator had the capability of making real-time allocation of function decisions. Now, with the deployment of intelligent interfaces, such as the ACC that can turn itself off, allocation of function is dynamic and no longer under the sole control of the vehicle operator. It is now within the scope of available technology to have the vehicle override a human decision. For example, an emergency vehicle approaching an intersection when the driver mistakenly thinks the vehicle transponder has set the traffic signal to green, when actually it is red, can receive a message from the infrastructure that can slow or stop the vehicle.

There are advantages and disadvantages of such intelligent control of vehicles. It might prove useful to initiate a research project on intelligent allocation of function for emergency vehicles under VII. This project could fill the research gap by creating new scenarios. Its final product would be a set of design guidelines and protocols for managing intelligent allocation of function.

4.5.2 Communicating driver intentions

One visionary new application for VII could be communicating driver intentions to other vehicles and to the highway system. While existing vehicles already contain devices to signal driver intentions to nearby vehicles (e.g., turn signals, horn, brake lights), such communication is often inefficient and may be ambiguous: Turn signals might remain blinking because the driver forgot to turn them off and horn signals might reflect an emotional state rather than a precise indication of traffic intentions.

Even when driver communication of intention is successful, as when a following vehicle decelerates in response to illumination of brake lights, such communication is limited to line of sight. Only vehicles behind the vehicle can detect brake lights, while nearby vehicles in adjacent lanes, which could profit from this communication of driver intent, remain unaware. A driver planning a lane change would be well served by receiving information that an adjacent vehicle intends to decelerate. DSRC communications between vehicles may be well suited for these types of signals, since DSRC features low latency and a proposed message set that includes much of this information.

While the example above refers to tactical information, strategic information about driver intentions could greatly improve highway system mobility. For example, the in-vehicle navigation system knows not only the driver's destination, but also the route that is planned. When this information is aggregated at a central infrastructure facility, future congestion can be ameliorated and optimized. New routing information could be sent back to the vehicle that takes into account the intentions of other vehicles in the system. Priority in this re-routing could be given to emergency vehicles, with other vehicles re-routed to alternate routes. Indeed, while such alternate routes might be slower than those planned for emergency vehicle operations, they still might be faster than potential congestion if all vehicles maintained their original plans to reach a destination. Thus, VII could create a win-win situation where mobility is improved for all vehicles on the roadway: Instead of a cost to other traffic, giving priority to emergency vehicles could be a benefit!

Figure 7 illustrates this communication of tactical and strategic driver intention.

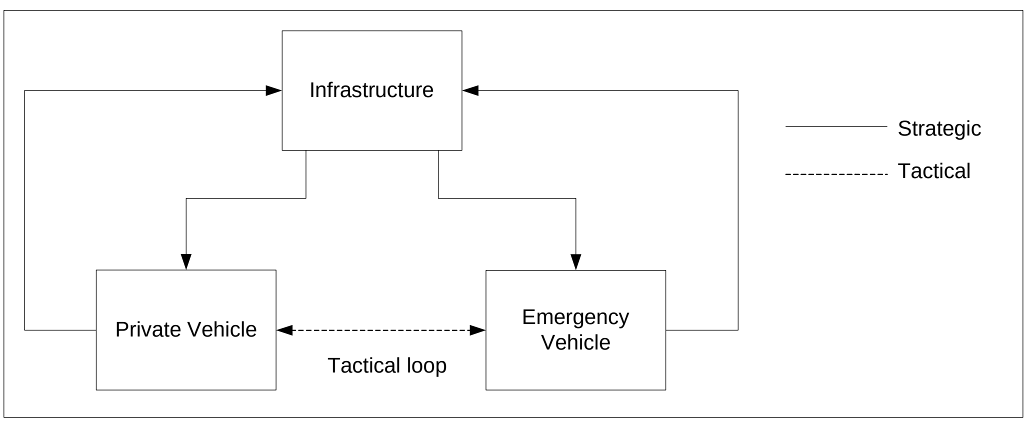

Figure 7. Communicating driver intention

4.6 Public agencies ceding control to individual drivers

At present, public agencies that operate highways have some control, although perhaps not as much as desired, over the behavior of individual drivers. Displaying a detour message on a VMS may influence some drivers to seek alternate routes. This may change when drivers are given the in-vehicle capability of seeking out information, especially when such information is presented by private entities making a profit by providing information to vehicles under VII.

Perhaps an analogy can make this point more salient. Before the widespread use of the internet, someone wishing to plan a vacation might simply call a travel agent to put together a trip package. Now many people prefer to use the internet because they can obtain the information by themselves. Thus, the nature of the travel business has changed and many travel agents are no longer thriving. The same process could occur in highway operations. Consumers may prefer to receive highway information from private instead of public sources. This will diminish the influence of the public sources.

This process could be another form of the discontinuity shown in Figure 5 on page 32 in which newer technologies displace older technologies. It is difficult to predict how and when this transformation might occur. Certainly, it implies future changes in highway operations in general as well as emergency operations in particular.

4.7 System-level gaps associated with possible service concepts

Table 14 lists service concepts for emergency transportation operations using cooperative systems. This list is compiled from Section 2.1, another list suggested by another FHWA project (see Booz, Allen, Hamilton, 2005), and a use case list shown in a recent FHWA public meeting (Jones, 2005). These are each described in one or both of those reports.

Table 14. Potential service concepts

Potential Service Concepts
Automatic collision notification (CAN) systems
Traffic control device preemption by emergency vehicles and emergency vehicle proximity warning for general public vehicles
Dynamic route guidance for emergency vehicles
Estimation of highway conditions by transportation management centers
Traveler information during evacuation
Wide area alert
Crash avoidance and pre-crash sensing aided by cooperative communications between vehicles or between vehicles and infrastructure

There may well be additional service concepts that are valuable and worth investigating, but for our purposes, the set in Table 14 is sufficient. Each service concept in the table requires a set of functions that, in turn, may rely on innovations in hardware, information, communications, processing, and/or human machine interface implementations. The service concepts are listed below, along with additional requirements that they suggest. The following requirements are basic assumptions regarding the discussion of these service concepts:

- Roadside equipment and onboard equipment to enable cooperative communications

among vehicles is available.
- The VII network has been created and is operational.

Automatic collision notification (ACN) systems and emergency response –
ACN systems are currently available commercially (e.g., as a feature of GM's OnStar system), and a different system was tested by the U.S. DOT in a field operational test in the 1990s. These first-generation systems use onboard crash sensors to trigger cellular modem calls to inform PSAPs. These systems require GPS, a cellular modem, and sensors and algorithms to detect the occurrence of a crash. Some units include occupant sensor data to communicate the number of passengers in the vehicle. Texas Instruments has applied for a U.S. patent for a handheld portable device that serves the same function (without occupant count) by comparing sensed acceleration profiles to those likely associated with a motor vehicle crash (Panasik and Salzman, 2004).

Booz, Allen, and Hamilton (2005) described an expanded set of capabilities that includes:
- Automatic decision-making regarding the dispatching of emergency crews
- Communications back to the vehicle indicating the status of emergency response
- Vehicle-to-vehicle communication to alert other traffic of the position and even the lane of the affected vehicle
- Real-time route guidance for the emergency vehicles, including the sensing of congestion on relevant roadways on the way to the scene

There are clearly no gaps for first-generation systems, since they are commercially available. For the broader set of functions from Booz, Allen, and Hamilton (2005), there may be the following technology gaps:

- Limited coverage areas of DSRC (perhaps more limited than cellular coverage)
- Lack of digital map accuracies to specify "whichlane" accuracy (VSCC, 2005), which would prevent other traffic from knowing the lane in which the affected vehicle is located
- Lack of algorithms to map model-specific crash information into decisions about whether to send emergency equipment
- Lack of HMI standards to guide decisions about whether and how to alert surrounding traffic, as well as guiding decisions about the display of information within the emergency vehicles
- Lack of validated algorithms for when to alert surrounding vehicles of an upcoming incident

Traffic control device preemption by emergency vehicles and emergency vehicle proximity warning for general public vehicles –
Traffic signal preemption is currently implemented in several metropolitan areas, as has been discussed previously. These are optical devices with line-of-sight requirements for transmission, and are therefore limited in range and reliability.

The discussion here assumes that two aspects of the Booz, Allen, and Hamilton (2005) description are not implemented. First, it is assumed that any instructions to drivers of the non-emergency vehicles would be computed on that particular vehicle, and not in the emergency vehicle (or infrastructure). It may be unwise for a single agent that has little knowledge of a complex environment to compute and command a "global solution" for all traffic, without knowledge of vehicle locations or awareness of the responses to initial commands. Instead, the emergency vehicle is assumed here to issue its position, motion, and intentions, with the surrounding vehicles each making their own computations and issuing advice to their drivers. Indeed, it may well be that the best information that those vehicles can provide their drivers is simply the general location and likely trajectory of the emergency vehicle, and allow the drivers to navigate their local situation, much as they do today. Second, Booz, Allen, and Hamilton (2005) include a dynamic route guidance function within this service concept (see Section 2.1).

The one gap in this concept is how to best communicate information or advice to drivers of the proximate vehicles that an emergency vehicle is approaching. Does the system advise specific actions, or merely provide the information? How can this be done without distracting drivers in a situation that already has heightened risk?

Wide area alerts –
Booz, Allen, and Hamilton (2005) describe this service concept as:

> *This application disseminates emergency information to wide area motorists about situations that may pose threats to the life and property of the traveling public. The information…includes emergency and reaction instructions to the public.*

This would address simply sharing information (e.g., child abductions) as well as advising drivers (e.g., during evacuations). Components of this functionality include:

- Dissemination of information to drivers, including recommended routes
- Estimation of roadway congestion and travel times to assist decision-making at emergency and/or transportation management centers
- Coordination with transit agencies

Gaps that may need to be addressed before this concept is deployed include:

- Research on public responses to such alerts, including recommended routes – including public reaction and compliance. This will likely limit the cases in which wide area alerts would be considered.
- Research on how to best present this information to drivers without compromising their driving safety
- Creation of workable plans for massive movement of populations using transit or private transportation. For example, the massive congestion during the evacuation of the Galveston/Houston area before Hurricane Rita in 2005 was exacerbated by factors that were not technology-related, but instead were due to gaps in planning.

Dynamic route guidance for emergency vehicles –
This discussion addresses the concept as described in Section 2, in which the emergency agency has identified a specific vehicle to visit an emergency scene. (Note that computing routes for multiple vehicles can assist the agency in selecting the appropriate vehicle.) Thus the problem of dynamic route guidance as discussed here is to optimize the route to minimize a function of travel time and expected safety risk. ("Dynamic" means that the route computation takes into

account quasi-real-time measurements of traffic flow along candidate paths and the optimization is repeated at times throughout the travel, so that the route may be altered at any time.)

The key element for this discussion is the real-time sensing of traffic flow and the likely travel times of the responding vehicles, as well as proper treatment of the ability to preempt traffic signals at known points along the candidate routes. The latter effect has been discussed already. Regarding the detection of travel times, this relates to the use of probe vehicle data for the estimation of travel time, which is a rather simple operation. Since navigation systems are available with synthesized-voice, turn-by-turn instructions, this service concept would be readily fielded with the assumption that the basics of VII are in place.

Estimation of roadway conditions for decision-making –
This concept is simply the gathering and use of field data to assess which roadways or infrastructure elements are available, and to quantify their current or predicted capacity. This may be used in large scale movements of vehicles during or following an emergency, as well as to guide emergency vehicles to incidents (as discussed above). Estimating roadway conditions has two basic components: the use of probe vehicle data to estimate travel time and available throughput, and models to help formulate the best decisions for the use of the roadway. We have discussed probe vehicle data. Also available are models for predicting the outcome of decisions to route traffic in a roadway network. Thus, assuming a basic VII deployment, there are no technical gaps for this concept.

Traveler information during evacuation –
A number of technology gaps have been mentioned, and these would serve to cover this service concept as well.

Crash avoidance and pre-crash sensing aided by cooperative communication –
VII has the potential to enable or enhance crash avoidance systems on emergency vehicles and private vehicles (which would naturally increase the safety of nearby emergency vehicles). Furthermore, cooperative communication between vehicles could enhance pre-crash sensing and improve the occupant protection systems on vehicles.

The Task 3 report from the Vehicle Safety Communications (VSC) project has generated a list of situations in which DSRC could enable or assist crash avoidance or pre-crash concepts (VSCC, 2005). The highest rated near-term applications were:

- Traffic signal violation
- Curve speed warning
- Emergency electronic brake lights

The highest rated applications in the medium term were identified as:

- Pre-crash warning
- Cooperative forward crash warning
- Left turn assistant
- Lane change warning
- Stop sign movement assistance

There may be several technical gaps associated with these applications beyond those associated with a basic deployment of VII on the roadside and in vehicles. First, the VSC report stresses that the outcome of ongoing work on security standards for DSRC communications is a critical item. It is possible that the needs of security could increase the latency of DSRC such that some of the applications could not be suitably supported.

Second, there would be a series of activities needed to validate the actual performance levels of these systems. The VSC project included a set of demonstrations with several of the vehicle-based approaches, and the Intersection Decision Support (IDS) consortium has demonstrated concepts related to intersections. However, further development and testing of these systems is needed.

An additional gap with several of these technologies is the lack of a mature and validated approach to the HMI for the drivers. While autonomous versions of several of these technologies – i.e., versions that do not utilize cooperative communications – are in development or even commercially available, others are not mature and HMI approaches are not developed.

Finally, research is needed to complete development and conduct validation testing for pre-crash systems that use V2V communications. This will clearly focus on whether GPS data via V2V would support pre-crash deployments, as well as discussing how to process V2V signals to provide a "zero" rate of false positives.

4.8 Summary of gaps

A summary of gaps identified in the previous sections is presented in Table 15. The gaps are arranged by general topic, as represented in the first column. For more details about the gaps and related issues, see the section called out in the table.

Table 15. Results of gaps analysis

Type of Gap	Gap No.	Gap Identified	Section	Possible Actions to Close Gap
Communications other than DSRC	1	Interoperability of land mobile radio systems with each other and with other networks	2.1	Promote standards (and compliance) to create more interoperability
Communications other than DSRC	2	Dependence of cellular, WiFi, and WiMax service on the service provider's decisions	4.4	Assist agencies in adopting other communications paths
Deploying VII	3	WiFi and DSRC: deployment of infrastructure and onboard units	2.1	Work to make VII deployment a reality
Deploying VII	4	Need to deploy networks to connect roadside units	2.1	Explore the feasibility WiMax as an alternative to land mobile radio systems
Deploying VII	5	Costs of migrating from one communications technology to another	2.1	Investigate the value and feasibility of software-defined radio
Deploying VII	6	Need funds to deploy roadside units for WiFi or DSRC	4.2	Determine requirements for installations; estimate funds required; announce a plan for deployment of RSUs
DSRC coverage gaps	7	Non-seamless DSRC coverage means that some areas will be without DSRC-enabled I2V or V2I communications	4.7	Augment VII research to consider whether remedies for the limited coverage of DSRC are needed
DSRC performance	8	Uncertainty in actual DSRC latencies due to unresolved security protocol	4.7	Support ongoing standards development, as well as continued validation of DSRC performance
Robustness of VII system	9	Possible vulnerability to power outages of DSRC-based V2I and I2V communication	4.4	Consider effects of loss of DSRC roadside unit power in emergency operations
Integrating emergency operations with VII	10	Interfacing existing emergency processes and algorithms with DSRC architecture	2.1	Consider emergency operations needs in architecture definition
Emergency operations – algorithms	11	Reduced public-agency control of driver behavior	4.6	Watchful waiting
Emergency operations – algorithms	12	Lack of R&D to map vehicle crash pulse information into decisions about first responder dispatches	4.7	Collect data on existing automatic crash notification system events, and create and validate algorithms for decisions on dispatches based on ACN data

Table 15, continued

Type of Gap	Gap No.	Gap Identified	Section	Possible Actions to Close Gap
Emergency operations – algorithms	13	Lack of experience with massive evacuations leads to uncertainty in the efficacy of evacuation procedures	4.7	Study experiences in recent hurricane evacuations, and overlay a simulated VII-like capability to develop and validate strategies for evacuation commands
In-vehicle digital maps	14	Digital maps not suitably accurate to let vehicles know which lane they are in	4.7	Assume that warning drivers that there may be an emergency scene ahead is adequate, and in-vehicle guidance about lane choice is not appropriate
Probe data algorithms	15	Lack of validated algorithms that use probe vehicle to assess and predict roadway network congestion	4.7	Create program to develop and validate such algorithms
HMI – Infrastructure operations	16	Understanding the performance of decision-making based on "displays" of large data sets	4.3	Study the effects of the combined technical-social process using approaches outlined in section 4.3
HMI – Infrastructure operations	17	Knowing how real-time transportation management decisions will affect the system	4.3	Study the effects of the combined technical-social process using approaches outlined in section 4.3
Cooperative crash avoidance and pre-crash systems	18	Lack of sufficient understanding of performance levels for cooperative crash avoidance and pre-crash systems	4.7	Continue to support R&D in this area
In-vehicle HMI	19	HMI design to promote appropriate allocation of function between operators and technologies	4.5	Research project on intelligent allocation of function for emergency vehicles under VII
In-vehicle HMI	20	Lack of R&D to know whether and how to alert drivers that they may be approaching an emergency scene	4.7	Launch R&D in this area
In-vehicle HMI	21	Lack of R&D to know how to use in-vehicle devices to alert drivers that an emergency vehicle is approaching	4.7	Launch R&D in this area
In-vehicle HMI	22	Lack of R&D on presenting drivers with evacuation information using in-vehicle systems	4.7	Launch R&D in this area
In-vehicle HMI	23	Lack of R&D on HMI approaches for cooperative versions of cooperative crash avoidance and pre-crash systems	4.7	Launch R&D in this area

5.0 CONCLUSIONS

Emergency transportation operations would be transformed by a network that wirelessly connects emergency vehicles, private vehicles, and the roadside. Such a network is being explored within the Vehicle Infrastructure Integration (VII) initiative of the U.S. Department of Transportation. This report describes potential uses of VII for emergency transportation operations, while also discussing the nature of technology and research development needed to realize its full potential. A framework based on communications paths is proposed as a useful organizing mechanism for considering the applications and their requirements. The requirements described address technical, financial, social, and human-interface issues.

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APPENDIX 1: LIST OF ACRONYMS

2G, 2.5G, 3G, 4G	2nd, 3rd, 4th generations of cellular technology
ACN	Automatic Crash Notification system
AVL	Automatic vehicle location
C2C CC	Car-to-car Communications Consortium
CAMP	Crash Avoidance Metrics Partnership
CDPD	Cellular digital packet data
CICAS	Cooperative Intersection Collision Avoidance System
CMRS	Commercial mobile radio system
DSRC	Dedicated short-range communication
EV	Emergency vehicle
EV2EV	Emergency vehicle-to-emergency vehicle
EV2EV	Emergency vehicle-to-emergency vehicle
EV2PV	Emergency vehicle-to-private vehicle
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GPS	Global positioning system
I2I	Infrastructure-to-infrastructure
I2V	Infrastructure-to-vehicle
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
ITS	Intelligent Transportation Systems
IVI	Intelligent Vehicle Initiative
LAN	Local area network
LMR	Land mobile radio
NHTSA	National Highway Traffic Safety Administration
NTCIP	National Transportation Communications for ITS Protocol
PATH	Partners for Advanced Transit and Highways (California)
PSAP	Public safety answering point
PV2EV	Private vehicle-to-emergency vehicle
PV2PV	Private vehicle-to- private vehicle

RFID	Radio frequency identification
SDR	Software defined radio
TMC	Transportation management center
TRB	Transportation Research Board
UMTRI	University of Michigan Transportation Research Institute
USDOT	US Department of Transportation
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
VICS	Vehicle Information and Communications System
VII	Vehicle-Infrastructure Integration
VSCC	Vehicle Safety Communications Consortium
WAN	Wide area network