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IVHS

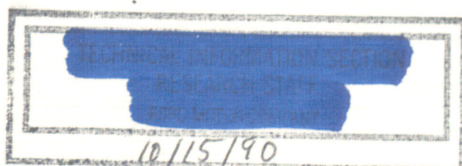
Intelligent Vehicle-Highway Systems

The Feasibility of
Quantitatively Characterizing the
Vehicle Motion Environment
(VME)

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September, 1990



IVHS Technical Report-90-9

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Abstract

A concept is presented for creating a measurement system that can quantify the specific motions which vehicles exhibit as they move in traffic, under the full array of traffic operations. Such quantification is seen as crucial to the development of automatic collision prevention systems and has spin-off utility for the study of many other issues in human factors and vehicle and highway engineering. This study has addressed the experimental and analytical challenges involved in wide-area sensing, large-volume data processing, and both deterministic and statistical analyses of the data which will characterize this so-called, "Vehicle Motion Environment" (VME). The basic concept which appears to be feasible for such measurements involves a remote sensor which is installed at the roadside, probably on a tall pole, and which produces electro-optic images of the traffic stream and converts them into a permanent data file of the quantified trajectory for each motor vehicle passing through the field of view.

The report covers the performance specifications for the VME measurement system plus considerations for the measurement package and the subsequent processing needed for deriving the variables of interest. Various applications of the VME system are also addressed.

1.0 Introduction

One of the major elements of the Intelligent Vehicle-Highway System (IVHS) concept entails technologies which will sense that a collision is pending and either warn the driver or provide automatic braking and/or steering action as a countermeasure. The achievement of such functions requires the development of what might be called a "Collision Prevention System (CPS)" technology. This technology, when fully mature, would support the engineering analysis, design, manufacturing, and deployment of systems that may offer a profound reduction in accident risk.

Putting the subject in very rough terms, the domain of collision prevention systems may be described by four basic elements, namely:

- 1) the actual near-field environment within which vehicles operate;
- 2) a sensory or other technology which characterizes the obstacle content of this environment, in real time;
- 3) a processor which can predict when a collision is pending, suitably concluding that all other cases are benign;
- 4) a warning or control intervention function whose activation results in successful evasion of individual accidents while, over the long term, also avoiding undesirable side effects in driver behavior such as risk homeostasis at one extreme (i.e., overconfidence) or an attitude of incredulity at the other extreme (i.e. lack of confidence.)

While items 2,3, and 4 represent the locus of functions which CPS's will provide, the current study has dealt with item 1 which represents the external reality to which these systems must be designed. We have labelled this external domain the "Vehicle Motion Environment" (VME), pertaining to the locations and relative motions of all vehicles, fixed objects, road edges, etc. which constitute collision hazards (or run-off-road boundaries) for any subject vehicle. The VME covers a space within which collision outcomes are formed, given vehicle travel speeds. The pertinent variables address vehicles in near proximity to one other, each having a certain physical shape which is exposed to collision, and each having certain spatial clearances, relative velocities, angles of nominal attack etc., vis-a-vis other vehicles and fixed objects.

An engineering characterization of the VME requires that real roads and traffic motions be measured—over the representative set of geographic, climatic, road design, and traffic variables. At a given road site, each motion and space variable must be quantified, from one instant in time to the next, so that, eventually, data are collected providing statistical distributions of these variables representing the road system within which CPS's would be deployed. The time history, or moment-to-moment quantification of the VME would be used for direct analysis of the requirements for CPS technologies. Candidate algorithms for determining, on board a vehicle, that a true collision is pending would be evaluated by "operating" the algorithm on the data for each vehicle whose motion environment has been "tracked" over real road sections using a VME measurement system.

The feasibility for creating such a measurement system has been the subject of this study. The study addressed the experimental and analytical challenges involving wide-area sensing, large-volume data processing, and both deterministic and statistical analyses of vehicular motions. The basic concept which appears to be feasible involves a remote sensor which is installed at the roadside, probably on a tall pole as sketched in Figure 1.1, and which produces electro-optic images of the traffic stream and converts them into a permanent data file of the quantified trajectory for each motor vehicle passing through the field of view. From the raw data on trajectories, later processing will enable statistical analysis in terms of inter-vehicle variables which directly express clearances and the extent of spatial conflict between vehicles.

This project is premised on the view the VME must be quantified, in engineering terms, before CPS Technology can mature. When the vehicle motion environments have been measured at a fairly complete sample of road types, traffic densities, intersection layouts, etc., the data set should enable extensive evaluation of candidate control laws upon which automated collision avoidance systems are based. Without such a data set, one is reduced to direct field studies on a one-at-a-time basis, requiring physical implementation of prototypes and posing the enormous burden to sample road types, traffic patterns, and associated variables over which any real collision prediction system must operate. A VME data set may also have spin-off value for the development of traffic models based upon the micro-mechanisms of inter-vehicular movement. Processing of the data will also allow us to identify dramatic events so as to locate, from a simultaneous videotape, the visual replay of near-misses and collisions.

This report address the following aspects of the VME subject:

- the specifications for a VME measurement system (section 2.0)
- alternative electro-optic sensors and image processors upon which to base a VME measurement system and produce trajectory-level data (section 3.0)
- the processing of vehicle trajectory data in order to derive other variables upon which the VME is to be quantified (section 4.0)
- discussion of the various applications of VME data (section 5.0)
- conclusions and recommendations (section 6.0)

Vehicle Motion Data

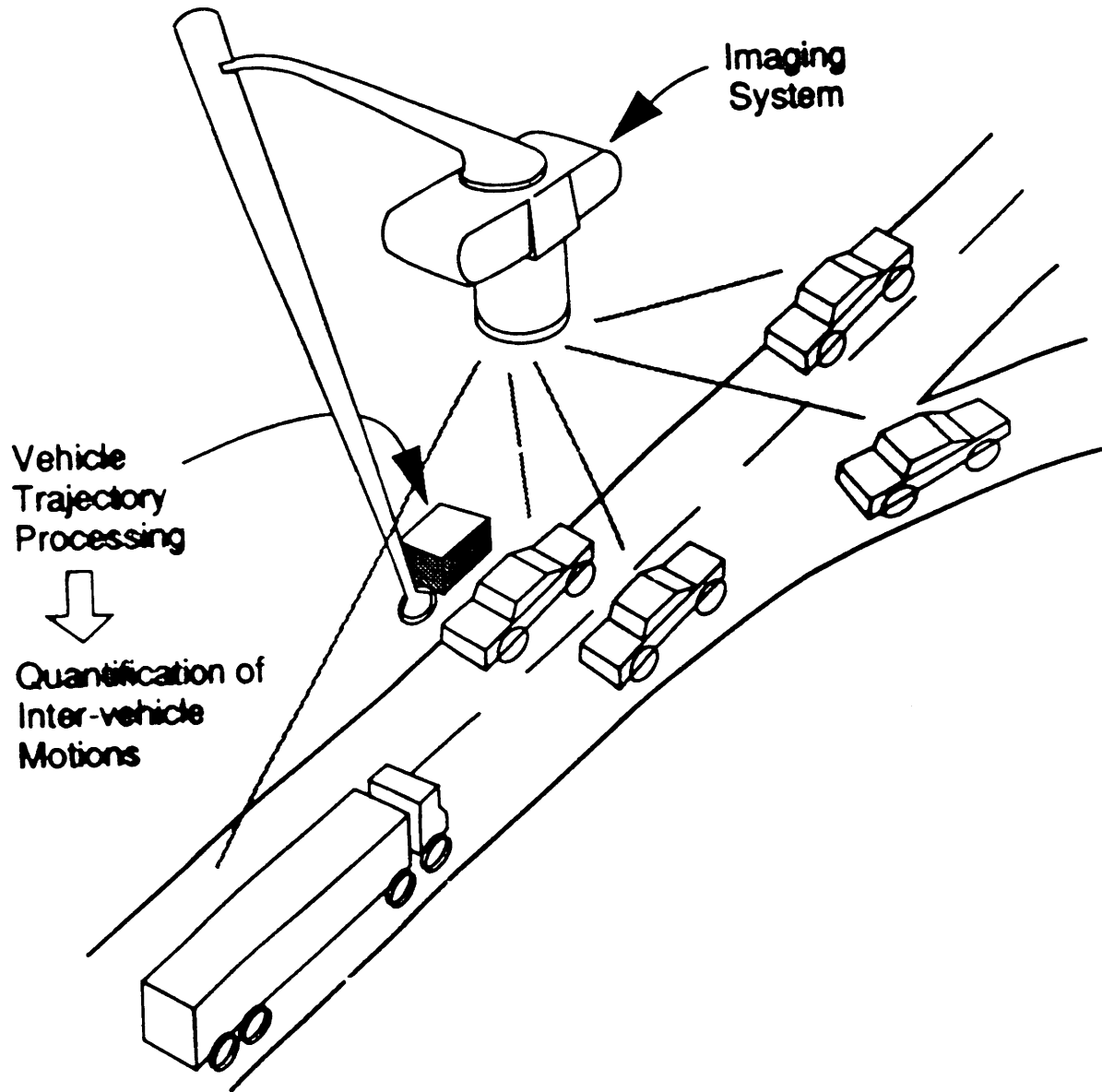


Figure 1.1 Sketch of a pole-mounted imaging system from which data are obtained for quantifying vehicle motions at a given road site.

2.0 Performance Specifications for a VME Measurement System

The requirements delineated below apply to the field apparatus which is actually installed at a given road site and operated over an extensive period of time to produce a permanent data record of the vehicle motion environment. These requirements do not embrace the off-line processing of data which would be needed to condense the raw trajectory data or compute statistical distributions of the derived, inter-vehicular variables. Further, they constitute specifications for an envisioned "Phase 1" measurement system which is simplified for operation in daylight only, and reflects other features which are intended to limit the costs.

Specific Requirements

1) Basic Data Requirement

The quantified motions of vehicles are characterized by the time histories of the following:

- the X and Y coordinates in horizontal space of the geometric centroid of each motor vehicle, relative to a ground-fixed datum,
- the yaw angle of each vehicle
- the length and width dimensions of a rectangle which outlines the plan-view shadow of each vehicle. (The yaw angle is defined as the compass orientation of the longitudinal axis of this rectangle. For articulated vehicles, such as tractor semitrailers, multiple rectangles will be generated, one for each vehicle unit.)
- the Z (vertical) coordinate of the vehicle is optional (to be provided only if it is virtually free.)

The data file containing these variables must provide a minimum of 10 Hz sampling of the actual vehicle trajectories for on the order of 100 to 500 hours of continuous measurement.

2) Derivatives

No time derivatives of the basic data set defined in (1) are required. It is intended that various derived variables will be computed off-line from the raw data file.

3) Ancillary Data

It is assumed that road edge and profile geometry will be available from engineering drawings of each measurement site. No data are needed on weather and pavement condition.

4) Data Precision

Data representing the trajectory and rectangular perimeter of each vehicle must be recorded with the following levels of precision, assuming that measurements are with respect to a datum fixed in the roadway:

- X & Y coordinates of the rectangle centroid are within +/- 1 inch
- length and width of the rectangular shadow are within +/- 2 inches relative to the actual extremities of the vehicle (assuming symmetric vehicle layouts, should one side be occluded from view.) Where a fender bulge or bumper point extend locally beyond the nominal fit of a rectangle to the vehicle shape, such small features shall be ignored.
- yaw angle is within 0.5 degrees

The net location accuracy implied by these specifications derives from accumulations of each band of imprecision. To determine the accuracy in the lateral coordinate of the left front corner of a full-sized station wagon, for example, one would add 1 inch for the centroid Y error, plus 1 inch error on the vehicle's half-width, plus a rotation error equal to the product of the sine of the yaw angle (approximately 0.01) times the half-length of the vehicle (assume 96 inches in this example.) The total maximum error in lateral position of the left front corner of the vehicle would be 3 inches. For the case of a 48-foot semitrailer, the error on lateral location of a corner would be increased to a total of 5 inches due to the greater effect of yaw angle imprecision. While complete statistical analysis is necessary in order to directly address the confidence bounds of a given measurement, the preliminary selection of specifications was based upon maximum error limits, alone.

5) Events

The prototype measurement system need not employ intelligent processing in real time for detection of special motion events on the roadway. Later, it is likely that some processing for event detection and characterization will be done as an off-line activity in order to guide an intelligent sub-sampling of the otherwise massive data file. The off-line condensation of the data file is likely to employ processed variables such as inter-vehicular clearances, rates of closure, time to collision, and so on, as the proper description level at which to identify events. A sub-sampling of the original data is then likely to include simple statistical coverage of the non-dramatic samples of the motion environment plus a comprehensive population of all samples which portray near-miss and actual collision events.

(It should be noted that the feasibility of the VME measurement concept does not rest singularly upon the prospect of directly recording a significant population of accident

events. Rather, the recording of the full spectrum of non-collision movements is of central value. In discussions with those actively engaged in developing CPS technology, it became clear that the largest challenge in CPS design is not the prediction that a high-threat collision is actually pending but rather the ability to detect that the overwhelming majority of all other near-proximity vehicle movements are, in fact, benign. This is not to say that it will be straightforward to detect pending collisions in sufficient time to activate a countermeasure, but merely to note that real collision trajectories will definitely look like collision trajectories, at some point—while many other non-threatening vehicle movements may also appear as a collision trajectory at some preliminary stage of development.)

6) Field of Regard

The field of regard defines the physical domain in which trajectory measurements are to be made at a given road site. Two applications appear to define a useful specification of the needed domains, namely:

- Freeway Case, +/- 500 ft in the X direction and +/- 100 ft in the Y direction
- Intersection Case, +/- 300 ft in both X and Y directions

In all cases, vehicle presence will only be tracked from shoulder edge-to-shoulder edge, with intervening ground spaces simply blanked.

7) Platform Constraints

The system is to function under the following application constraints:

- Daytime lighting conditions
- Good weather conditions (although the physical package must be contained within an all-weather enclosure.)
- A semi-fixed installation that may stay set up at a given site for 1 week to 3 months.
- The sensor head would be mounted on a high pole, extendable tower structure, or a tethered balloon, but would function in such a way as to tolerate the physical oscillations of the platform while still delivering the desired measurement performance. (Physical movements of the platform would typically be compensated for with the aid of known "match-points" on the ground, in the field of view.)
- The cost to deploy the system at a given site (simply to set it up and initiate data collection) would desirably be within \$10,000.

8) Range of Traffic Conditions to be Monitored

The measurement and recording system will be deployed at virtually any conceivable road site. The most common application would be on a 2,3, or 4-lane roadway, including expressways, although expressway installations may be confined to one side of the facility, perhaps with merge lanes included in the field of regard. Right angle and oblique intersections are also to be provided for, as are all forms of simple and compound highway curves. Traffic densities would cover the following cases as more-or-less extreme conditions:

- Gridlock, - one vehicle every 30 feet in each of 4 adjacent lanes, moving at speeds from 0 to 20 mph.
- Maximum Throughput - four adjacent lanes of a freeway each carrying traffic at 50 mph, spaced every 60 feet.

9) Tracking

All vehicles are tracked at a 10 Hz sampling rate throughout the field of regard. Any vehicles that are occluded from view through part of the scene should be represented by means of a suitable interpolation through the occlusion, and the corresponding data tagged as "interpolated" in the data file.

10) Data Structure and Media

Data structure of the trajectory information is to be determined based upon selection of a specific measurement technology. Formats must be eventually compatible with large scale processing techniques and storage media.

11) Classification

No classification of vehicles, by type, is necessary in the raw (trajectory plus rectangular shadow) data set. With multi-element vehicles having articulation, however, (like car/trailer combinations, tractor semitrailers and double-trailer combinations) a separate rectangle must be developed for each vehicle element; viz., the tractor cab, the semitrailer itself, etc. Subsequent processing of the trajectory data will serve to assign vehicle classifications, where needed, by noting that the longitudinal clearances between rectangles is extremely short and remaining constant wherever coupled units exist. The rule of thumb on assigning rectangles for the various shapes that appear on the road is that we must completely cover the plan view shadow which is cast by each vehicle insofar as it represents the perimeter which, if intruded upon, connotes an accident.

12) Time Domain

The data produced by the sensor system is to be recorded for archival use only. No real-time usage of the data is envisioned.

13) Regulatory Considerations

The sensor system must employ only safe radiations, as defined by federal law, and must comply with FCC requirements for use on public roadways.

14) Video Backup

A conventional video image of the field of regard is to be recorded as a complement to the data collection system. The video images will be used in debugging the data-generation system and in understanding the relationship between trajectory data and directly-observable vehicle activity on the roadway.

3.0 Sensors for Determining Vehicle Motion

Characterization of the vehicle motion environment (VME) is intended to provide data for development and evaluation purposes in the following areas: (1) automatic collision warning and avoidance, (2) traffic models based upon the micro-mechanisms of inter-vehicle motion, and (3) traffic studies using peculiarities in the data to signal events, such as identification of near-misses and collisions, and simultaneously recorded CCTV videotape for visual verification.

The following material explores the capability of four sensing approaches to provide data of sufficient quality for the vehicle motion database. The sensors examined include (1) laser-radar (LADAR), (2) MMW radar, (3) passive infrared, and (4) passive visible.

Summary

Of the four sensor concepts investigated in this study, two were found to be capable of providing data suitable for characterizing vehicle motion (see the Specifications Section for details on performance requirements): (1) laser-radar (LADAR), and a (2) passive visible (CCD) sensor. Of these two, the LADAR is the preferred sensor because it is active, and thus the quality of the measurement can be controlled, and it provides range data which can significantly reduce the complexity of the tracking problem. MMW radar cannot meet the performance specifications for this application and passive infrared sensors do not offer advantages over passive visible sensors. However, all four techniques are described in detail in the remaining sections.

ERIM has developed and is in the process of developing systems which will track single objects in both 2-D (visible and IR) and 3-D data. For example, a system is being developed for Eglin Air Force Base to track an object in sequential frames acquired from film. A model is matched to the object and the object's position and orientation are determined in six degrees of freedom. The expected accuracy is 2" and 2° at 50 ft (± 1 pixel) [1]. Additionally, ERIM has performed processing on 3-D range data as a part of the navigation function for the Autonomous Land Vehicle (ALV).

The primary issue involved in this application, however, is tracking multiple vehicles in a scene within high tolerances. Many problems must be overcome to accomplish this task. Most significantly, occlusion is difficult to avoid because of the wide area coverage required. Generally, in order to achieve the specified coverage, the sensor is placed in a position which allows larger vehicles to occlude smaller ones. For instance, with a sensor looking down the middle of a four-lane highway, large (high) trucks can obscure vehicles directly in front from the sensor's view. In terms of processing for tracking of multiple vehicles, algorithms need to be developed which will deal specifically with the problems associated with this application. At this point, no software is known to exist which can be applied directly to this application.

The deployment of a sensor system that can acquire data of sufficient quality for characterizing the vehicle motion environment to the stated accuracies can be achieved. There is, however, a development effort required to reduce the data and produce the necessary vehicle track files.

Recommendations

A limited field experiment (data collection and subsequent processing) is recommended to accurately determine the magnitude of the development effort [Note: ERIM has a 3-D laser scanner which can be used for testing purposes].

3.1 LASER-BASED SYSTEMS

The laser-based systems discussed here are imaging sensors, capable of producing range images by modulating a laser beam. These laser radar (LADAR) systems can be modulated using pulse modulation, amplitude modulation, or frequency modulation. Scanning can be performed either mechanically (e.g., with motor driven mirrors) or electrically (e.g., with detector arrays). The system described below will involve an amplitude modulated continuous wave (AM CW) approach, employing 2-D mechanical scanning to provide the required field of view.

It is believed that in the scanning mode, the laser dwell time will be sufficiently short enough so as to be eye safe. Fail safe mechanisms can also be installed to ensure that the laser is not powered when the sensor is not in scan mode. However, detailed calculations and a better understanding of the full implications of eye safety and liability must be examined further if this approach is to be tested.

3.2 Summary (Laser-Based Systems)

Laser-based imaging sensors have been applied to many different areas, including vehicle navigation [2], robot guidance [3, 4, 5], machine vision inspection, and vehicle collision warning [6]. Specific design parameter values for a LADAR for vehicle motion characterization are given in sections 3.3 and 3.4. These values are realistic component parameters available using current technology.

It has been found that a LADAR can be designed to operate in the ± 500 ft range, with a spatial sampling of approximately 10 in.; which produces a LADAR with sufficient S/N margin (i.e. performance). However, trading S/N for denser spatial sampling, it should be possible to provide the 1/5 subpixel estimation required to give ± 2 in. performance for the vehicle bounding rectangle. For centroid calculation within ± 1 in., it also may be possible to obtain subpixel estimation (on the order of 1/10 pixel). These are still research topics, however, which will require some development of the actual image processing software. The yaw angle requirement of 0.1° can also be met with this design. Range resolution for this scenario is on the order of 4.5 in.

In the 150 ft range (intersection scenario), the LADAR can provide spatial resolution on the order of 2 in. for a vehicle bounding rectangle and, through interpolation, 1 in. centroid resolution. Range resolution in this case is on the order of 0.8 in.

Although theoretically it may be possible to obtain the resolutions specified for vehicle motion characterization, realistically a number of other factors, which cannot be quantified as easily, must also be considered. Among these are the changing reflectance properties of vehicles as they travel through the field of view; it may not be possible to track the same point (or points) on a vehicle throughout the scene. Some points may drop out because of low signal return or occlusion. Having the range data, however, will improve the prospects of compensating for occlusion since the shape of a vehicle can be determined more accurately with range data as compared with visible reflectance data.

One of the most important parameters of a laser-based system, such as an AM-CW LADAR, is the signal to noise ratio (S/N); the range accuracy, and thus the vehicle location accuracy, is inversely proportional to the square root of the S/N. The S/N is affected by the following factors:

- Distance to the objects
- Required range resolution
- Required angular resolution
- Area of coverage
- Coverage rate
- Weather conditions (atmospheric transmission)
- Scene reflectance
- Background

The S/N, along with other sensor parameters, are estimated below for both scenarios in which the sensor must operate.

3.3 Case 1: Freeway Scenario

In the freeway scenario, a sensor is required to cover at least one side of the roadway (i.e. one direction), which may constitute 2, 3, 4, or more lanes (including merge lanes, if at all possible). The field of view (FOV) is approximately ± 500 ft (≈ 152.4 m) down-lane and 100 ft (≈ 30.5 m) across lane.

LADAR Specifications:

The following parameters have been selected for the LADAR sensor, based on the requirements of the Freeway Scenario outlined above. Only currently available components are used in the following analysis.

Laser = Modulated CW GaAlAs

Wavelength = 820 nm

Modulation Frequency = 4.7 MHz

Sample Rate = 10 Hz

The bandwidth would be approximately 500 kHz (500 x 100 x 10 frames/sec).

Range Ambiguity (R_a) = $c / (2 f_m) = 10.71$ m

Currently, 3 W GaAlAs laser diodes are available. It is possible to cascade (by polarization) two laser diodes to achieve the 6 W output power.

The S/N is calculated as follows:

$$S/N = \frac{2S(\omega) \left[R_O P_L \left(\frac{\rho}{\pi} \right) \left(\frac{A_R}{R^2} \right) T_t T_r T_A^2 \right]^2}{2e FBR_O P_L \left(\frac{\rho}{\pi} \right) \left(\frac{A_R}{R^2} \right) T_t T_r T_A^2 + 2e FBR_O \rho A_r \left(\frac{IFOV}{2} \right)^2 E_\lambda \Delta \lambda T_r T_A + (NEP)^2 R_O^2 B}$$

where $S(\omega)$ = Modulation Form Factor (0.25)

R_O = Current Responsivity (0.55 A/W)

P_L = Average Laser Power (6 W)

ρ = Scene Reflectivity (10%)

A_R = Receiver Aperture Area ($2.02 \times 10^{-3} \text{ m}^2$)

D_R = Receiver Aperture Diameter (0.05 m)

R = Range (500 ft, ≈ 152.4 m)

T_t = Transmitter Efficiency (0.7)

T_r = Receiver Efficiency (0.4)

- T_A = One Way Atmospheric Attenuation (1)
- τ_A = One Way Atmospheric Attenuation Coefficient (1 dB/km)
- e = Electron Charge (1.602×10^{-19} C)
- F = Excess Noise Factor (3)
- B = Bandwidth (≈ 1 MHz)
- IFOV = Full Angle Receiver Instantaneous Field of View (0.37 mrad)
- E_λ = Background Spectral Irradiance ($1060 \text{ W m}^{-2} \mu\text{m}^{-1}$)
- $\Delta\lambda$ = Optical Bandwidth (5 nm)
- NEP = Noise Equivalent Power ($2 \times 10^{-14} \text{ W Hz}^{-1/2}$)

$S/N \approx 30 \text{ dB}$

The range resolution is calculated as follows:

$$\sigma_r = \frac{c}{4\pi f_m \sqrt{2S/N}}$$

Using the S/N value found above, $\sigma_r \approx 0.11 \text{ m}$ ($\approx 4.5 \text{ in.}$)

To obtain a FOV of $\pm 500 \text{ ft} \times 100 \text{ ft}$, the sensor must be placed at least 100 ft above the roadway. This results in a scan angle of $\pm 79^\circ$ to achieve a $\pm 500 \text{ ft}$ spatial coverage in the down-lane direction as shown in Figure 3-1. Such large scan angles result in a significant expansion of the LADAR footprint¹ at the extremes of the field of view and thus degraded image quality. Either a greater platform height or multiple sensors would be preferred. Again, S/N , and thus range accuracy, can be traded for denser sampling.

¹From 4.5 in. at nadir to approximately 10 in. at the edge of the image.

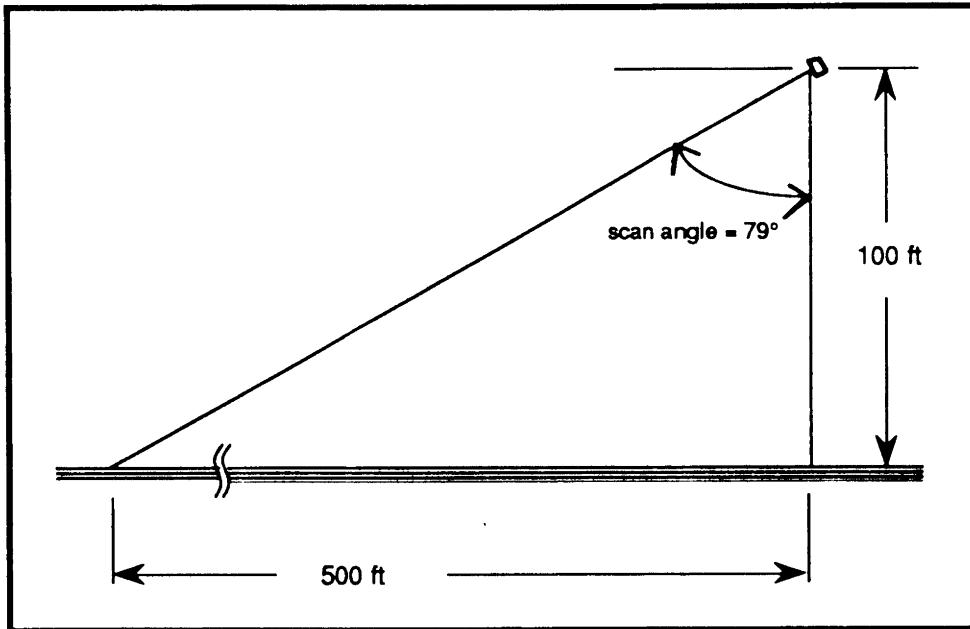


Figure 3-1. LADAR Sensor Geometry for Freeway Scenario

3.4 Case 2: Intersection Scenario

Since the FOV is smaller in this case, the performance criteria are more easily met. For the intersection scenario, the sensor field of view must be at least 150 ft (≈ 45.7 m) in both the down-lane and across-lane directions.

Laser = Modulated CW GaAlAs

Wavelength = 820 nm

Modulation Frequency = 4.7 MHz

Sample Rate = 10 Hz

The bandwidth would be approximately 225 kHz (150 x 150 x 10 frames/sec; 150x150 pixel image).

$$\text{Range Ambiguity } (R_a) = c / (2 f_m) = 10.71 \text{ m}$$

In this scenario, only one 3 W GaAlAs laser diode is required. Using the S/N equation detailed under Case 1, the S/N \approx 45 dB. Based on this S/N value, the range resolution $\sigma_r \approx$ 0.02 m (\approx 0.8 in.).

To obtain a FOV of 150 ft x 150 ft, the sensor can be placed 50 ft above the roadway at a look angle of 18.4°. A spatial resolution of approximately 2 in. can then be achieved at 150 ft (IFOV \approx 0.4 mrad).

3.5 MMW RADAR

The following material discusses an investigation into the measurement of vehicle motion with a millimeter-wave radar. Two millimeter-wave radars were considered: an imaging radar and a MTI radar with imaging capability.

3.6 Summary (MMW Radar)

A millimeter-wave radar sensor could be designed to monitor vehicle traffic. Such a radar, which would be located at the side of the roadway, would scan the area of interest and record the returns from the vehicle targets in the area. Although such a sensor can make a record of vehicle traffic passing through the field of regard, it cannot meet the basic data requirements needed to characterize the vehicle motion environment. At millimeter wavelengths, the radar return from a vehicular target will not necessarily coincide with the target outline; consequently, the radar can not provide a plan-view. A millimeter-wave radar does not have the resolution required to locate the target centroid within \pm 1 inch, nor is there any way of knowing where the centroid is relative to the scattering centers on the target, or determining the yaw angle. Concrete is reflective, and the targets would be imaged in an environment rich in multipath reflections which could cause confusion.

A millimeter-wave MTI radar could also be designed to monitor vehicle traffic. Such a radar would be located over the roadway or close to the side, and it would be aimed down the road where the Doppler shift of approaching or receding traffic could be determined. The MTI radar would also form images of the target scene like the imaging radar, and these images would suffer from the same deficiencies as the imaging radar. The advantage of the MTI radar is the additional capability of velocity measurement, but this capability would require additional system and processing complexity. The MTI radar would be more costly than the imaging radar, and it would require a higher site to minimize the occlusion of one target by another because of the viewing angle.

3.7 Imaging Radar

To monitor vehicle traffic, an imaging radar would be located at right angles to the roadway to minimize the occlusion of one target by another. The radar antenna beam

would scan back and forth across the scene of interest and record returns from the scene. A radar operator, if one were present, could monitor a PPI display.

The range resolution ρ_r depends on the transmitted bandwidth ΔB :

$$\rho_r = \frac{c}{2\Delta B}$$

A resolution of 12" will require 600 MHz of bandwidth which is obtainable at millimeter wavelengths. The azimuth resolution ρ_a depends on the range R and the antenna beamwidth ΔB

$$\rho_a = \Delta BR$$

The advantage of operation at a millimeter wavelength is that a narrower antenna beamwidth can be obtained with a smaller aperture than at lower frequencies. For typical geometries, the range can vary from about 210 to 500 ft. It is recommended that the system be built at 95 GHz, because 95 GHz is the highest frequency for which millimeter-wave components are readily available. At 95 GHz, an antenna beamwidth of about 0.2° (3.5 mrad) can be obtained with a 48 inch antenna aperture; surface tolerance limitations make it impractical to construct a larger antenna with a narrower beamwidth. With the 0.2° beamwidth, the azimuth resolution will vary from about 0.7 to 2.1 ft, a resolution well above the centroid accuracy tolerance.

Another difficulty with using a millimeter-wave sensor results from the scattering characteristics of the target. The target dimensions are large compared with the wavelength, and the return from the target originates from a number of isolated scattering centers. These centers do not necessarily coincide with either the target centroid or the edges of the target, and it would be impractical to place a retroreflector at the centroid of each passing target. As a result, the image of a target will not provide enough information to furnish a plan-view of the target, to locate the target centroid, or to determine the yaw angle. The concrete surface of the highway will be smooth, and there are likely to be numerous multipath reflections involving the concrete and the targets, and the multipath reflections could be confusing when the data is processed. Multipath reflections involving the metal surface of different vehicles are also possible.

It is technically feasible to build an imaging radar for collecting vehicle data, if the limitations listed above could be reconciled. The cost of millimeter-wave radars, however, is another consideration; millimeter-wave components, especially the narrow-beam antenna which must scan at high speed, are expensive.

3.8 MTI Radar

It is well known that target speed can be measured by finding the Doppler shift f_d of a target where

$$f_d = \frac{2V_r}{\lambda}$$

Here V_r is the target's radial velocity, and λ is the wavelength. A 95 GHz MTI radar could be built and located at the side of the roadway or above it, so that the radar beam is parallel to the roadway, and the target velocity could be measured at the same time images are generated. If the radar were located perpendicular to the roadway, the target Dopplers will pass through a null at broadside and could not be measured. The maximum range will be about 1200ft, and the azimuth resolution at the far range will increase to about 4 ft. The occlusion of one target by another is more likely than for the imaging radar because the MTI radar is looking down the roadway, and the range is longer; consequently, the MTI radar height should be on the order of 120 ft or more to minimize occlusion effects.

The theoretical RMS error in the measurement of Doppler frequency δf is

$$\delta f = \frac{1}{\alpha \sqrt{2 \frac{E}{N_0}}}$$

where α is the signal duration, and E/N_0 is the ratio of the received energy to the noise spectral density. It is estimated that the RMS error in the measurement of the Doppler frequency will be a few percent.

The comments made in the section on the imaging radar are also applicable for the MTI radar images. With the target scattering properties and the available resolution, it will not be possible to meet the basic data requirements on centroid location, plan-view shadow, and yaw. If the output information of the imaging radar is processed properly, the target velocity could be found from target position changes, and the Doppler measurement capability would not be needed. The cost for the millimeter-wave MTI radar will be higher than for the millimeter-wave imaging radar because of its increased capability.

3.9 PASSIVE (INCOHERENT OPTICAL)

An alternative to the active imaging techniques described above is a passive approach based on visible reflectance or infrared emittance.

3.10 Infrared

Thermal infrared sensors are commercially available and have been used for some time in tracking applications and have even been tested for traffic surveillance. The advantages of an infrared sensor lie in its ability to detect thermal changes in the scene. At first glance, this may seem to offer a distinct advantage over visible wavelength sensors at night. However, research has shown that the infrared does not offer a clear advantage over visible even at night (visible sensors detect headlights), and is not as effective during normal

daylight operation. Infrared sensors generally provide low contrast imagery and higher spatial resolution can be achieved with visible wavelength sensors. The cost is also higher per sensor than for a visible wavelength CCD. For this application, infrared sensors offer no advantages over visible wavelength sensors and will not be considered further.

3.11 Visible

As shown in Figure 3-2, a visible wavelength CCD camera (referred to from now on as simply the CCD camera), located 10 m (32.8 ft) above the roadway, can provide coverage of a 3-lane highway for approximately 1000 ft (down-lane). A 512 x 512 element CCD array having 50 μm detector elements is assumed. High resolution, large array CCD cameras are available off the shelf. A sample of these cameras is provided in Table 3-1. A long focal length lens (200 mm) is required to achieve the 1000 ft field of view down-lane. The resolution at 1000 ft from the sensor is approximately 7.6 ft. To obtain ± 2 in. positional accuracy of a bounding rectangle around a vehicle, subpixel estimation is required (to 1/4 pixel). Centroid positional accuracy of ± 1 in. requires almost 1/8 subpixel accuracy. For passive reflectance imagery, the ability to obtain subpixel positional accuracy is dependent upon the number of pixels on the target, the edge contrast, and number of frames in the sequence. Dirt or film buildup on the camera lens and some weather conditions, for instance, will degrade the contrast and inhibit the edge detection process. Nonetheless, this level of subpixel performance has been reported in the photogrammetric/remote sensing and computer vision literature.

TABLE 3-1
Commercially Available CCD Arrays

Manufacturer	Array Size (Pixels)	Pixel Spacing (μm)
Kodak KAF-4200	2048 x 2048	9 x 9
Kodak KAF-1400	1340 x 1037	6.8 x 6.8
Kodak KAF-1300L	1280 x 1024	16 x 16
Tektronix TK2048	2048 x 2048	27 x 27
Tektronix TK1024	1024 x 1024	27 x 27

The CCD camera offers many advantages for the tracking application. With a fairly low cost per site compared to active or even infrared sensors, it is possible to use multiple CCDs to overcome problems typical to the freeway and intersection scenarios. For instance, several CCDs can be placed along the roadway at a nearly vertical look angle and provide the 1000 ft of coverage over one direction of traffic (2, 3, or 4 lanes), as illustrated in Figure 3-3. Since the cameras are nearly vertical, occlusion presents less of a problem.

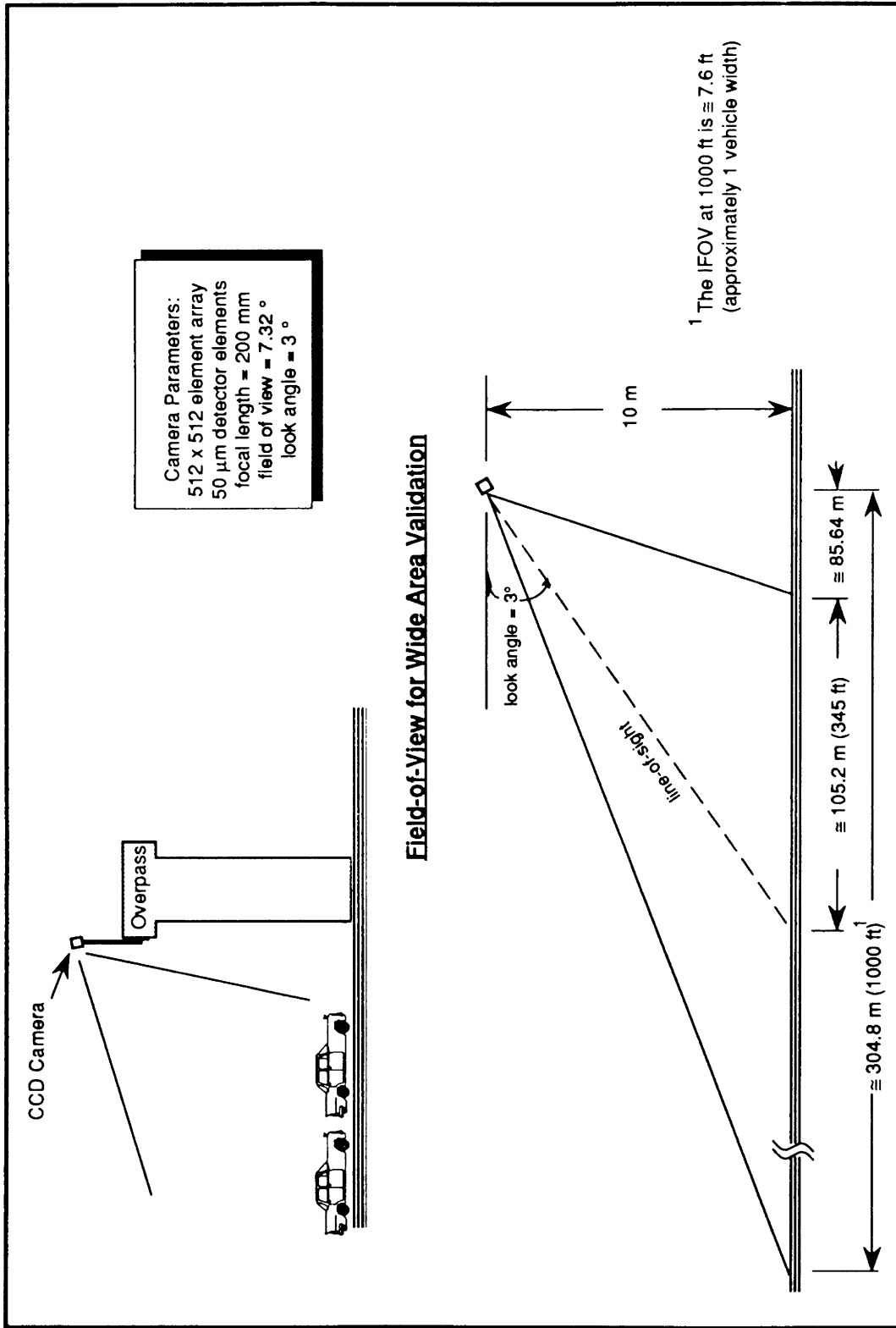


Figure 3-2. CCD Sensor Geometry for Vehicle Tracking

The images from each camera can be registered using an overlapping region between FOVs. This would increase the computational complexity only slightly, and would be more than offset by the reduced occlusion problems.

Assuming the following parameters for the geometry of Figure 3-3:

- 512 x 512 element CCD array
- 50 μm detector elements
- 12 mm focal length lens
- Height above the roadway \approx 100 ft

a FOV of approximately 210 ft x 210 ft can be achieved, with an instantaneous field of view (IFOV) of approximately 5 in.

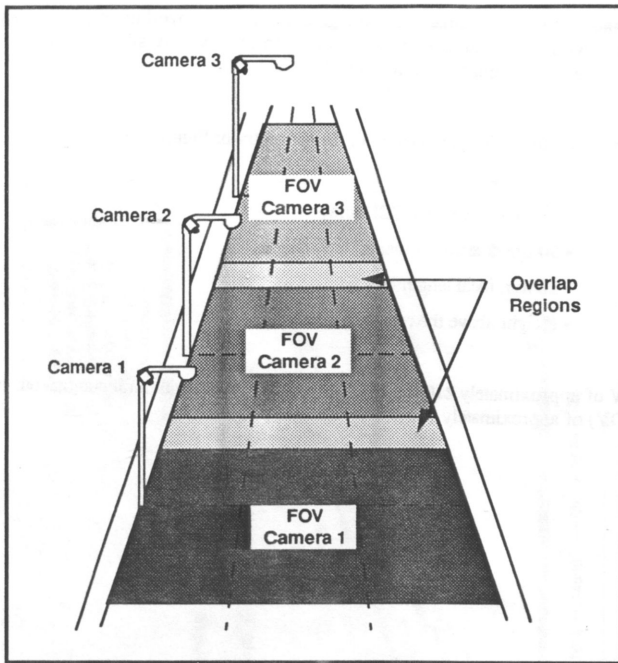


Figure 3-3. Multiple CCD Camera Set-up for Wide-Area Vehicle Tracking

4.0 Considerations for Further Processing of "Trajectory Data"

In this section of the report, we focus upon issues of post-processing whereby the raw characterizations of vehicle trajectory may be further enhanced so that additional variables are extracted, thus providing more utility for the engineering of collision prevention systems. For example, we will wish to be able to derive, from the raw trajectory data, such variables as vehicle yaw rate and longitudinal and lateral acceleration and even the driver's nominal inputs at the steering and braking controls which have produced the observed vehicle motions. The higher level control input variables can be deduced through Kalman filtering techniques [7, 8, 9, 10, 11]. In the discussion which follows, Kalman filtering has been used in an exploratory exercise both for studying the required accuracy of the initial trajectory data and for illustrating the method of extracting driver/vehicle control inputs.

Track Files

The field deployment of a sensor / raw data processor device will produce, for each vehicle detected within the field of regard, an individual data file referred to here and subsequently as a "track file." A track file would simply contain time histories of forward (x) and lateral (y) displacement of the vehicle geometric center (centroid or some equivalent reference point) and its angular orientation (yaw angle). Each track file would also contain a header record which might contain such information as the time of day, date, the length and width of the vehicle mask/shadow, and other useful information pertinent to the vehicle and the observation site. See Figures 4-1 and 4-2.

Data Processing Issues

Data processing issues that are foreseen arise mainly from the perceived ultimate usage of the VME data. End-users who are not interested in additional vehicle response information or driver steering control activity, for example, may be content with the direct measurements of x, y, and yaw angle, alone. They may simply require that the data be smoothed and that a few statistical measures be calculated to summarize the basic time history behavior of interest to them. On the other hand, other users may desire specific vehicle and driver responses such as vehicle yaw rate and driver control inputs. To obtain these latter vehicle/driver responses that are not being directly produced within the track file, it is possible to extract (with varying degrees of accuracy) such additional information by means of a relatively common signal processing scheme known as Kalman filtering.

Other data processing questions derive from how and when "events" (near-collisions, unusual inter-vehicular movements, etc.) within the traffic stream should be detected, characterized, and classified for subsequent scrutiny. Detection of events, prior to any other data processing activity (ala Figure 4-3), may be a preferred way of guiding subsequent and more time-consuming data processing activities, since for many end-users it may be that only the anomalous vehicle movements are of interest.

Figure 4-1. Basic Scheme

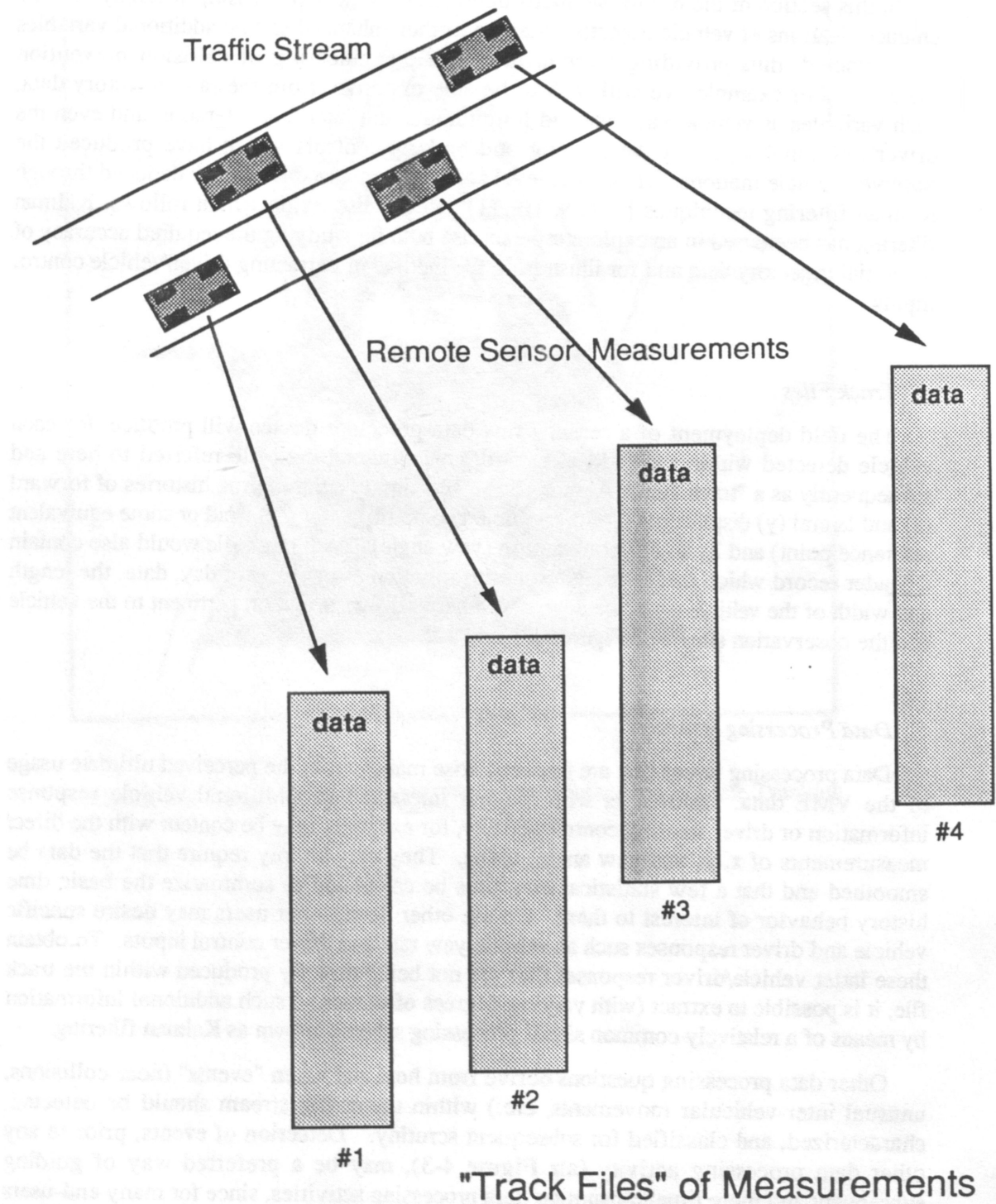


Figure 4-2. Example Track File

x is forward distance measurement in feet

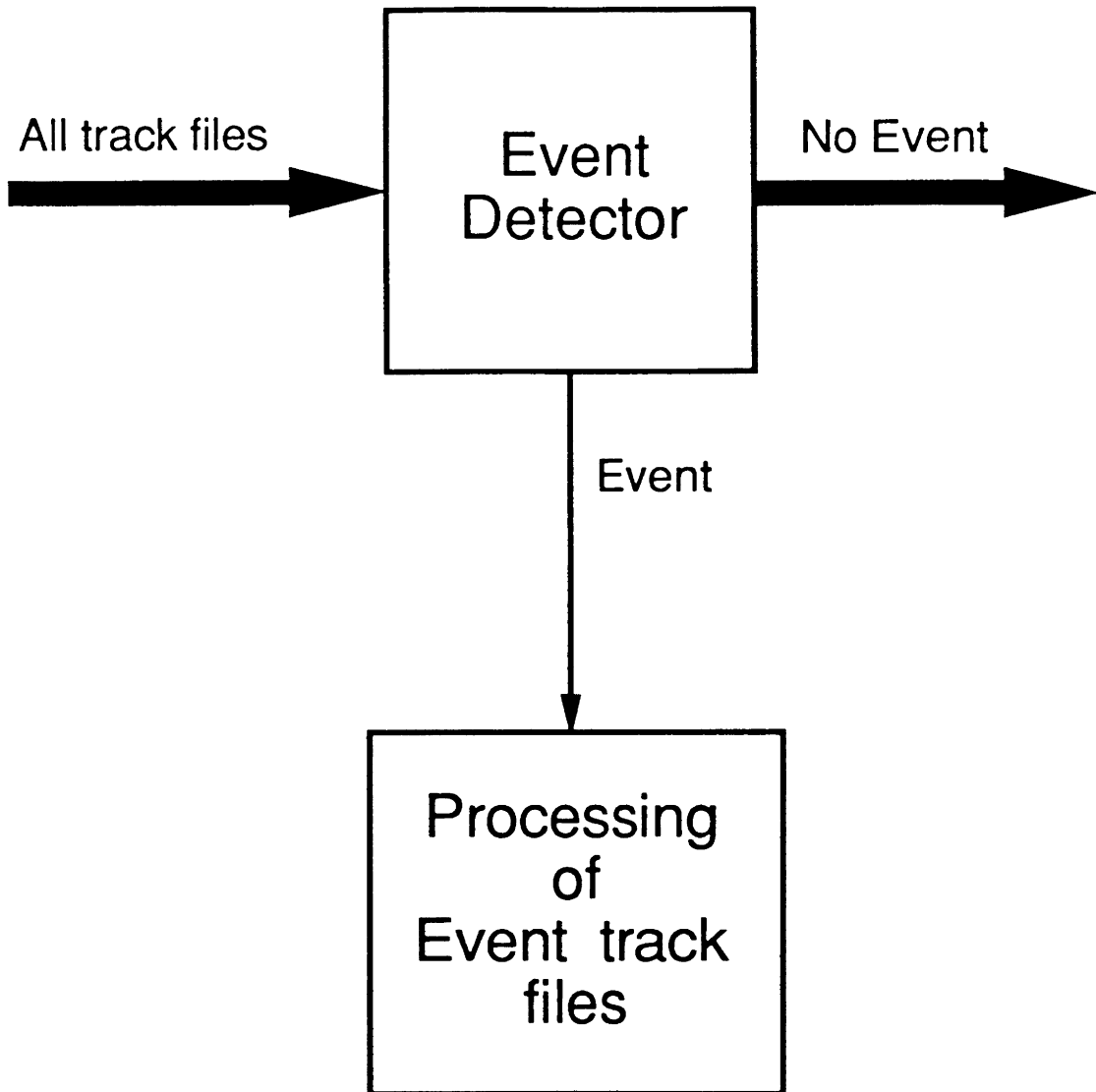
y is lateral distance measurement in feet

yaw is heading angle of vehicle in degrees

Track File			
Header Record Information (e.g., width & length dimensions of rectangular vehicle shadow, location of vehicle in traffic stream, time of day, date, etc.)			
time	x	y	yaw
(sec)	(ft)	(ft)	(deg)
0.0	0.0	0.0	0.0
0.1	8.0	0.1	0.05
0.2	16.0	0.07	0.12
.	.	.	.

One track file per vehicle

Figure 4-3. Data Processing Considerations



Relevant questions regarding the detection of events can be:

- How should an "event" be defined? Is it sufficient that we simply search for excessive values of relative (inter-vehicular) motion variables?
- Should "event" detection take place at or just after the sensor stage so that the track file, itself, can be tagged to indicate a potentially interesting set of data? Or, should such assessments be performed at a later stage?
- Should data smoothing and/or Kalman filtering only be applied to "event" data? That is, should only track files for which an event occurred be processed to contain the computational load?

These and other related issues and questions are noted in Table 4-1.

Assuming that Kalman filtering will likely be employed in the data processing for certain applications, the following discussion and example illustrates the basic mechanics of this particular processing scheme.

Kalman filtering

The basic idea behind Kalman filtering is to combine knowledge of the dynamics of the system being observed (i.e., the vehicle dynamics in this application) with a sequence of measurements of that system over time. Basic knowledge of the system dynamics permits the likely estimation of the system motion over time, while the direct sequential measurements provide a correcting mechanism based upon relative accuracies assumed for the sensors versus that assumed for the system dynamics. In essence, the Kalman filter employs an internal model (usually in a simplified form) of the system being measured and utilizes that model in combination with the measured data to obtain a best estimate of the system behavior from measurement to measurement.

To a certain extent, the more sophisticated and accurate the internal model used by the Kalman filter is, the more accurate will be the chances of improving the estimation. Likewise, the more accurate the sensors are in measuring the system behavior, the more accurate will be the estimation process. Tradeoffs between cost and accuracy are directly controlled by these factors since more accurate sensors usually mean more expensive sensors, and, more sophisticated internal models imply increased computer processing time.

Example Application of Kalman Filtering to Track File Data

For purposes of the following example, the accuracies adopted in the *Specifications* document are used; namely, it is assumed that accuracies are +/- 1 inch for vehicle position measurement and +/- 0.5 degrees for vehicle yaw angle measurement. That is, the assumed sensor system can locate the vehicle centroid to an accuracy of +/- 1 inch anywhere in the field of regard (+/- 500 feet) and can likewise measure the vehicle yaw angle in this same field of regard to an accuracy of +/- 0.5 degrees.

Table 4-1. Some Data Processing Issues.

Having collected (x, y, yaw) data in track files:

- How should such data be processed?
- What are end-user's needs and potential areas of application?
- Is simple filtering/smoothing of (x, y, yaw) sufficient to extract all the information that we may need?

Or,

- Can additional vehicle response data be extracted from the x, y, yaw measurements? For example, yaw rate, vehicle sideslip, driver steering activity? Is there a perceived need or future application for such data?
- Can Kalman filtering techniques or other smoothing techniques be utilized to process the collected data for extracting estimates of these additional vehicle responses?

Since no actual sensor hardware has yet been assembled for measuring such data and producing track files, artificial track files of the trajectory data were generated for this example. The artificial track files, complete with sensor noise, were generated by: (A) performing a nominal highway maneuver (55 mph lane-change or obstacle-avoidance maneuver; See Figure 4-4) with a relatively comprehensive full degree-of-freedom computer simulation (subsequently referred to as the "truth model"), (B) extracting x , y , and yaw from the simulation result to produce a noise-free track file, and then finally, (C) adding simulated sensor noise to the noise-free track file to produce a realistically noisy track file. The noisy track file was then used as input to the Kalman filter processing scheme in this example. See Figure 4-5. Time histories of "y" and "yaw" from the simulated track file (with added noise) are seen in Figure 4-6. The track file data were generated by sub-sampling the simulation result at a rate of 25 Hz.

The internal vehicle dynamics model utilized within the Kalman filter assumed a fairly simple form. The filter dynamics are for a linear passenger car with forward and lateral translational degrees of freedom and one yaw rotational degree of freedom. Steering control and braking control inputs are also represented. The state vector is comprised of forward and lateral translation of the mass center, sideslip velocity at the mass center, yaw angle, and yaw rate. The simplified filter dynamics assume that the vehicle has one mass and moves (translates and yaws) in a horizontal plane.

In addition to the assumed sensor noise levels noted above, the uncertainty in the filter dynamics were represented by "process noise" having amplitudes comparable to those assumed for the sensor. ("Tuning" of the Kalman filter requires some alteration of these values during the filter design.) The sensor and process noise characteristics were assumed to be "white" and were produced with a random number generator having a zero mean.

Results showing a direct comparison between the Kalman filter output and the noise-free "truth model" are seen in Figures 4-7 to 4-9. In Figure 4-7 comparisons are shown for lateral displacement (y) and yaw angle. The "truth model" indicates how the vehicle actually moved, while the Kalman filter output indicates how it was estimated to have moved based upon the noisy track file "measurements" input to the filter.

In Figure 4-8, two of the "derived" filter responses, vehicle sideslip and yaw rate, are seen and compared directly with the "truth model" result. Again, the Kalman filter outputs shown here are derived only from the (x, y, yaw) track file inputs and the assumed simplified vehicle dynamics noted above. The "truth model" shows how the vehicle actually responded during the maneuver.

Lastly, in Figure 4-9 a similar comparison is made for the driver steering wheel input (displayed as the steer angle at the front road wheels).

Discussion

The results of this analysis show that the selected accuracy specifications will guarantee a high quality vehicle motion representation. We see that not only are the directly-measured quantities (x , y , yaw angle) being estimated quite accurately, but also, that several

Figure 4-4. Example Obstacle Avoidance Maneuver at 55 mph

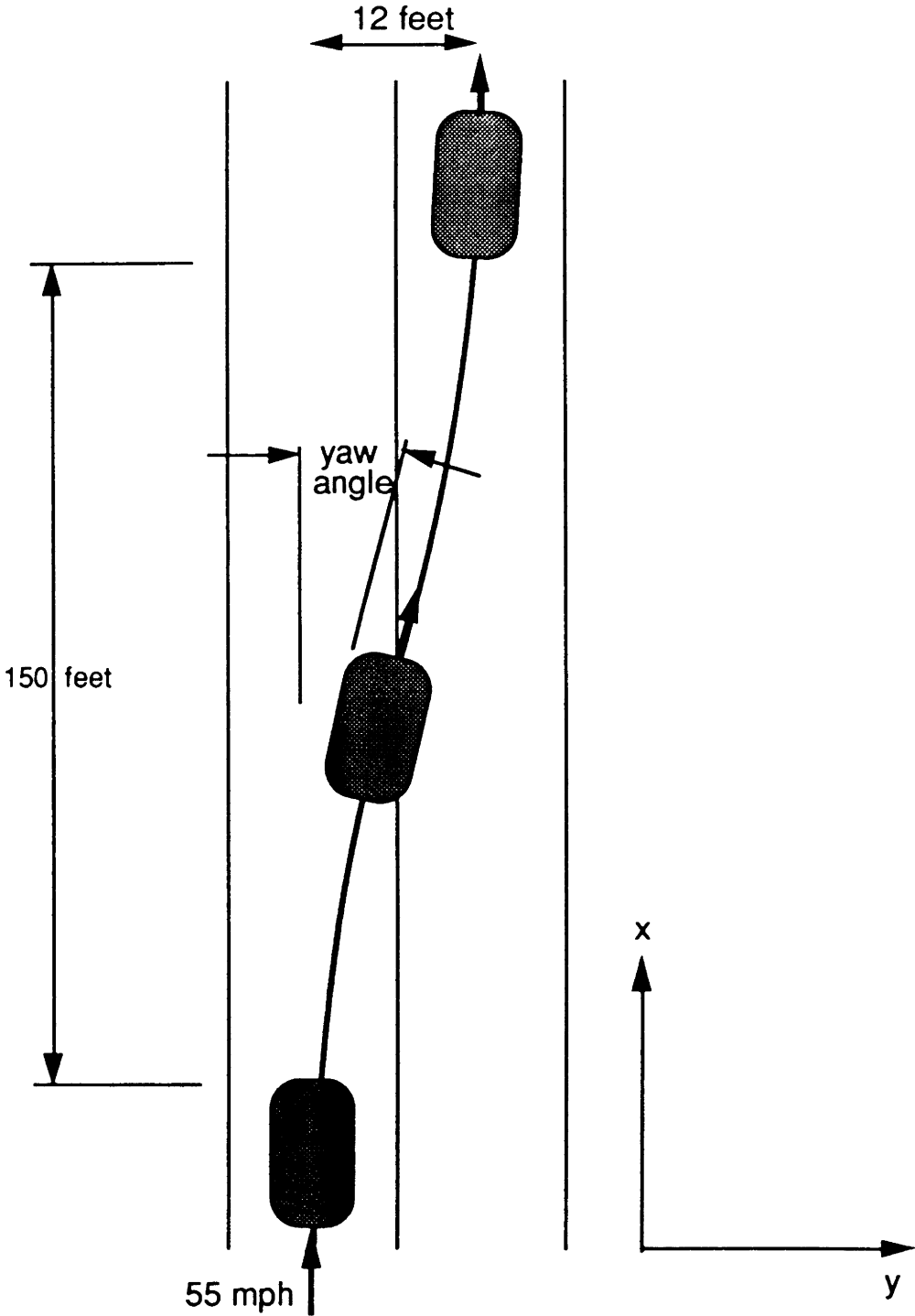


Figure 4-5. Example Calculations Performed to Illustrate Kalman Filter Application:

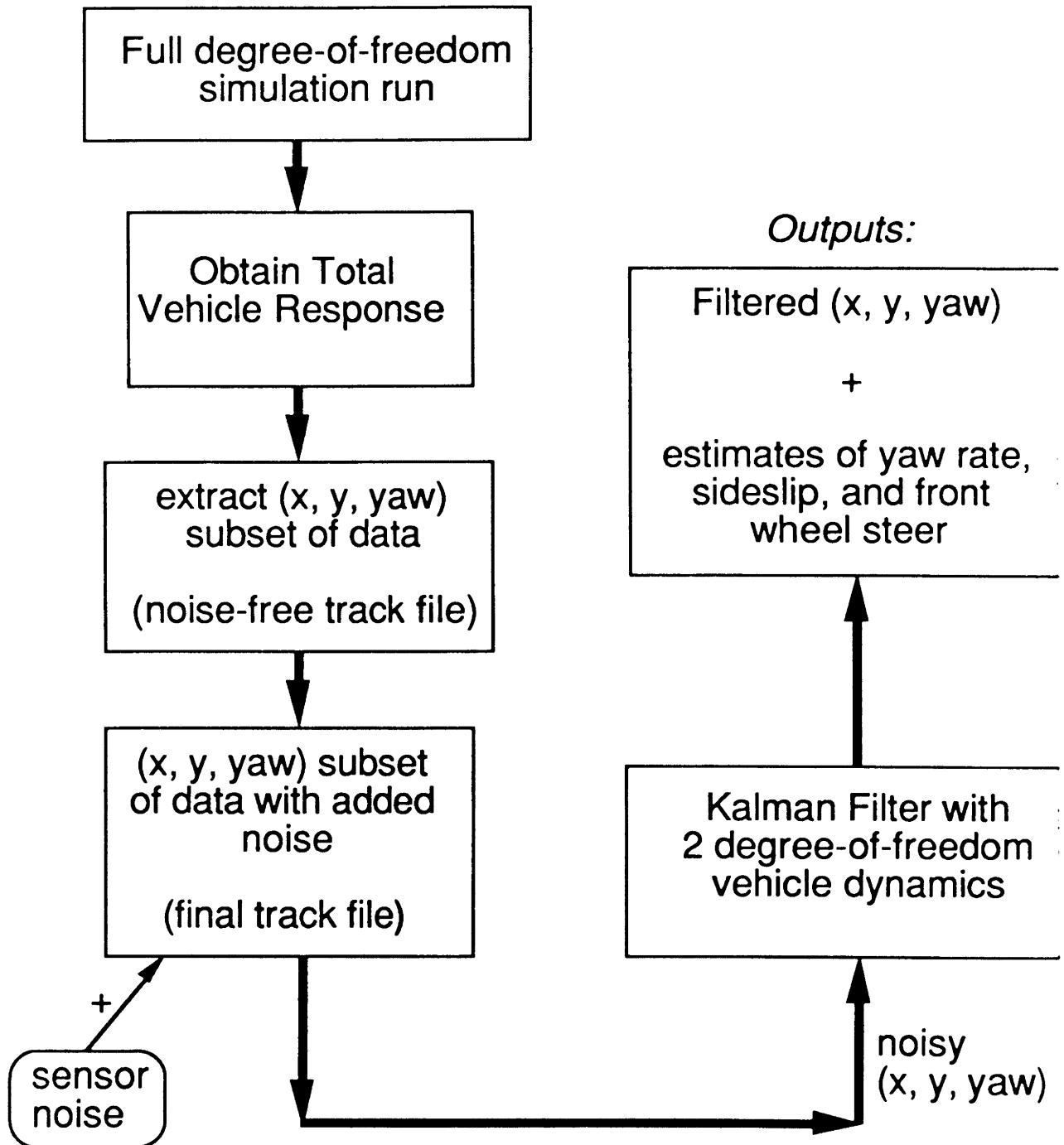


Figure 4-6. Artificial Track File (with Noise).
(55 mph Lane-Change Maneuver)

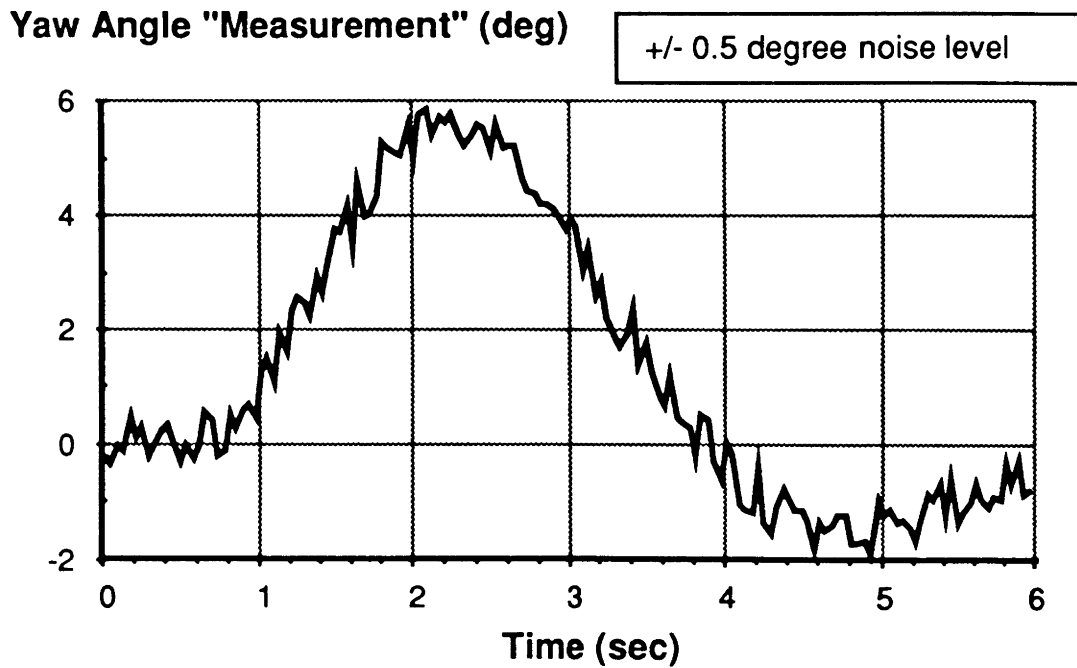
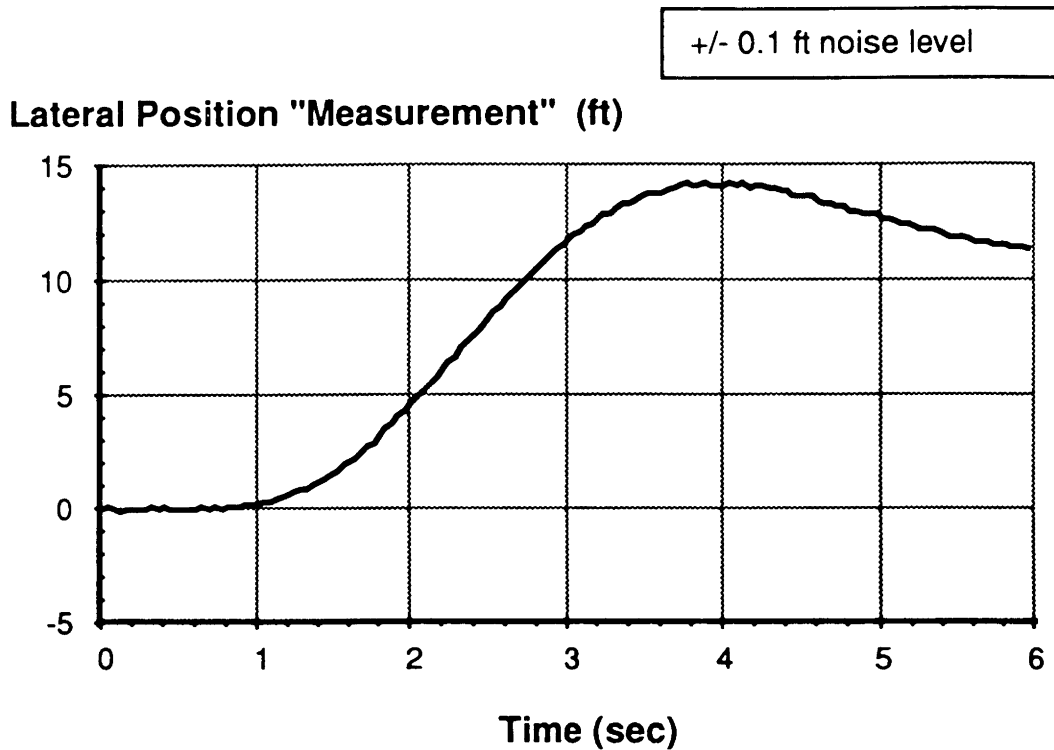
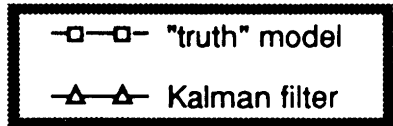
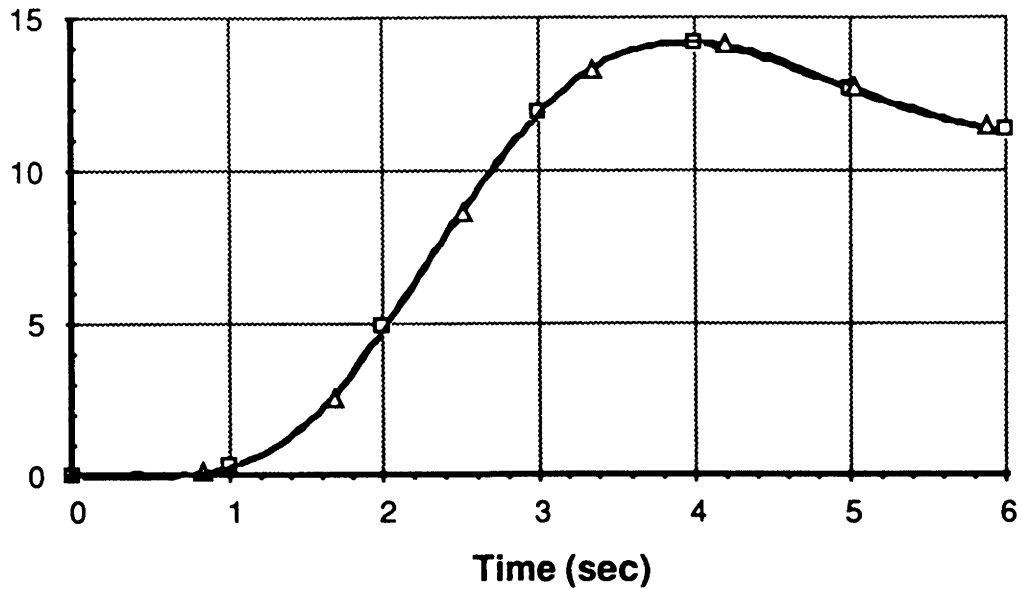


Figure 4-7. Kalman Filter Example Comparison.
(55 mph Lane-Change Maneuver)

Lateral "y" Position (ft)



Yaw Angle (deg)

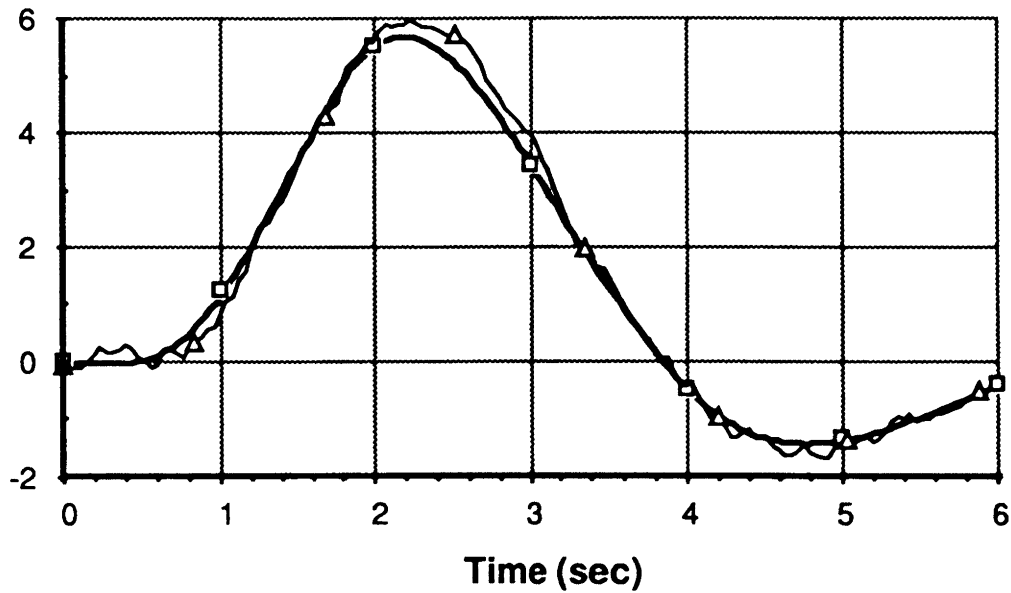
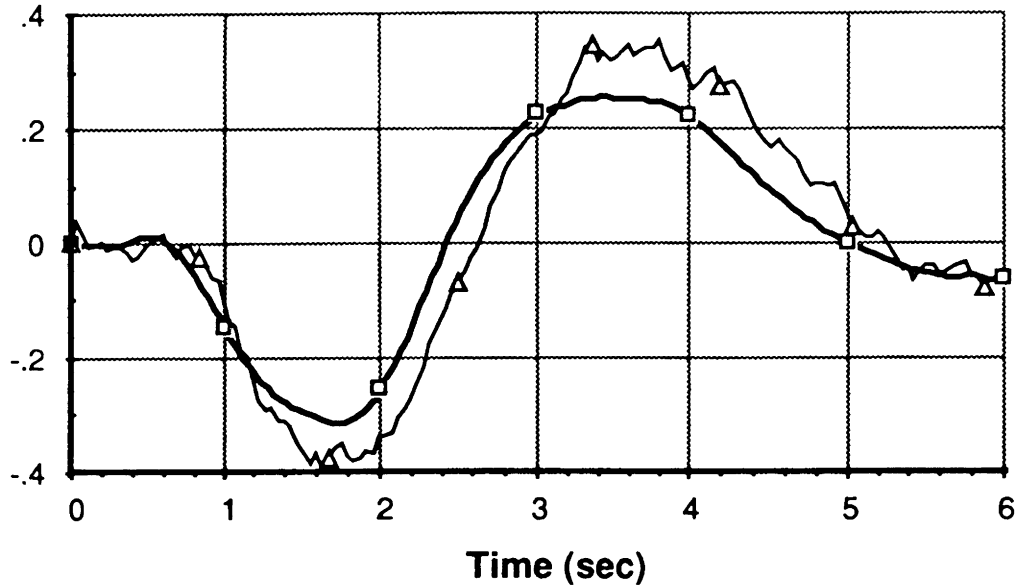


Figure 4-8. Kalman Filter Example Comparison.
(55 mph Lane-Change Maneuver)

Sideslip Angle (deg)



Yaw Rate (deg/sec)

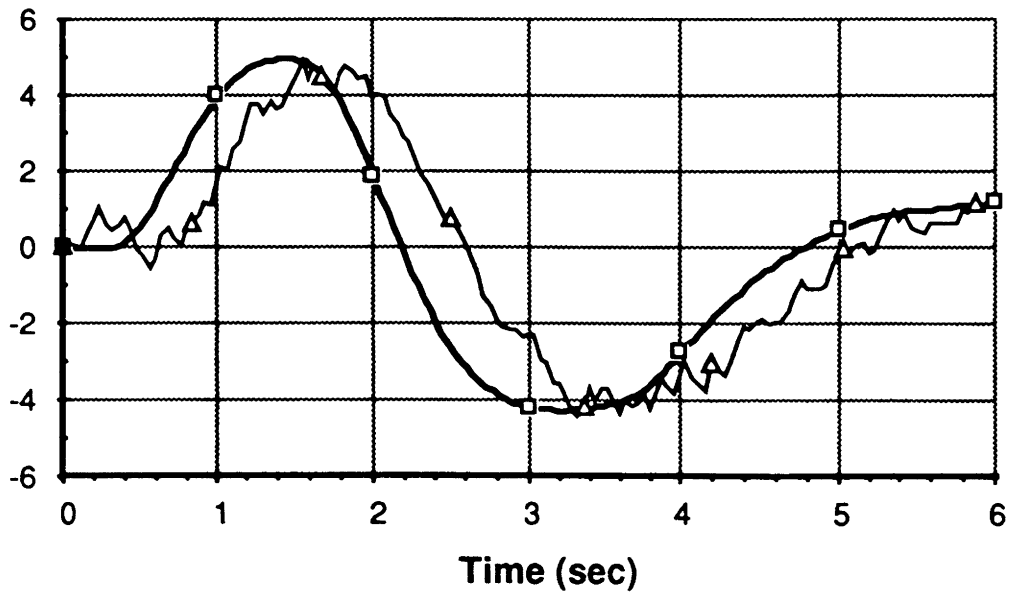
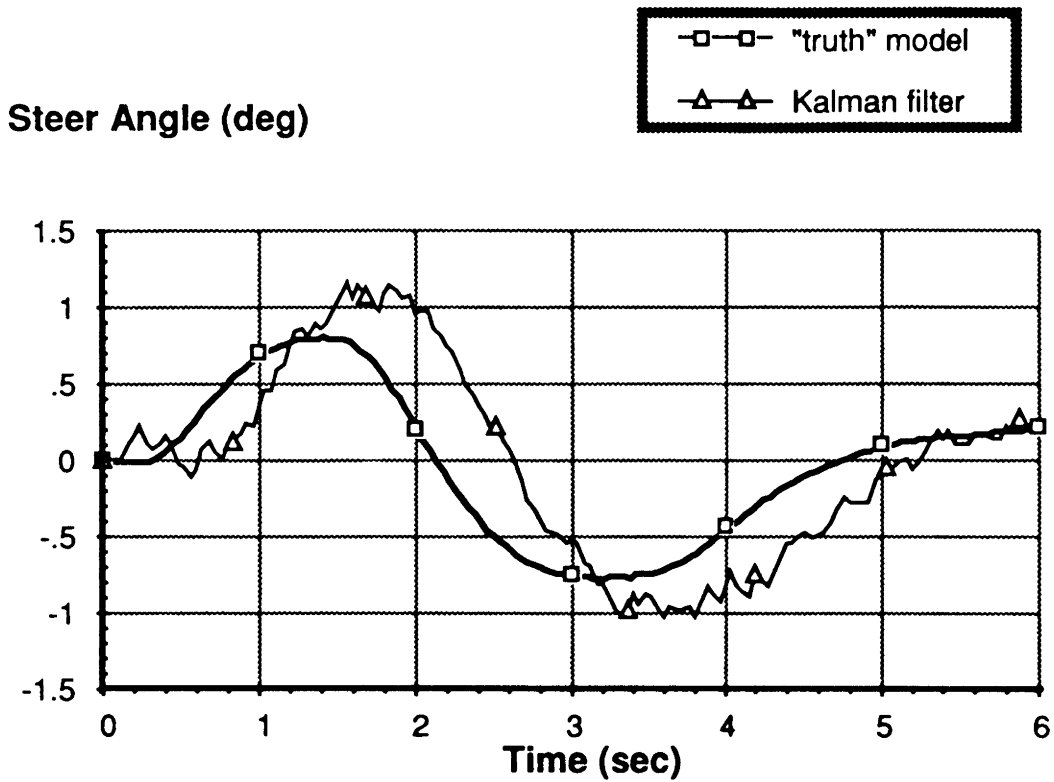


Figure 4-9. Kalman Filter Example Comparison.
(55 mph Lane-Change Maneuver)



additional driver/vehicle responses not being measured can be estimated reasonably well (yaw rate, sideslip, and driver steering activity) by this processing scheme. The greatest accuracy from the filter estimates are, of course, seen for those quantities that are being directly measured; that is, for x, y, and yaw angle. The principal discrepancy observed in the additional "derived" quantities such as yaw rate, sideslip, and driver steering is in the form of a time lag. It appears that further improvements in this feature can be obtained simply by incorporating additional "smoothing" algorithms in the data processing scheme. (This essentially involves combining the conventional forward-moving Kalman filter estimate with a similar Kalman filter estimate running backwards in time through the same data.)

Similar processing calculations performed for larger and smaller vehicles, but using the same Kalman filter seen here (which utilizes a nominal "mid-size" set of vehicle dynamics), produced similar results and comparable levels of error. This may indicate a relative insensitivity of the filter design to moderate changes in vehicle properties and thereby permit some sort of general assignment of filter designs according to vehicle type. That is, passenger cars (as identified by the size of their mask/shadow geometry) could be processed with one Kalman filter design, straight trucks or large vans with another, and tractor-semitrailers with a third filter design. This concept will be examined further in the on-going project activities.

Another area for improving the Kalman filter lies in the degree of detail represented in the internal vehicle dynamics model of the filter. Relatively modest improvements could be added to enhance the basic vehicle dynamics presently used. For example, a roll degree of freedom could be added to improve side-to-side load transfer representations and roll-steer effects within the model. Also, a basic steering system compliance could be included. These two items are major sources of understeer in most vehicles and may also help to enhance the dynamic transient behavior predictions from the Kalman filter.

Conclusions and Future Extensions

Based upon these and other results observed to date using this approach, it appears that the assumed sensor accuracies of +/- 1 inch and +/- 0.5 degrees on translational and angular position, respectively, are sufficient for demonstrating the feasibility of this technology at the prototype stage. Furthermore, refinements in the details of the Kalman filtering approach with "smoothing algorithms" and extended dynamics will further enhance the data processing accuracies and capabilities.

5.0 Considerations for Applying the VME System

In the broad VME concept, a measurement system would be built and deployed at multiple road sites as part of the "mainstream effort" of characterizing the U.S. traffic environment from the viewpoint of vehicle motions. The various uses of data coming out of the mainstream characterization will be summarized below. In addition, other envisioned uses of the measurement and subsequent processing technology are also cited.

Use of "Mainstream" Data

Assuming that a representative set of "mainstream" data have been produced characterizing traffic motions, at large, the following example studies can be conducted:

- quantification of overall trajectories within the conventional traffic stream for the sake of showing a) statistical distributions of motion variables and b) traffic flow characterization, given a micro-view of vehicle movement—these results would have various usages including the validation of theoretical models and the formation of base data for the study of vehicle dynamics and traffic engineering.
- quantification of vehicle motions on the basis of inter-vehicular variables such as car-following clearances, lateral clearances, closure rates, angles of attack, time to collision, etc.—these results present the quantitative data, with representative distributions, for designing collision prevention systems.
- detection and capture of anomalous events such as peculiar traffic conflicts, near-misses, and accidents (with video image backup)—providing an efficient means of focussing upon the mechanics of accident production, allowing an "instant replay" of near-misses and accidents in terms of both visual coverage and quantified closure variables.
- generation of driver control variables, such as brake application, steering inputs, and throttle application, given the application of Kalman filter techniques to deduce control actions from the raw trajectory data—providing for the study of representative driver behavior (as expanded more below) and enabling simultaneous computation of CPS algorithms which are based at least in part on driver control inputs.
- operation on the traffic stream data, using raw and generated variables as needed, to represent the functioning of a collision prevention system, gaining a representative estimate of the performance of the system given the probabilistic content of the actual vehicle motion environment. Each vehicle coming through the field of regard would be assumed to have the CPS installed such that the ensuing computation of its operation, given the nearby vehicles and their motions, serves as a surrogate for actually operating the system in the field.

Use for experimental validation of a vehicle's on-board, near-field sensor

The VME measurement system could be employed on a spot basis as a tool for determining the accuracy of a near-field sensing system mounted on-board a vehicle. A prototype sensing package would be installed on a vehicle and evaluated in a proving grounds setting, sensing other nearby vehicles and fixed objects—all within the view of the VME measurement system mounted on a pole or balloon above the scene. The VME data then serve as the reference set of information giving a "true" quantification of all vehicle motions and positions for subsequent comparison with the recorded outputs of the prototype vehicle-mounted sensor.

For studying the behavior of drivers

There is a broad literature pertaining to the study of driver control behavior in actual traffic environments. The VME system offers opportunity in the study of such issues as:

- driver behavior in construction zones, given use of barriers, signing, etc.
- driver behavior in weaving sections of roadway as a function of section length, traffic density, signing etc.;
- behavior while merging into or out of traffic;
- stopping behavior and friction demands;
- behavior through signalized intersections (where, for example, there is a keen interest in optimizing signal timing and making it traffic-adaptable through real-time controls;)
- behavior in passing zones relative to signing/stripping treatments;
- behavior of car drivers around heavy trucks;
- truck drivers' use of road space while turning, and the resulting offtracking movements of heavy trucks;

For studying the implications of special vehicle equipment

It may also be attractive to conduct experiments in which specially-outfitted cars operate on public roads, beneath the view of a VME measurement system. The special equipment could involve The purpose of such experiments would be a) to watch how other vehicles behave in the presence of the special vehicles and b) to quantify the behavior of the driver in the special vehicle, itself.

Relative to item (a), for example, the VME could have been used to evaluate the utility of center, high-mounted stop lamps, by watching the behavior of vehicles which followed specially-tagged vehicles having the new stop lamp (where the "tagged" vehicle is uniquely detectable through VME processing and thus is discriminated from other traffic in the observed scene.)

Relative to item (b), one could tag all vehicles equipped with an experimental route guidance packages to see how the corresponding drivers behaved when diversion advisories were given at varying distances upstream of a recommended exit point. Such information is needed in the safe design of route advisory strategies. As another example, we could watch changes in driver behavior when in-car signing is provided vs. conventional external signing, or we could monitor driver response to changeable message signing, perhaps as a function of the wording of the sign.

In all these cases, the VME measurement system offers the means to directly measure the motions—and to infer driver control activity through Kalman filtering—without directly instrumenting the car and while simultaneously measuring the motions of other traffic. Since the output of the VME system is quantitative, it constitutes a method around which figures of merit can be developed such that massive amounts of data can be uniformly reduced to meaningful results. By way of contrast, note that direct (human) visual observation of traffic movement is inherently qualitative—the observation results cannot be time-shrunk and do not yield generally definitive measures.

Moreover, the mere breadth of the above applications suggests that the VME measurement concept represents a revolutionary tool which can aid IVHS research as well as conventional studies of highway and vehicle operation.

6.0 Conclusions and Recommendations

The study has involved a deeper consideration of the VME concept, resulting in a statement of system specifications and a feasibility assessment of the measurement system and data processing considerations that will be entailed. As the VME measurement system has been envisioned, it appears to have application for many aspects of IVHS research as well as in conventional vehicle and highway engineering. The following conclusions can be drawn:

- 1) The VME concept has fundamental significance for the engineering of collision prevention systems and the study of basic driver and traffic behavior.
- 2) It appears feasible to create a VME measurement system, using available sensor technology, to track the trajectory of a vehicle's nominal centroid within approximately +/- one inch over a piece of roadway measuring 1000 feet long.
- 3) Over this trajectory, the outer extremities of each vehicle will be located to within +/- 3 inches for a typical passenger car and +/- 5 inches for a typical truck semitrailer.
- 4) All vehicles over the 1000 ft road section would be tracked simultaneously at a rate of ten samples, each, per second.
- 5) Achievement of such measurements, though supported by available sensor technology, will require a substantial programming task for the interpretation of sensor images in the highway context.
- 6) Post-processing of trajectory data will readily yield inter-vehicle motion variables such as clearances between vehicles, closure rates, and angles of attack.
- 7) Through conventional Kalman filter techniques, it is feasible to deduce driver control actions such as brake application, steering and throttle input, by processing trajectory data in conjunction with a crude dynamic model of the vehicle type.

It is recommended that an effort be undertaken to demonstrate a very basic form of the VME measurement concept in operation. Such a demonstration would reinforce the findings of feasibility and would support a proposal for a larger effort to deploy a prototype VME system for the collection of a high quality data set.

References

1. Sherman, J.W., Lake, C.D., 1989, "Determination of Object Location and Orientation Using Automatic Wire-Frame Model Matching," Society of Manufacturing Engineers, MS89-227
2. Zuk, D.M., Delleva, M.L., 1983, "Three-Dimensional Vision System for the Adaptive Suspension Vehicle," ERIM Final Report No. 170400-3-F, DARPA 4468, Defense Supply Service-Washington, (January)
3. Sampson, R.E., Swonger, C.W., Van Atta, P.W., 1984, "Real-time 3-Dimensional Image Processing for Robotic Applications," Addendum to Conference Proceedings, Robots 8, Future Considerations (2), Society of Manufacturing Engineers, Dearborn, MI
4. Riggs, A.J., Sampson, R.E., Tomko, L.M., 1985, "Application of 3-D Vision and High Speed Image Processing to Robot Control," *Proceedings of the Systems and Applied Technology Conference*, (October)
5. Loughheed, R.M., Sampson, R.E., 1988, "3-D Imaging Systems and High-Speed Processing for Robot Control," *Machine Vision and Applications*, 1:41-57
6. Wild Leitz Ltd., 1990, Car Distancer Product Information
7. T. F. Elbert, *Estimation and Control of Systems*. Van Nostrand Reinhold Co., New York, 1984.
8. G. F. Franklin and J. D. Powell, *Digital Control of Dynamic Systems*. Addison-Wesley Publishing Co., Reading, Mass., 1980.
9. A. Gelb et al., *Applied Optimal Estimation*. Gelb ed. The M.I.T. Press, Cambridge, Mass., 1974.
10. B. W. Leach, *An Introduction to Kalman Filtering*. 1984.
11. K. S. Miller and M. S. Leskiw, *An Introduction to Kalman Filtering with Applications*. Robert E. Kreiger Publishing Co., Malabar, Florida, 1987.

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