California AHMCT Program
University of California at Davis
California Department of Transportation

AUTOMATED HIGHWAY SYSTEMS (AHS) CLASSIFICATION BY VEHICLE AND INFRASTRUCTURE*

Ty A. Lasky
Bahram Ravani

AHMCT Research Report
UCD-ARR-94-1-25-01

Interim Report of Contract
DTFH61-93-C-00189

January 25, 1994

* This work was supported by Federal Highway Administration (FHWA) Contract Number DTFH61-93-C-00189 and by the California Department of Transportation (Caltrans) Advanced Highway Maintenance and Construction Technology Program at UC-Davis.

Abstract

Interest and research in Automated Highway Systems has increased dramatically in the last few years, especially since the passage of the Intermodal Surface Transportation Efficiency Act of 1991. New researchers are entering the field quickly, in part due to the recently awarded Federal Highway Administration Precursor System Analyses in Automated Highway Systems (AHS). A wide array of vehicle and infrastructure technology is available to implement envisioned AHS configurations. This report is an initial attempt to classify the technology available for vehicle and infrastructure use, to identify the operating characteristics of the technologies, and to provide pointers to some of the relevant literature in the field.

Contents

Disclaimer/Disclosure

The contents of this report reflect the views of the authors. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION and the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification, or regulation.

This work was supported by Federal Highway Administration Contract No. DTFH61-93-C-00189.

Chapter 1

Vehicle Systems

- Vehicle Class[1]
  - Full-Size Passenger Vehicle or Light Truck.
  - Narrow Vehicle, including Narrow Light Truck.
  - High-Performance Vehicle.
  - Truck or Transit Vehicle.
  - Narrow Truck or Transit Vehicle.
- Actuators[2]:
  - Braking
    * Hydraulic Braking
    * Electronic Braking:
      (IVHS AMERICA, 1992): This was listed as an enabling technology.
    * ABS:
      This is generally viewed as the technology needed to enable evolution to Autonomous Intelligent Cruise Control, and eventually longitudinal vehicle control, including platooning. For a discussion of ABS, traction control, and active suspensions, see (McLellan et al., 1992).
  - Throttle
    * Hydraulic Throttle Valve Control
    * Electronic Throttle Valve Control:
      (Chang et al., 1991): The experimenters first used a DC servomotor. Its response rate was 24 deg/sec in opening and closing the throttle butterfly. This

[1] See (Stevens, 1993) for sample values for these vehicle classes.

[2] The authors have elected to leave out several types of actuators, including traction control, as well as a number of actuators that may be internal to the engine. We see the engine actuators as being integral to most modern vehicles at this time, and are concentrating on actuators that would have to be added to support AHS operation.

means it took about 3 seconds to reach full throttle from the zero position. This delay effected the controller performance. This actuator was replaced with a stepper motor which provided a throttle angle change rate of about 800 deg/sec. This addition significantly reduced oscillation in the response, especially during high speed tests.

(IVHS AMERICA, 1992): This was listed as an enabling technology.

- Steering
  - Hydraulic Servo Steering:
    (Peng et al., 1992): This reference included experimental results. The system used here was connected in series with the standard steering system, and had only about 10% of the full range. It is noted in this reference that the state of California's recommended minimum radius of curvature for freeways is 1524 m in rural areas and 914 m in urban areas. This may be important in design considerations for steering actuators and controllers.
  - Electric Servo Steering:
    (Shladover et al., 1991)
    (IVHS AMERICA, 1992): This was listed as an enabling technology.

- Communications
  - Vehicle to Vehicle Communication
    - Infrared Transceiver:
      (Shladover et al., 1991): This reference describes a prototype unit. This unit, designed at PATH, requires Ethernet boards and computers. It transmits packets at 10 Mbps. As of this writing, the system was excessively sensitive to the transmitter/receiver alignment. The effects of fog and rain on the packet error rate had not been examined, but the selection of a high transmission rate relative to the desired target rate should help here.
    - Microwave Transceiver
    - Radio Frequency Transceiver[3]:
      (Shladover et al., 1991): This was the communications technology used in the experiments, as the IR system was still being developed.

      (Chang et al., 1991): The experimental system here used spread-spectrum digital radio transceivers. The lead vehicle transmitted its time clock, vehicle speed and acceleration to the follower vehicle. Throttle and brake actuation signals were calculated, but as of this paper, only throttle actuation was used.
    - Ultrasound:
      (Shladover et al., 1991): It is noted that the data rate (typically less than 20,000 bps) of ultrasonic communication is too low for control purposes.
    - Other Line-of-Sight Techniques

[3]Such a system will require protocols to solve multiple access problem.

    * Other passive or active transponders.

- Vehicle to Roadside Communication
    * Vehicle Detector for Inductive Loop Signal:
      This is mentioned as a very primitive form of VRC in some references.
    * Infrared Receiver:
      (Varaiya, 1993)
      (Miller and Keel, 1993): The system discussed here is a system for communication between a parked airplane and a ground-based network, but some information appears relevant to the needs of AHS. The system offers a high speed (100 Mbps) Fiber Distributed Data Interface (FDDI) data link using either a fiber umbilical cable (not of interest for AHS applications) or an infrared wireless connection with full duplex transmission. The unit requires a broad beam transmitter to accommodate variations in plane and bridge geometry, as well as variations in plane parking alignment. Because of this, the transceivers must be located close together due to the power loss of the wide beam. When selecting the required data rate, the makers of Gatelink could not find 4/16 Mbps Token Ring or 10 Mbps Ethernet chip sets that met their environmental requirements. However, they were able to find such chip sets for 100 Mbps FDDI. IR links were selected over various RF link choices (HF, VHF, and microwave). The problems identified with RF included frequency congestion at airports, electromagnetic interference (EMI), and health concerns. IR neither causes nor is susceptible to EMI. Worst case signal losses occurred in cold and humid conditions, which lead to heavy white frost build-up on the window of the transceivers. The losses in this study were high (17 dB), so that some method of inhibiting frost is needed. A simple heater for the window is sufficient. This is a relevant concern for AHS applications as well. In the application here, due to the small distance, rain, snow and fog losses are not severe, but this will be a problem in AHS. Effects of temperature variation caused a 2.5 dB loss.
    * Other Line-of-Sight Receivers:
      3M Corp.: An example LOS receiver is contained in literature from 3M. They have a commercially available system called Opticom Priority Control which can be used by emergency response vehicles. These vehicles are equipped with an emitter which transmits a coded optical message to a detector mounted above a traffic signal. The detector converts the optical message to an electronic impulse and sends it to the phase selector in the intersection controller cabinet. The phase selector directs the controller to provide a green light for the approaching emergency vehicle. Once the vehicle passes through the intersection, the signal returns to normal operation. The range between the detector and the emitter is adjustable from 1800 feet down to a few hundred feet.
    * Ultrasonic Receiver
    * Microwave Transceiver

* RF Transceiver:
  (Varaiya, 1993)
  Hughes: Hughes has a vehicle to roadside communication system that they have dubbed the VRC. It consists of readers in the infrastructure and communicators or transponders in the vehicle. The VRC uses the Slotted Aloha Time Division Multiple Access protocol so that two-way data communications can occur at high data transfer rates. The reader can cover up to four lanes, or, if mounted in the median, an entire eight lane freeway. It contains an RF transceiver, power supply, electronics, and antenna. The transponder can be mounted in the vehicle near the rear-view mirror. It does not require line-of-sight, so metallized windshields are not a problem. The antenna is polarized horizontally so as to minimize interference with cellular phones, which are vertically polarized. Applications include electronic toll collection, driver information systems, CVO, emergency beacons, vehicle tracking, and electronic license plates and credentials. The Slotted Aloha TDMA protocol works as follows: a radio signal from the reader triggers all communicators in range to identify themselves; each communicator randomly selects one of sixteen available "Activation Time Slots" to transmit its ID to the reader; the reader picks up to four communicators and sends or requests up to four individual messages in one of four "Data Time Slots" to or from them; any communicator not selected randomly selects a new activation time slot to then re-broadcast its ID; up to four selected communicators transmit variable messages to the reader or read messages from the reader; the reader acknowledges each communicator ending its transaction or reassigns the communicator a new time slot in which to obtain a retransmission of the message. Hughes estimates the theoretical bit error rate of this system to be less than 1 failure in 37 billion bits, i.e. 3.7×10^{-10}.

  ORBCOMM: ORBCOMM offers an interesting product for low volume messaging. It is essentially a Low Earth Orbit (LEO) satellite communication and location system. It is independent of military systems, such as GPS. It is fairly primitive by AHS standards, as communication occurs between 2400 and 4800 bps, and vehicle location accuracy is only 375 m. It communicates with the satellite at about 150 MHz. Communication is optimized for messages of 6 - 250 bytes, but there is no actual maximum message size. There are 26 satellites in the entire system.

* RF Transponder:
  Mark IV Industries, Ltd: This system uses an overhead antenna and a roadside reader in the infrastructure, and an RF transponder in the vehicle. It operates in 902 - 928 MHz band, uses 16-bit Cyclic Redundancy Check (CRC), and can read the transponder data five times at vehicle speeds of up to 100 mph, which results in a read error rate of less than 1 in 10,000. Reading speed is 500 kbps, with up to five reads per transponder with vehicles present in eight lanes simultaneously. In-pavement antennas can also

be used. The transponder itself transmits at 500 kbps, and has an RS-232 interface operating at 9600 bps. Each data frame is 128 bits.

* FM Radio Broadcast
* Packet Radio Network:
  Pinpoint: This company's literature refers to dedicated packet radio networks, which have been developed to overcome some of the weaknesses of analog voice radio architectures. Pinpoint notes that such networks are still based on voice-radio channels, where capacities are limited to 1200 - 19,200 bps, and more typically 2400 - 4800 bps of effective user data throughput.

  ARDIS: This literature discusses the RAM MobileData network. This literature indicates that coverage in metropolitan areas is very good, with little interference from tall buildings.
* Active or Passive Transponder
* Cellular Radio:
  (Catling and de Beek, 1991): SOCRATES was the largest program in the European DRIVE program. It developed techniques for using cellular radio as the basic communication medium for their "Integrated Road Transport Environment." This system provides duplex communication between vehicles and control centers. It uses a common downlink and a single multiple-access uplink in each cell of the radio network to provide the high capacity duplex link that is necessary without unduly loading the radio network. The application here is in dynamic route guidance. As noted in this reference, the cells in a cellular radio system are typically between 2 km and 35 km across, at least in Europe.
* Satellite Communication Link:
  Pinpoint: This technology is more for wide area communication, e.g. nationwide for fleet applications. The particular service discussed in this literature is the "Mobile Satellite Service" (MSS). Such systems are extremely expensive, and support only low data rates.
* Variable Message Sign (to driver only):
  (Varaiya, 1993)
* Smart Cards:
  AT&T: One use of these cards is for electronic toll collection. When a driver approaches a toll plaza, he inserts his smart card into a transmitter mounted on the dashboard. Information stored on the card is transmitted to the toll station via radio link, and the cost of each toll is debited from a prepaid amount on the card, or recorded for later billing. Such a system is installed on the Austrada, Italy's highway system, and will be installed on three new toll roads in Orange County, CA. The smart card can serve multiple purposes, including employee identification, computer security, telephone calling cards, medical record storage, and financial transactions. It is essentially a computer in a credit card form. Its memory can hold the equivalent of several

pages of typewritten personalized information. The card has an 8-bit microprocessor, 3 kilobytes of EEPROM, an asynchronous serial data link, and a security system. Power and communication reach the card using a contactless interface. The operating system is similar to UNIX, and allows different security levels and user access for different files. Encryption, decryption, and message authentication are supported.

- Control
  - Lateral Position Control
    - PID:
      (Hessburg et al., 1991): The experiment presented here includes feed-forward preview.

      (Peng et al., 1992): This experimental study continues previous work. It is noted that PID gains require more experimental tuning than FSLQ gains, i.e. PID gains that work in simulation may produce unacceptable performance in the vehicle, while FSLQ gains that work in simulation also work in practice.
    - Frequency Shaped Linear Quadratic (FSLQ):
      (Peng and Tomizuka, 1990)
      (Shladover et al., 1991)
      (Peng et al., 1992): Gain tuning aspects of this experimental controller are discussed in the above PID comments. Drawbacks relative to PID include a more complicated control structure which requires a state observer that doesn't work at low speeds, longer computation time, higher sensitivity to the steering angle measurement, and poorer performance at low vehicle speeds. FSLQ control is superior to PID in terms of better ride quality (as evaluated from lateral acceleration measurement and passenger perception), reduced sensitivity to lateral position measurement noise, and greater ease in tuning the feedback gains. In addition, with FSLQ, the designer can include the frequency-dependent ride quality index explicitly in the cost function. The performance of this and the PID controller were good, with lateral deviation maintained within ± 20 cm on both straight and curved (74 m radius) roads at speeds up to 60 km/hr.

      (Peng et al., 1993): This experimental study includes closed-loop responses under a variety of test conditions, including low tire pressure, measurement noise, perturbed lateral reference system, hard braking, and snowy roads. It also investigates the effects of increased marker spacing and missing markers. Tests were performed at 50 km/hr, and the vehicle was able to track even curved sections under these adverse conditions with less than 15 cm error. Comparison of automatic and manual control, including plots, is also included; the current authors have not seen this useful data elsewhere.
    - Adaptive Control

* Preview Control, i.e. Feedforward of Road Geometry[4]:
(Shladover et al., 1991)
(Peng and Tomizuka, 1991a): This controller utilizes preview information pertaining to road curvature as well as superelevation angle to get an "effective curvature". Without the use of the superelevation angle, large errors may occur in the estimation of the average tire cornering stiffness, which indirectly degrades controller tracking.

  (Peng and Tomizuka, 1991b)

  (Peng et al., 1992): The experimental controller as presented here requires the use of FSLQ or just LQ control theory to design the gains.

  (Peng et al., 1993): This reference includes closed-loop response under a variety of test conditions, including low tire pressure, measurement noise, perturbed reference system, hard braking, and snowy road.

* Nonlinear Dynamic Cancellation:
(Sheikholeslam and Desoer, 1991c): This reference discusses combined longitudinal and lateral control. The controller presented here cancels vehicle dynamics nonlinearities due to road geometry, engine dynamics, and longitudinal and lateral dynamics. The development uses small angle approximations to simplify lateral dynamics for roads with a large radius of curvature under nominal conditions. The nonlinear dynamic cancellation is used in conjunction with a PD controller and an acceleration error term. The controller requires sensors for lateral and longitudinal velocity and acceleration, yaw rate, steering angle, lateral position deviation, and longitudinal deviation from desired position. The technique assumes the availability of a road map in the sense of the (x, y) coordinates of points on the lane center as a function of arc length along the road, so that tangents and normals can be obtained, as well as the radius of curvature. Simulations showed that the proposed controller performs well under nominal operation on roads with suitably large radius of curvature. The controllers used here were nonadaptive, so they will be sensitive to parameter variations.

* Neural Network:
(Kornhauser, 1991)
(Lubin et al., 1992)

* Fuzzy Rule-Based:
(Hessburg and Tomizuka, 1991): The simulation results in this study showed good lateral tracking, with robustness to external disturbances and parameter variations of the vehicle. The fuzzy rule-based controller presented can handle large numbers of input variables in an effective manner.

[4]Such a controller is to be used in combination with other techniques. It will require a sensor system that can supply road geometry information, e.g. discrete magnetic markers or a vision system.

* Learning Control

- Longitudinal Spacing and Speed

    * PID, typically with feedforward of lead vehicle velocity and acceleration:
      (Shladover et al., 1991)
      (Frank, Liu and Liang, 1989)
      (Sheikholeslam and Desoer, 1991b): This controller uses PD and acceleration feedback, with feedforward of the preceding vehicle's acceleration and velocity. It uses no lead vehicle information, so that a communication link is not required. The authors use a constrained optimization approach to design the controller gains. Simulation results show that the vehicle following performance is degraded due to the lack of communication, but may be acceptable under communications failure. In contrast to controllers that use lead vehicle communication, here vehicle deviations increased from one vehicle to the next. However, peak values were within acceptable performance limits, and the deviations did not exhibit excessive oscillatory behavior. As no communications is needed, this system is cheaper to implement. However, the current authors envision this controller as only a fall back controller in the case of communications failure. The simulations in this study were for straight-line motion only.

    * Adaptive:
      (Sheikholeslam and Desoer, 1991a): This reference gives a local indirect adaptive control scheme for a class of interconnected nonlinear systems. The main advantages of this scheme are first that through the use of *local* measurements, computational and measurement costs are reduced, while reliability and flexibility of the control system as a whole are increased, and second that the adaptive nature increases the robustness of the control system with respect to parameter uncertainties. Conditions are given on inputs, parameter uncertainties, and the dynamics of the nonlinear plants, under which it is possible to meet the design objectives using local, nonlinear adaptive control laws. The conditions are: for longitudinal control, sufficiently slow changes in the lead vehicle's velocity and sufficiently small parameter errors of the first vehicle, and for lateral control sufficiently slow changes in the road curvature and slope and sufficiently small parameter errors for each vehicle. Under such conditions in longitudinal control, headway error is bounded, approaches zero, and the peak deviation of the k_{th} vehicle position monotonically decreases as k increases. For lateral control, the lateral error is bounded, and approaches zero.

      (Sheikholeslam and Desoer, 1992): This reference presents a decentralized adaptive control scheme for interconnected nonlinear systems. The example used is longitudinal control of a platoon of vehicles. The controller can monotonically decrease magnitude of deviations of the k_{th} vehicle as k increases. The deviations are bounded independent of parameter errors.

* Variable Structure:
  (Chang et al., 1991) A variable structure controller is used to compensate for the inherent nonlinearities in the automobile plant. The controller uses the following measurements: distance and closing rate (using a radar sensor), speed, acceleration, throttle angle, brake pressure, engine speed, engine intake manifold air pressure and temperature. In addition, the controller uses communicated lead vehicle information. The control sampling rate is 50 msec. The experiment consisted of a two car platoon, with intervehicle separation of about 15 m. Test 1 was at 10 m/s, with the lead vehicle traveling at a constant speed. Test 2 was at 25 m/s with acceleration and deceleration of the lead vehicle. In test 1, the maximum range deviation was about 0.6 m, and below 0.2 m in steady state. In test 2, the maximum range deviation was 0.8 m during "steep deceleration" of the lead vehicle. During constant velocity travel, the range deviation was within 0.5 m.
* Nonlinear Dynamic Cancellation: (Sheikholeslam and Desoer, 1991c): The controller presented here cancels nonlinearities in longitudinal vehicle dynamics. The development includes eight approximations to simplify the dynamics, which amount to the assumption that the longitudinal dynamics of a platoon of closely-spaced vehicles on a road with suitably large curvature is approximately the same as the longitudinal dynamics of the same platoon on a straight road. This controller includes PD and acceleration error feedback, as well as feedforward of lead vehicle velocity and acceleration.
* Neural Network
* Fuzzy Rule-Based
* Learning Control
* Multimode Control:
  As described in (Fenton and Mayhan, 1991), controllers with different characteristics are needed for six different longitudinal control modes, including: overtaking, emergency braking, and car-following modes.

- Displays[5]:
  - Information Type
    * Warning Information
    * System Status
    * Vehicle Status
    * Environmental Conditions
    * Maps
  - Display Type
    * Liquid Crystal Displays (LCD):
      (Ohara, Matsumoto and Fraser, 1992)

[5]Coverage here is cursory.

* Vacuum Fluorescent Displays (VFD):
  (Iwase et al., 1992): This VFD contains all the primary gauges of an electronic instrument panel, including speedometer (digital and analog), tachometer, fuel and temperature gauges, odometer/trip odometer, and gear indicator.

  (Davis et al., 1992): This display adds a color shift capability which can convey more information to the driver. This is done using a Liquid Crystal Color Shutter (LCCS).
* Chip-in-Glass Fluorescent Indicator Panel (CIG-FIP):
  (Akiyama et al., 1992): CIG technology solves the problem of the large number of external connections needed in conventional graphic display panels. Additionally, a CIG-FIP offers low total system cost, easy assembly, and high reliability.

  (Ishizuka and Saeki, 1992): The display presented in this reference also serves as an input device due to the inclusion of keyboard interface.
* Dot Matrix Display:
  (Akiyama et al., 1992)
  (Markatos and Nixon, 1991): This reference details design efforts in prototyping a dot matrix display subsystem, as well as some recommended enhancements for future applications.
* Thin Film Transistor (TFT) Active Matrix Display:
  (Akiyama et al., 1991): As noted in this reference, TFT is too expensive for many applications. However, this Fluorescent Indicator Panel (FIP) has the following advantages: low driving voltage, large scale, high capacity, and low cost. In conventional graphic-type FIPs, brightness decreases with increasing number of picture elements, leading to a need for high driving voltages. The Active Matrix TFT FIP solves this problem, as it is capable of driving the phosphor in static mode.
* Heads-Up Display:
  (Ohara, Matsumoto and Fraser, 1992)
  (Weihrauch, Meloeny and Goesch, 1989): This HUD uses Vacuum Fluorescent Display (VFD) tube and reflective optics, including the standard windshield as the final element, to project a virtual image of the digital speedometer and other information just above the hood near the front bumper.

  (Kato et al., 1992)

  (Enderby and Wood, 1992): This reference details development of a low-cost automotive HUD using aerospace technology, with a 1000:1 cost reduction.

  (Ayres, 1993): The system presented in this reference can be installed as an after-market HUD, as the optics do not need to be matched to the windshield.
* Night, Fog, and Rain Vision Enhancement:

(Bulkeley, 1993): Jaguar is testing systems in this area. Their car is equipped with an IR camera placed inside the windshield in front of the rearview mirror. Using thermal imaging, the system detects heat thrown off by any object in the path of the driver up to 100 m away. The system translates heat emissions from car engines, lights, signs, and the human body into thermal images. These images are used to make a black and white picture that is clearer than the human eye can see in dark or fog. Possible displays to the driver include a monitor mounted near the glove compartment, or a HUD.

    * Audio Warning (Voice or Tone)

- Interface to ATMS and ATIS
  - CD-ROM[6]
  - Map Databases:
    Geospan: This company is currently using "GeoVans" to map every urban street (population over 25,000) in the United States, including images of street surfaces, roadside infrastructure, and roadside real estate, as well as electronic street maps, street addresses, and vehicle routing data such as speed limits. The expected completion date for the collection is some time in 1995. The images captured are overlapping stereo images, allowing use of photogrammetry to measure accurate locations and sizes of objects. Differential GPS sensing is incorporated to obtain positioning accuracy better than 5 m, and a secondary navigation system is used when GPS signals are lost. To give an idea of the storage available on a single CD, consider the curb-side view, front and back, full screen JPEG (a standard image compression technique) CD, which shows images of visible signs, parking meters, fire hydrants, utility poles, curbs, sidewalks, and other infrastructure along the streets. The average distance between views is 20 feet, and each disk contains approximately 100 miles of data, including front and rear views. Another disk, containing quarter-screen JPEG views of both street and curb-side images contains approximately 200 miles of data. According to Geospan, one CD-ROM contains approximately 50,000 JPEG images.

    DeLorme: This is another company making CD-ROM maps and atlases, computer mapping systems, and geographic databases. They have a product called StreetAtlas USA which they claim contains every street in the United States on a single CD-ROM, including backroads, dirt roads, etc. They also make a product called MapExpert that lets the user search for locations by latitude and longitude, and display location information in measurements "as precise as thousandths of seconds." The company also makes a product called GPS MapKit SV, which is software to link a GPS receiver to their maps. This software interprets GPS data and places a blinking dot on a moving map display. Features include constant visual indication of location, active readout of latitude and longitude, ability to monitor vehicle speed, direction, and altitude, detailed maps, "bread crumb"

[6] These high-capacity devices are useful for mapping and GIS database storage.

function to trace route, calculation of approximate point-to-point and cumulative mileage, five million US roads, 1.1 million geographic and man-made features, and address ranges in major metropolitan areas. The company also configures hardware setups for this software that include CD-ROM drive, Rockwell NavCore V GPS receiver, 12V power connection, and antenna.

Etak: Etak also makes digital maps, mapping software development tools, and navigation technology. Their systems were used in the TravTek, PathFinder, and ADVANCE projects.

– In-Vehicle Navigation Unit:
  Blaupunkt: This company makes the TravelPilot system, which combines a CD-ROM system for map databases with a navigational computer. The system uses maps from Etak. Blaupunkt was involved in the ALI-SCOUT field trials in Berlin. The system includes a flux-gate (electronic) compass to determine the direction of the vehicle, so that the map can be reoriented based on the direction of travel. Dead-reckoning, using small plastic encased magnetic field sensing coils on the wheels, is used to track the vehicle's position on the map.

– Flexible Format Display for Maps, Real-time Congestion Data, Route Guidance, and Road Sign Information[7]:
  (IVHS AMERICA, 1992): This was listed as an enabling technology.

  (Corsi and Sattler, 1989): This paper lists some of the advantages of a reconfigurable display, including use for night vision enhancement, route guidance, and travel information. In addition, such a display can provide for advanced diagnostics for drivers and repair technicians, allow driver customization, and reduce the need for duplicate hardware across vehicle lines, as a different appearance can be achieved by using different graphics package software. The technology selected, Liquid Crystal Shutter/Cathode-Ray Tube (LCS/CRT), was technically inferior to a Thin Film Transistor/LCD, except that the LCS/CRT provided substantially more viewing area, and gave sufficient performance in other areas.

  (Gumkowski and Shaout, 1993): This reference discusses a dot matrix display system for use as a flexible format display.

– Use of AVCS vehicle travel information for real-time congestion and incident detection. Vehicles can store average travel times by link and time of day. Data aberrations indicate incidents.

– Highway Advisory Radio

– Integrated ATIS/AVCS. Use ATIS systems as a means of communication with the ATMS.

– Direct ties between route guidance and AVCS so that AVCS command decisions are based on planned route.

[7]This display can serve as an interface for AVCS warning and status information as well.

- Integrate ATMS and AVCS. ATMS can transmit commands to vehicle at signals to enhance the flow of vehicles at intersection. Also, ATMS can set variable speed limits on freeways to slow traffic before it encounters incidents and congested areas. These speed limits can be fed into AVCS system as the speed command for individual vehicles or platoons.

- Processor Equipment
  - Computer systems and data acquisition equipment[8]:
    (Chang et al., 1991): This reference describes an example system and software for an experimental longitudinal control setup. The system uses an IBM PC (80386) running the VRTX-PC real-time operating system.

    (Peng et al., 1992): This reference describes an example system and software for an experimental setup of lateral control.

- Sensors
  - Absolute Vehicle Location
    * GPS:
      (Getting, 1993): This author provides an overview of GPS and other radionavigation technologies.

      (Kao, 1991): Kao notes that GPS accuracy is dependent on satellite geometry, measured by "Dilution of Position" (DOP), and other factors, including satellite ephemeris uncertainty, signal propagation errors, timing errors, multipath, and receiver noise. Kao claims that using Precise Positioning Service (PPS), RMS error will be about 30 m, and using Standard Positioning Service (SPS), RMS error will be about 100 m, due to the "Selective Availability" (SA) technique, which adds noise to the pseudoranges measurements and varies the ephemeris data broadcast from the satellites. To achieve these accuracies, perfect reception is required. Note that differential techniques can greatly enhance the accuracy. Road vehicles will be subject to interference from tunnels, overpasses, tall buildings, and trees. The multipath problem is compounded in areas with tall buildings. These effects can lead to large and random errors.

      (Scapinakis and Garrison, 1991): The authors discuss several radiodetermination techniques. One pertinent comment regarding GPS is the concern whether the user community is prepared to accept a system which is under the control of the military of a single country. The GPS is described herein as a constellation of 18 satellites plus backup units at an orbit of 20,000 km.

[8] These systems are necessary to support control, communications, and sensing, and interface with sensors and actuators. They also allows storage and use of roadway databases and maps. Use of such systems requires clean power supplies.

More satellites have been added to the system since this time. The possibility of fees being charged for GPS use, as well as concerns over the responsiveness of the military to users also raise some questions. The merits of GPS versus a competing system, Geostar, are also discussed. GPS allocates frequencies fairly efficiently, using only 2 MHz of bandwidth, as opposed to 115 MHz for the Geostar system. Also, GPS is purely a broadcast system, so it can serve an infinite number of users, whereas Geostar requires transmitting and receiving data, so it can serve only a limited number of users. At this time, the GPS user pays once for the receiver, and does not pay for the use of positioning information. Finally, it appears that GPS will become the dominant technology, so that the price of receivers should drop substantially. Geostar appears limited in use, as for accurate positioning, users must input their geocentric height. Geostar claims to have the technology to achieve accuracy to within 2 - 7 m with a small portable radio, but this has not yet been demonstrated.

Trimble: Literature from Trimble provides an overview and tutorial on GPS (Sprague and Woo, 1993). The authors list the "Five Steps of GPS": triangulation from satellites, measurement of distance using travel time of a radio message, use of very accurate clocks to measure travel time, knowledge of satellite location in space, and receiver compensation for ionosphere and atmosphere delays. DOD monitoring stations measure satellite ephemeris (altitude, position, and speed) errors. This information is relayed back to the satellite, and the satellite broadcasts this information in addition to its pseudo-random code, which can be used by the receiver for minor corrections. Ionospheric and atmospheric conditions affect the speed of GPS signals. Ionospheric conditions can be corrected, assuming average conditions, but clearly this cannot correct for variable conditions. Atmospheric conditions, mainly water vapor, also effect the signal speed, and these errors are almost impossible to correct. The Scout receiver from Trimble is listed as having an accuracy of 25 m.

ACC-Q-POINT: To obtain accuracies in the range of 1 - 20 m, it is necessary to use differential techniques. This requires the user to establish a base station at a precisely surveyed location, a Differential GPS (DGPS) reference receiver with pseudorange correcting capabilities, and a communication link to transmit and receive data corrections. ACC-Q-POINT, an alliance between Magnavox Electronic Systems and CUE Network Corp., supplies a nationwide (major metropolitan areas at this time) DGPS subscription service. They establish the base station, and provide a subcarrier FM data receiver that receives the DGPS correction signal and outputs industry standard differential correction data. This system does not include the GPS receiver itself, which can be obtained from other sources. They offer two levels of service, RTL service with 1 - 5 m accuracy, and RTS service with 10

- 20 m accuracy. Availability of this service means that companies without the means to establish GPS base stations can still achieve DGPS accuracies.

DCI: Differential Corrections, Inc. offers a similar FM subcarrier broadcast differential corrections service. The system uses the Radio Data System (RDS) communication protocol, which is a worldwide standard. DCI generates highly accurate differential corrections using a small fraction of the available RDS FM subcarrier bandwidth, leaving room for other data services, such as real-time traffic information. The company offers different levels of service, with accuracy of below 1 m (2D RMS) for high quality GPS receivers (2 - 3 m for low-end receivers), 5 - 7 m (2D RMS), and 10 - 12 m (2D RMS). The required hardware is an RDS receiver. The RDS system transmits data synchronously at 1187.5 bps (the 19 kHz stereo pilot tone divided by 16) (Weber and Tiwari, 1993)).

Magellan Systems Corp.: This company offers a GPS receiver called the NAV 5000 PRO, which they claim is the most advanced receiver on the market. It has a 1500 data point buffer, and five continuously tracking channels providing a one second update rate. This receiver is the only hand-held receiver that offers *sub-meter accuracy*. This level of accuracy is achieved through the use of postprocessing software that analyzes carrier phase data. Based on their literature, this level of accuracy seems to require many readings, on the order of ten minutes worth, and requires differential mode operation. Accuracies cited for this mode were on the order of 0.18 - 0.70 m. The time to the first fix is about 35 seconds. Without the optional post-processing, accuracy for a single position fix is 15 m RMS in 2D or 3D. With averaging, this drops to 12 m RMS. In differential mode, the unit achieves 3 m RMS horizontal and 5 m RMS spherical. Using RTCM mode, accuracy is 5 - 10 m RMS spherical, and velocity is measured to within 0.1 knots (0.12 mph) RMS. The unit has an interface for standard differential corrections data, and an RS-232 port to allow data to be downloaded to a PC.

Rockwell: This company offers a very interesting product: a GPS receiver in a PCMCIA Type II extended format card. This is an emerging standard for expansion cards on notebook computers (and some desktop systems). Thus, one can include a GPS receiver in a notebook computer for mobile applications requiring high accuracy positioning. With power management, this card requires less than 750 mW of average power to operate. The card supports differential mode operations as an option, so that accuracy of better than 5 m is possible. The unit has five channels to receive and interpret satellite data, so that its initialization time is very low   20 - 30 seconds from a warm start. The five channels can track up to nine satellites. The system also comes with developer's software, including an Applications Programming Interface (API). It includes an integrated removable antenna, which can be replaced with an external antenna if necessary.

  * Other Radio-Navigation Systems[9]:
    (Olsen, 1991)
    Pinpoint: Literature from Pinpoint indicates that Loran-C has accuracy to 270 m, clearly not sufficient for AHS purposes. Also, the system operates at very low frequency, so blockage by buildings will lead to further reduction in accuracy. The system that Pinpoint offers gives accuracy of 20-50 feet, which is significantly improved, but still not sufficient for AHS use. The interesting aspect of this system is that it also supports short duration data communication on top of its AVL capability. AVL is done using Time-Difference-Of-Arrival (TDOA) hyperbolic multilateration.
  * Triangulation w. Roadside Beacons[10]
  * Inertial Navigation System[11]
  * Integration of GPS and Dead-Reckoning with Map-Matching:
    (Kao, 1991): This system uses GPS signals to adaptively calibrate dead-reckoning sensors, and to rescue the system from unexpected position errors. Dead-reckoning with map-matching provides feedback to calibrate GPS position errors. Kao notes that GPS accuracy and availability are affected by satellite geometry, Selective Availability, and environmental effects.

- Headway Measurement
  * Radar:
    (Shladover et al., 1991): The system used in these experiments provided accurate spacing measurement at distances on the order of 10 m or more, but shorter range performance was not assured at the time.

    (Chang et al., 1991) In this system, special circuits in the radar system recognized conditions that could affect the control algorithm and set indicator flags, including: driver braking, radar signal strength, radar signal multipath, and target direction. The system used here could not provide absolute distance information when closing rate is low, due to use of the Doppler effect; instead, the system used integration of closing rate to obtain distance.
  * Laser Radar:
    (Fujioka, Yoshimoto and Takaba, 1993)
    (Yanagisawa, Yamamoto and Kubota, 1992)
  * Ultrasonic Sensing:
    (Shladover et al., 1991)
  * GPS[12]

[9]For example, Loran-C (Long Range Navigation). Note that the US DOT and DOD may cancel other forms of radionavigation aids, including Loran-C, in favor of GPS, according to (Getting, 1993). As such, it will be assumed here that GPS is the favored radionavigation technique.

[10]Requires IR (or other LOS) sensor.

[11]Such systems should suffer from drift due to integration of accelerometer signals.

[12]This technique will require communication between vehicles. Note that this use requires relative distance

    * Triangulation:
      (Shladover et al., 1991)
    * Vision:
      (Varaiya, 1993)
  - Headway Closing Rate
    * Doppler Radar:
      (Shladover et al., 1991)
    * Laser Distance Sensing with Differentiation
  - Vehicle Lateral Position
    * Embedded Wire with EMF Sensor in Vehicle:
      (Fenton and Mayhan, 1991)
      (Olsen, 1977)
      (Parsons and Zhang, 1988)
      (Fujioka, Yoshimoto and Takaba, 1993): The Japanese are apparently planning actual implementation using this technology.
    * Side Radar Detecting Barriers (Guideway):
      (Mayhan and Bishel, 1982)
      (Fenton and Mayhan, 1991)
      (Bender, 1991)
      (Parsons and Zhang, 1988):
      · AM Continuous-Wave Radar
      · Two-Frequency Doppler Radar
    * Side Acoustic (Ultrasonic) Sensors Detecting Barriers (Guideway):
      (Clemence and Hurlbut, 1983)
      (Parsons and Zhang, 1988)
      (Shirley, 1989): In this introductory article, a number of relevant facts regarding ultrasonic sensors are presented. This reference does not discuss AHS, but contains useful beginning material for AHS researchers. Some ultrasonic sensors suffer from the presence of side lobes, which can degrade the measurement. These can be removed, but at a higher sensor cost. Narrower beam angles are typically desirable for the sensor, as fewer unwanted objects will be detected, and there is less susceptibility to background noise. One exception to this rule may be in the application of obstacle detection. Ultrasonic sensors are susceptible to attenuation as well. Higher frequency sensors give better resolution and are less sensitive to background noise, but also have higher attenuation, and consequently lower range. As the speed of sound varies with temperature, they are also temperature sensitive, although this effect can be compensated. A more difficult problem arises from air turbulence and convection currents. These problems are more random, and are difficult, if not impossible to compensate. If background noise in the ultrasonic spectrum is

between vehicles, rather than absolute position of vehicles. Thus, identical errors in the GPS sensing, due to satellite position and ionospheric-induced errors, will cancel out.

present, for example whistling sounds with harmonics in the ultrasonic range (which seems feasible in AHS applications), special arrangements must be made, e.g. baffles around the sensor. According to this reference, ultrasonic sensors are also affected by radio frequency interference, which is also an issue in AHS.

Massa Products: Based on their literature, this company offers sensors with ranges of 3"-24", 5"-60", 2'-20' & 2'-30'. These models have 0 - 10 VDC & 4 - 20 mA proportional outputs, and resolution of 0.1with temperature compensation to correct for ambient temperature drift. Transducer frequencies appear to be around 20 kHz - 215 kHz.

* Discrete Magnetic Markers with Magnetometer (Hall Effect) in Vehicle:
(Marhrt, 1971)
(Shladover et al., 1991): This paper reviews the algorithms for overcoming interference problems, including: overlap with the Earth's magnetic field, high frequency magnetic noise generated by the vehicle's electrical system, and spontaneous vertical movements of the vehicle. The last is the most critical issue.

(Zhang, 1991): According to the author, the vehicle will require at least two magnetic sensors to sample both the vertical and horizontal components of the magnetic field of each marker. The system uses a low-pass filter to eliminate high frequency noise, and a computer which filters the low frequency noise and derives the vehicle's lateral displacement relative to the center of the reference marker.

(Peng et al., 1992): This reference details experimental using discrete magnetic markers. The magnetometers used were powered by 9V batteries. The output voltage range was $\pm$2V, corresponding to a full scale range of $\pm$3500 milligauss. The sensing system is designed for a range of about 80 cm with a high resolution region near the center of the vehicle ($\pm$25 cm). In terms of information resolution for the roadway reference system, a benchmark example is given: assuming all information is coded in the roadway rather than in an on-board database, a length of 50 m is needed to encode the geometry for a curve of radius 1100 m and length of 700 m, assuming a marker spacing of 1 m and information resolution of 1 m. This reference gives a maximum position error of the magnetic referencing system relative to an independent (vision based) measurement system of 0.015 m, with a standard deviation of less than 0.01 m. The system as presented here has been proven to be robust at various vehicle speeds up to 60 km/hr.

(Peng et al., 1992): The markers used at PATH are 10 cm tall and 2.3 cm in diameter, and are installed at 1 m intervals. The magnets actually consist of a stack of smaller magnets.

(Peng et al., 1993): This reference includes closed-loop response under a variety of test conditions, including low tire pressure, measurement noise, perturbed reference system, hard braking, and snowy road.

(Andrews, 1992): The author presents theoretical and empirical modeling, as well as some investigation of disturbance due to rebar.

* Discrete Optical Sensing System with Retro-Reflective Markers in Roadway:
  (Johnston, Assefi and Lai, 1979)
  (Parsons and Zhang, 1988)

* GPS:
  NOTE: GPS currently does not have sufficient accuracy for lateral control purposes. At this time, differential mode GPS accuracy falls in the range of 1 - 5 m. However, within the next few years, cm-accuracy GPS is anticipated, using carrier phase detection techniques. This accuracy will be achievable using differential mode, so accurately surveyed base stations must be installed along the roadside. Based on a conversation with an engineer at Acc-Q-Point, a base station can cover a few hundred miles, so this is not a serious limitation. On the other hand, any area that has good FM reception (i.e. any well-populated area) can receive the differential corrections with an FM receiver, so that it is possible to use a differential GPS system without installing base broadcasting stations. The SRI study is expected to yield significant results in the area of GPS for lateral position sensing.

* Vision System to Detect Lane Markers[13]:
  (Parsons and Zhang, 1988)

  (Shladover et al., 1991)
  (Peng et al., 1992): The experiments here used vision as independent sensor to verify calibration of the magnetic referencing system.

  (Hashimoto et al., 1992): The approach here uses a Hough transformer for real-time detection of road and lane edges.

* Triangulation w. Roadside Beacons

* Dead-Reckoning System[14]:
  (Kanemitsu et al., 1991): The authors discuss the use of a beacon system to calibrate a dead-reckoning system.

  (Kao, 1991): The dead-reckoning system requires position error correction using, for example, map-matching, to remove accumulated errors. Kao notes that map-matching may have difficulties in picking out the correct vehicle

[13] This should require remarking of roadways using brighter, more regular marking patterns. This is not a major infrastructure investment.

[14] To augment other systems, as it cannot work as a standalone system.

location from streets with similar geometric shapes in urban areas with dense road networks.

Systron Donner: This company has a product called a MotionPak, which contains three solid-state gyros and three solid-state accelerometers to sense angular rate and linear acceleration, thus providing a six degree-of-freedom sensor cluster. This system can be used as the input for a dead-reckoning sensing system to track all six DOF of the vehicle position. The rate sensor has an output range up to ± 1000 deg, with output noise of 0.01 deg/sec/$\sqrt{f}$, where f is the signal frequency in Hz in the 100 deg/sec operating range. The linear accelerometer operates in the range of ± 20 g, has threshold/resolution better than 10 μg/g^2.

Siemens: The Ali-Scout system uses dead-reckoning based on the speed signal from either the odometer or the transmission.

- Vehicle Heading
  * Gyroscope and dead-reckoning:
    (Tsumura and Komatsu, 1989)
    (Kao, 1991): Kao notes that gyroscopes are subject to drift from changing operating temperatures. Gyros also require a long warm-up time period. Due to A/D conversion and quantization errors, they have difficulties in measuring small angular velocity when driving on freeways, where curves have relatively large radii of curvature.

    Systron Donner: Please see the discussion under yaw rate for the Systron Donner GyroChip, which could be used as the gyro input for dead-reckoning. Also, see above under absolute vehicle location for the MotionPak, which can be used for dead-reckoning of all six DOF.
  * Differential Odometry:
    (Pikula and Calvas, 1991): The authors review this form of dead-reckoning which estimates vehicle heading based on the difference in wheel travel between laterally opposed wheels.

    (Kao, 1991): Kao notes that vehicle speed, tire pressure, vehicle payload, tire thread wear, and other factors all affect the actual tire size and thus the distance measurement accuracy. In addition, the heading measurement is affected by the difference between left and right distance measurements, even on straight roads.
  * Flux-Gate Compass:
    (Kao, 1991): This type of compass uses a pair of perpendicular coils to measure the direction of the Earth's magnetic field. The actual sensed field direction is a mixture of the magnetic fields of the Earth and the vehicle. Thus, accuracy is affected by vehicle magnetization. The vehicle effects can be cal-

ibrated, but the calibration is dependent on the Earth's field, so it is area dependent. Also, the vehicle magnetic field can be affected by steel items carried on the vehicle, on-board electrical devices, etc. Such errors are long-term errors. There are also short-term errors (noise) due to power lines, steel structures such as bridges or tall concrete buildings, and freeway underpasses and tunnels. This noise is short-term and high-frequency in nature.

  * Triangulation using Laser Beam Transceiver on Vehicle, Corner Reflectors on Roadside:
    (Tsumura and Komatsu, 1989): This system uses the triangulation to compensate for errors in dead-reckoning.
  * Triangulation using Laser Receiver on Vehicle, Laser Transmitter on Roadside:
    (Tsumura and Komatsu, 1989)
  * Triangulation using Millimeter-wave (MMW) Corner Reflectors on Roadside, Forward and Side-Looking MMW Radar on Vehicle:
    (Martin Marietta, 1993)

- Vehicle Yaw Rate:
  (Shladover et al., 1991): The longitudinal controller described in this reference requires this measurement.

  (Sheikholeslam and Desoer, 1991c): The lateral controller described here requires yaw rate sensing.

  * Gyroscope:
    Systron Donner: This company offers a product called a GyroChip, which is a solid-state angular rate sensor designed for high reliability. It uses a micro-machined quartz crystal sealed along with microelectronics. Inertial angular rate is sensed using a subminiature oscillating quartz element, a vibrating tuning fork, which senses angular rate by acting as a Coriolis sensor. This fork drives a similar fork which produces the output signal. The ultimate output signal is a DC signal directly proportional to the input rate. Output range can vary from ± 10 deg/sec to ± 1000 deg/sec. Bandwidth is greater than 60 Hz. Typical output noise is listed as 0.012 deg/sec/$\sqrt{f}$, where f is the signal frequency in Hz. MTBF is 10 years, typical, or over 100,000 hours. Vibration survival is 20 g rms, 20 Hz - 2 KHz random, vibration operating is 4 g rms, 20 Hz - 2 KHz random, and shock survival is 100 g, 2 milliseconds, half-sine.
  * GPS with Two Antennas:
    (Galijan, 1993)

- Vehicle Speed:
  (Sheikholeslam and Desoer, 1991c): The control in this reference, as well as those in other longitudinal control references, requires longitudinal vehicle speed. This controller needs both longitudinal velocity and lateral velocity.

* Digital Speedometer
* Timing of Discrete Magnetic Marker Pulses:
  (Peng et al., 1992): The system described here uses three successive time intervals to increase accuracy.

  (Peng et al., 1993)
* "32-pole counter on nondriven axle":
  (Shladover et al., 1991): The researchers claim this sensor provides "accurate measurement" of vehicle velocity; unfortunately, this is not quantified.
* Wheel Encoder with Differentiation
* Wheel Encoder with Timing of Pulses:
  (Tsumura and Komatsu, 1989)
* GPS:
  GPS systems can provide velocity accuracy as good as 0.1 m/s.
* Non-Contact Optical Sensor:
  Datron Technology, Inc.: The system provided by this company uses an optical correlation sensor based on spatial filter theory. It has a range of 0.3 - 250 mph (0.5 - 400 km/h), a resolution of 0.1" (2.5 mm), a typical accuracy of 0.1%, and a reproducibility of 0.1%. The system is shock protected to 50 g half-sine, 6 msec, and vibration protected to 10 g, 10-150 Hz. It provides analog and serial digital output.

– Obstacle Detection

* Radar:
  (Nauman, 1992): This article discusses a project in which Greyhound is installing crash-protection radar on their buses. The system includes a grill-mounted antenna and a dash-mounted driver control unit. The system alerts the driver with a warning light and a tone. The system also includes a "black box" to record the last fifteen minutes of speed and other driving actions.

  VORAD Safety Systems, Inc.: Their vehicle detection and driver alert system uses high frequency Doppler phase shift radar comprised of an antenna/transmitter and receiver assembly, a central processor, driver control unit, and a speaker assembly. It detects vehicle closing rate in the range of 0.25 - 100 mph. The typical operating range is 1 - 350 feet (0.3 - 110 m). The forward radar unit operates at 24.125 GHz. The optional blindspot radar operates at 10.525 GHz. Transmitted RF power is 0.5 milliwatts. The system withstands vibration to 10 g at 10 - 2000 Hz. The unit as packaged can track up to twenty moving or stationary objects within its range. It maintains data on the three vehicles closest to the host vehicle. The signals are passed on to the driver through lights and audible warning tones. The system also offers black box capabilities to assist in reconstructing events leading up to an accident. Other options include blind spot sensors, trip recorder functions, data download cards in 32K - 512K ranges, ignition security interface, and driver fitness-for-duty evaluations. The radar penetrates darkness, dense fog, dust, and smoke. Greyhound has installed the system on all 2400 of their buses.

(Furukawa, 1992): This reference discusses some of the technical problem areas, including: elimination and control of the effect of reflective waves coming from different configurations of objects, how to treat signals from the ups and downs of the road surface, and how to deal with radar sensors that have been splattered with mud, etc.

(Kamimura et al., 1993): This system measures distance and speed of targets accurately and stably. The method used here can identify multipe targets. It uses FFT frequency identification and spectrum phase information.

* FM-CW Radar:
  Safety First Systems, Ltd.: This company's system has been installed in school buses in Long Island. The information here is based on company literature and video. The bus system watches fifteen feet in front of the bus and three feet to the side of the right wheel, the most dangerous blind spots on school buses. The other system documented is a back-up aid and adjacent lane blind spot warning device. For backup, the system indicates a green light for obstacles in 11 - 20 feet, yellow light for 6 - 11 feet, and a red light and warning sound for less than six feet. The system includes self-testing. The backup indicators are mounted in an overhead unit. For lane changes, the blind spot warning is activated by the turn signal. The indicators are mounted near the mirrors. If the turn signal is on and a vehicle is in the blind spot, then a red indicator is lit and an audio warning sounds. The system can detect stationary and moving objects up to 40 feet, with a relative range resolution of 0.6 feet. The company claims that the proprietary FM-CW method used provides 20-fold improvement over conventional techniques. Cited range accuracies are from 0.6 - 2 feet. The unit operates at 10.525 GHz with 50 MHz bandwidth, and does not interfere with similar units due to low output average power (50 μwatts), low duty cycle (3%), and narrow IF bandwidth (100 KHz). It has a gear shift status input for reverse, and inputs for left and right directional signals. It can be configured to detect large objects (cars and trucks) at distances greater than 150 feet, with resolution better than 3 feet. It can give relative velocity readout, and different detection zone geometries can be provided. A drawing of the empirically determined detection zones is provided with the literature.

* Laser:
  (Furukawa, 1992)
  (Yanagisawa, Yamamoto and Kubota, 1992)
  (Bulkeley, 1993): Mitsubishi Motors Corp.: This company offers a distance-warning system for its line of large trucks. The system has a laser radar unit which sends out laser beams to the vehicle ahead and then receives the reflection, a control unit which processes the data, and a monitor, which

displays the results to the driver. The unit emits three beams in different directions. The article mentions the beams striking a reflector on the vehicle ahead, so it is unclear if this system will detect distance to all vehicles or only specially equipped vehicles.

* Infrared Detector
* ITV Cameras:
  (Fujioka, Yoshimoto and Takaba, 1993)
* Acoustic Echo Ranging:
  Sparton Electronics: This company offers a blindspot detection system using air acoustic echo ranging, another term for ultrasound. Their transducers mount in the sideview mirror housings. A DSP is used to analyze the echoes from objects in the blindspots. Audible alerts (or LEDs) are used to warn the driver. Side detection range is up to 40 feet. Frequency range of the transducers is in excess of 20 kHz. The beam width can be up to 45 deg. The system withstands salt and sand spray and commercial vehicle washing facilities, as well as ice and snow.

  Armatron: This company makes a similar product, called EchoVision, which can be configured for various blindspots. It can be used as a back-up aid for rear blindspots, or for side and front blindspots. It uses ultrasonic pulses which are timed by the computer, and audible warnings to the driver. The system includes automatic activation and system verification.
* Vision System:
  (Bulkeley, 1993): Jaguar is developing a computerized vision system to provide an early warning collision avoidance system to drivers. A camera digitizes the road scene into a computerized map identifying road edges, white lines, and objects ahead of the vehicle. By recognizing road lanes and the trajectory of the host vehicle and surrounding vehicles, warnings can be issued to the driver.

- Rollover Detection
  * Gyroscope
  * GPS with Two Antennas:
    (Galijan, 1993)
- Vehicle Angle of Attack
  * Gyroscope
  * GPS with Two Antennas:
    (Galijan, 1993)
- Steering Angle
  * Potentiometer:
    (Peng et al., 1992): The experimental system presented here uses potentiometers on the steering wheel and the steering actuator.

* Encoder

- Throttle Position or Fuel Flow Rate
  * Potentiometer
  * Flow Meter
- Vehicle Acceleration:
  (Sheikholeslam and Desoer, 1991c): The control in this reference, as well as those in other longitudinal control references, requires longitudinal acceleration. This controller needs both longitudinal and lateral acceleration.
  * Accelerometer:
    (Shladover et al., 1991): The controller in the experiments here did not use an accelerometer. The authors noted that if the differentiation of the vehicle velocity was too noisy, then they would use an accelerometer.

    (Peng et al., 1992):
    (Kao, 1991): Kao discusses the use of accelerometers in dead-reckoning to obtain velocity and distance traveled. Such systems are subject to drift during integration. Also, due to A/D conversion and quantization, they will have trouble measuring small accelerations, such as those that typically occur in freeway driving.
  * Differentiation of Velocity Measurement:
    (Shladover et al., 1991)
- Equipment Status Sensors, In-Vehicle Monitoring
- Driver Alertness Sensors
- Driver Impairment Sensors
- Lane Change/Blind Spot Warning Sensors
  * Radar:
    (Furukawa, 1992)
  * FM-CW Radar:
    Please see the note above in the obstacle detection section for the system by Safety First Systems, Ltd.
  * Laser:
    (Furukawa, 1992)
  * Ultrasonic
  * Video
  * Acoustic Echo Ranging
- Side Collision Sensing
  * Acoustic Echo Ranging
- Backup Warning Sensor
  * Acoustic Echo Ranging

- Traction Sensor
- Lane and Road Departure Sensing
- Head-on Collision Sensing

• Alternative Vehicles

  - Lean Vehicles:
    (Egan, 1983)
    (Garrison and Pitstick, 1990): This work refers specifically to the "Lean Machine" from GM. The statistics for this vehicle are given as: weight about 400 pounds, tread width about 28 inches, width about three feet, wheelbase about six feet, and overall length about nine feet. Freeway capacity increases are expected due to a combination of shorter vehicles and the possibility of side-by-side driving.

    (Garrison and Pitstick, 1990): This reference provides further statistics on the "Lean Machine". This vehicle accommodates "1+ persons," accelerates to 60 mph in under eight seconds, and achieves 100 - 150 mpg depending on accessories. It has three wheels, and achieves cornering stability by leaning the body and the single front wheel. Capacity increase for a single line of lean machines is estimated at 5% for free flow on a two-lane undivided highway, 13% for free flow on a multi-lane divided highway, and 18% for saturation flow at a single signalized intersection. The authors characterize these estimates as conservative. Experiments cited in this reference have shown that a 1.8 m wide lane should be adequate for a 1.0 m wide lean vehicle in most urban driving situations. This implies the possibility of side-by-side driving of lean vehicles in a 3.6 m lane, without application of lateral control.

    (Pitstick and Garrison, 1991)
  - Electric Vehicles
  - Hybrid Electric Vehicles:
    (Gris, 1991): This reference provides a large amount of data. Here, we will include only a few of the summary comments for a passenger automobile; Gris also considers postal vehicles, mini-vans, delivery vans, and buses. For a city scenario automobile with a 60 mile range, Na-S, Ni-Fe, and Ni-Zn electric vehicles are the best choices. Adding a range extender (RX) produces no benefits.

    For the large metropolis automobile with 200 mile range, with or without AC, Na-S, Ni-Fe, and NiZn hybrid vehicles are the only available options, but the battery and RX together weigh about 1/3 of the total vehicle weight.

    For intercity auto travel with a 480 mile range with or without AC, the options are NA-S, Ni-Fe and Ni-Zn HV's. Most of the range comes from the RX, but this can run cleaner than regular internal combustion powered autos. On days which 40 miles or less are driven, these vehicles could offer pure battery operation. With AC, they would offer 27 miles of pure electric operation.

Please refer to (Gris, 1991) for discussion of other transportation types.

Chapter 2

Infrastructure Systems

- Communications
  - Roadside to Vehicle Communication
    - Inductive Loop:
      3M: This company produces a system called a "Microplexer", which is an inductive loop system that can measure vehicle speed, occupancy, and volume with a single loop. Speed measurement normally requires two loops.
    - Infrared Beacon:
      Siemens: The Ali-Scout system uses an infrared beacon mounted on traffic lights to communicate with IR transceivers in vehicles to send traffic data to (digitized map of beacon area and dynamic route recommendations) and from (travel and queueing times per link) the vehicle. The in-vehicle transceiver has a transmit range of 60 m, and a data rate of 500 kbps.
    - Other Line-of-Sight Beacons
    - Ultrasonic Beacon
    - Microwave Transceiver:
      (Kanemitsu et al., 1991): The communication zone for the system in this study was about 70 m long and 15 m wide. In one frame of information, a total of 388,096 bits were communicated in 758 msec. The transmission frequency was 2.538 GHz and the reception frequency was 2.598 GHz. The transmission power was 10 mW, and the transmission speed was 512 kbps. This system was used in part to provide error-correction for a dead-reckoning system. In all cases, position marking of the beacon was within 6 m. The error here was in part due to delays in the calculation. If this is accounted for, greater accuracy is achievable.
    - RF Transceiver Beacon
    - FM Radio Broadcast Station
    - Packet Radio Network

    * Cellular Radio:
      (Catling and de Beek, 1991)
    * Active or Passive Transponders, such as those used in AVI:
      (Deacon, Pigman and Jacobs, 1991)
    * Satellite Communication Link
  - Roadside to Control[1]:
    * Radio Broadcast
    * Wide Area Network
    * Point-to-poit Fiber-Optic Network:
      Allied Signal Aerospace: This is one form of Wide Area Network (WAN). The information here is based on literature from Allied Signal Aerospace regarding an ATMS system that they are integrating in San Antonio. The network backbone speed is 155 Mbps, using the SONET international synchronous optical transmission standard. The system uses cable running through concrete-encased conduit along both sides of the highway. Communication channels are subdivided at roadside communication "hubs", which perform multiplexing/demultiplexing and conversion from fiber to copper cabling. The communication network interfaces with the computer system through a 40,000 packet/sec asynchronous switch. Note that the 155 Mbps speed is more than fifteen times the speed of standard Ethernet. This network connects the control center to video cameras, Changeable Message Signs (CMS), and loop detectors, through a 24.5 mile section of roadway. This installation also includes are a 1600-line voice switch (PBX), a 512-inputs-by-512-outputs digital video switch, and a comprehensive communications network management system to monitor and report on the status of all communication devices and enclosures.
    * Spread Spectrum Radio Network:
      Hughes Transportation Management Systems: Hughes uses spread spectrum radio in their Vehicle to Roadside Communication (VRC) systems. Their literature identifies problems with landlines including costly installation, inflexibility after installation, and damage from construction activity. On the other hand, standard narrowband RF communications operate in highly congested regions of the RF spectrum, resulting in poor performance and susceptibility to noise. Hughes' systems use spread spectrum radio (SSR) LANs, long-haul point-to-point microwave, and Very Small Aperture Terminal (VSAT) satellite communications. Applications include networking VRC roadside transceivers for toll collection, probe sampling, and driver information systems, intersection control and monitoring, system time synchronization, remote CMS control, remote transfer of operations data, freeway ramp meter control, and video, voice, and data messaging. SSR uses three frequency bands to allow users to spread the energy of transmitted signals to avoid interference from other radios in the service area within the same band. The

[1] For link to traffic management system.

two major SSR approaches are frequency hopping and direct sequence. Interference is minimized by either randomly occupying a different frequency, or randomly modulating the narrowband signal with a wideband signal. The SSR receiver knows the random sequence. There are two products available from Hughes currently. Their low speed, long range, omni-directional model has data rate of 9.6 kbps, a link range of 5 miles, 1 watt output power, and uses frequency hopping and Time and Frequency Division Multiple Access protocols (TDMA/FDMA). It has an RS-232 interface, can be pole or wall mounted, and can be applied for detector data collection and CMS control. The higher speed, short range, omni-directional model has data rate of 242 kbps, a link range of 1 mile, 100 milliwatt output power, uses direct sequencing and Time and Frequency Division Multiple Access protocols (TDMA/FDMA). It can be applied for traffic signal control and mesh networking of roadside equipment. Another model, which may not yet be available, will have 1.544 Mbps data rate, and a 10 mile directional range, with point-to-point access only. This model could be used as the radio link between mesh networks of roadside equipment and the traffic management center.

Cylink: This company also provides systems using spread spectrum technology (SST). The FCC has allowed unlicensed SST commercial use in the following bands: 902 - 928 MHz, 2.4000 - 2.4835 GHz, and 5.725-5.850 GHz. SST is resistant to jamming, interference, detection, and interception. SST transmits a signal "spread" over multiple frequencies much wider than required for transmission of the data, e.g. a 64 kbps data stream transmitted over 5 MHz of bandwidth. Regulations require that users of the SST bandwidths keep output power below 1 watt. SST consists of both an RF portion and a digital portion. The RF component transmits the signal from one location to another, while the digital component interfaces with the digital signal of the user's system and provides signal spreading, code matching, and data routing. It can also provide error detection and correction. The signal is spread in one of two ways: direct sequencing, which modulates a carrier by a digital code with a bit rate much higher than the information signal bandwidth, and frequency hopping, which "hops" the radio carrier from frequency to frequency in discrete increments determined by a code. By spreading the signal, the system can attain error-free information transmission in a noisy signal environment, with reduced interference. The SST signal, when spread out, is below the noise floor of a conventional receiver, making it invisible to such receivers, yet it can still be received by a spread spectrum receiver.

* Roadside Processor Equipment
* Cellular Radio:
  (Catling and de Beek, 1991)
* Changeable (or Variable) Message Signs:
  Allied Signal Aerospace: The road-spanning CMS available from this com-

pany has three lines of 18 inch characters. They also provide smaller one-line signs which can be stationed at ramps.

  * Smart Call Boxes:
    U.S. Commlink: This company offers the SmartBox 2000, which communicates with data collection devices and monitoring systems via the radio network through RS-232 interfaces. The transceiver is a 3 watt cellular full-duplex system. Modem is available in 2400 bps to 9600 bps. There are four RS-232 serial ports for multiple inputs, and eight inputs for alarm condition monitoring. Customized software configurations are available, so that a variety of applications can be supported. The system can be installed in existing call boxes, which still function as a normal emergency call box. It is powered by a 10 watt solar panel, and a 12V maintenance-free battery. It allows remote downloading of traffic data, weather and air quality data, and accurate prediction of roadside surface conditions for ice and snow control management. The system can interface to road surface sensors, loop detectors, surveillance cameras mounted on top of the call box pole, and weigh-in-motion equipment. It can also interface to changeable message signs to download new messages.

- Processor Equipment

  - Computer Systems to support control, communications, and sensing. Examples include "area" or "link" controllers to indicate speed and obstacles in a local roadway section:
    (Fujioka, Yoshimoto and Takaba, 1993)
    (Rao and Varaiya, 1994)

- Freeway Interchange Configuration[2]:

  - Diamond
  - Single-Point Diamond
  - Split Diamond
  - Half Diamond
  - Folded Diamond
  - Partial Cloverleaf
  - Cloverleaf with Collector-Distributor
  - Directional
  - Cloverleaf
  - Scissor
  - Trumpet

[2]This information is mainly taken from (FHWA, 1994), which has illustrations of these interchange types. Similar information is available in the Caltrans Highway Design Manual

  - Direct Connection
  - Buttonhook
  - Left Side
  - Cloverleaf with Collector-Distributor and HOV Connections

- Entrance to AHS
  - Automated Check-in:
    (Stevens, 1993): This reference lists check-in time of less than two minutes as a functional specification for AHS. However, many researchers agree informally that this should be reduced to less than one minute, with some arguing for sub-thirty second check-in times.
  - Ramp Metering[3]
  - Installation of a Detachable Electronics Package:
    (Bender, 1991)
  - Dedicated AHS On-Ramps
  - Ramp Transponders for Check-in

- Exit from AHS
  - Automated Check-out
  - Removal of a Detachable Electronics Package:
    (Bender, 1991)
  - Dedicated AHS Off-Ramps
  - Ramp Transponders for Check-out

- Transition to Automated Lane
  - Transition Lane
  - Gates in Barriers
  - Direct Entry to Automated Lane

- Separation Mechanism
  - Jersey Barriers
  - Electronic Barrier
  - Completely Separate Structure
    * New Lanes in Right-of-Way
    * Viaduct (Overhead in Median)
    * AHS in Railroad Right-of-Way

[3]This technique is used by Traffic Management Centers to reduce freeway congestion.

    * Specialized lanes for lean vehicles:
      (Pitstick and Garrison, 1991): This reference provides several examples, including stacked lanes in tunnels, lanes inside the bridge structure below regular lanes, outrigger lanes on bridges and viaducts, exclusive shoulder lanes, reversible lanes in the median, and exclusive elevated lanes in the median.
    * Exclusive Lanes for Heavy Vehicles
  - None

- Lane Width
  - Standard 12 foot lanes
  - 8 - 10 foot lane using tight lateral control:
    (Stevens, 1993): Lists 8 feet as a functional requirement for normal passenger cars, and 10 feet as a functional requirement for trucks.
  - 5 - 8 foot lanes for lean vehicles:
    (Garrison and Pitstick, 1990): According to this reference, a standard 12 foot lane would easily support side-by-side driving of two lean vehicles, while a single vehicle should be able to operate in a 5 - 6 foot lane.

- Lane Marker
  - Active Embedded Wire:
    (Fenton and Mayhan, 1991)
    (Olsen, 1977)
    (Parsons and Zhang, 1988)
    (Fujioka, Yoshimoto and Takaba, 1993): According to this reference, the Japanese are planning actual implementation using embedded wires.
    (Kornhauser, 1991): This author notes that this method requires significant capital investment in infrastructure.
  - Discrete Magnetic Marker:
    (Marhrt, 1971)
    (Shladover et al., 1991)
    (Peng et al., 1992)
    (Andrews, 1992): This reference includes theoretical and empirical modeling of the discrete magnetic marker reference system, including investigation of disturbance due to rebar.
  - Paint Stripes for Vision
  - Side Barriers:
    (Mayhan and Bishel, 1982)
    (Bender, 1991)
    (Parsons and Zhang, 1988)

- Millimeter-wave (MMW) Corner Reflectors on Roadside with Forward and Side-Looking MMW Radar on Vehicle:
  (Martin Marietta, 1993)
- Corner Reflectors on Roadside, Laser Transceiver on Vehicle:
  (Tsumura and Komatsu, 1989)
- Laser Transmitter on Roadside, Laser Receiver on Vehicle:
  (Tsumura and Komatsu, 1989)
- Discrete Retro-Reflective Optical Markers:
  (Johnston, Assefi and Lai, 1979)
  (Parsons and Zhang, 1988)

- Sensors
  - Intersection Hazard Sensors (blind corner, oncoming vehicle)
  - IR Beacons for Triangulation Position Sensing
  - Infrastructure System Status Sensing
  - Weather Sensors[4]:
    * LIDAR:
      Santa Fe Tech., Inc: This company provides a laser measuring device which can determine visibility levels on rural highways.
    * Visibility Sensors:
      SCAN Systems and Services: This company makes a Weather Identifier and VISibility (WIVIS) sensor, which identifies and discerns type of precipitation (rain, snow, drizzle), intensity of precipitation (in National Weather Service format), precipitation rate measurements, and visibility measurements (25 feet to 7 miles). It uses a long life LED source which is safe to the human eye. The system is insensitive to background light, evaporation, and splash. In addition, it is completely solid state, with no moving parts, and is designed for long life.
    * Ice Detectors:
      DNE Technologies, Inc.

      SCAN Systems and Services: This company also makes the SCAN pavement monitoring system for roadway and runway surfaces. This system detects and reports pavement conditions (dry, wet, frost, ice, and chemical concentrate on the pavement under wet conditions), in addition to pavement temperature.
  - Imaging System, e.g. Closed Circuit TV[5]:

[4]Such sensors are important as the performance of a variety of AHS sensors and systems may be very weather-dependent. For example, the knowledge of the coefficient of friction between the tire and the roadway is very important for precise vehicle control in some approaches (Furukawa, 1992),(Hitchcock, 1994)

[5]The rest of these sensors are used to provide flow and congestion information to the traffic management system. They are included here as TMS will be an important aspect of the overall AHS, and these sensors are important from a construction and maintenance standpoint.

(Labell et al., 1989): The sensors discussed here are Wide Area Detection Systems (WADS) or Video Image Detector Systems (VIDS), and consist of a video camera which takes continuous pictures of the road. The image processor then compares several pre-selected "critical points" for inter-frame and background lighting variations to determine volume and occupancy estimates. One device can cover several lanes and measure speeds of vehicles. Such systems can also determine queue lengths As the sensor is pole-mounted, installation can occur without disrupting traffic. Concerns over the success of image processing techniques for all commonly occurring field conditions, including variations in lighting levels and weather conditions, must still be addressed.

– Inductive Loop:

  (Labell et al., 1989): Installation of these sensors requires pavement saw cuts. A single loop is typically used in each lane. Inductive loop detectors (ILD's) measure the presence of a vehicle in the detection zone, not just the passage, so they can be used to calculate flow, speed, and occupancy. One drawback is their tendency to double-count trucks. Some algorithms to avoid this have been developed at PATH (Chen and May, 1987). ILD's are not usable in all roadway configurations, and are subject to failure due to improper installation and pavement shifts and fractures. Installation, repair, and replacement require excavation, necessitating a lane closure. As of the writing of (Labell et al., 1989), one claim from Caltrans was that only half of the installed inductive loops were in operation, and there was no budget to fix the broken detectors.

  3M: According to this company's literature, inductive loops will not work in areas containing large amounts of iron.

  (Palm, 1982): This author provides a review of inductive loop theory for vehicle detection. For loop systems, the magnetic field (effective sensitivity) increases approximately as the square of the number of turns. To detect small motorcycles, loops should have at least two turns, and not exceed six feet in width. The loop length can be any practical dimension from six feet to over 100 feet. The detectors work based on the fact that a vehicle present near the detector will cause an induction reduction. For a three-turn, 6' x 6' loop, an car centered over it will cause about a 3.5 μH reduction, a small 70 cc motorcycle an 80 nH reduction, and a 10-speed bike about a 16 nH reduction. Even the car represents a reduction of only 200 parts per million. Digital measurements have greatly increased the capabilities of inductive loop detection.

  (Lowrie, 1992): According to this reference, the Sydney Co-Ordinated Adaptive Traffic System (SCATS) relies exclusively on inductive loop detectors for strategic purposes, i.e. flow and occupancy information for network-wide decision-making. Lowrie states that the loop detector is the only detector type that presents a well-defined zone of detection which allows reliable measurement of space between vehicles. Other types of detectors give ill-defined zones, with some not restricted to a single lane. SCATS also employs microwave detectors for less stringent use, i.e. single intersection phase modifications.

- Magnetometer[6]:
  (Labell et al., 1989): This sensor is easier to install and maintain than an inductive loop. They can also be used in isolated spots where ILD's will not fit, such as under bridge decks. Lane closure time for installation, repair, and maintenance, is shorter. However, the frequency of lane closures is higher. Magnetometers, essentially point detectors, are more likely to double-count trucks, but the solution in (Chen and May, 1987) can also be applied here. A magnetometer may also miss motorcycles at the lane edges due to its small (1 foot) detection radius.

  3M: This company provides Canoga vehicle detection systems. These units have high sensitivity, and can detect all licensable vehicles including small motorcycles and bicycles. Its point detection capability means it can independently sense/detect closely spaced vehicles for high count accuracy. With a 0 - 100 mph speed range, vehicle approach speed is not critical. The units allow a long lead-in (up to 5000 feet of cabling with six probes per channel), which may be important from an installation and maintenance perspective. Installation costs are greatly reduced relative to inductive loops. $\frac{7}{8}$" diameter, 3.5" length probes install vertically in 1" cored holes. The four-conductor lead-in installs in a $\frac{1}{4}$" sawcut. The overall installation requires less than $\frac{1}{3}$ the sawcut of a 6' x 6' inductive loop. The system also works in high iron environments. It provides higher reliability than loops as it is unaffected by temperature changes, water, snow, ice, pavement deterioration, or electromagnetic noise.

- Magnetic Detectors (Coil):
  (Labell et al., 1989): These are easier to install than inductive loops, as only a single groove perpendicular to the flow of traffic must be cut. They withstand greater stresses and break down less often. Alternative installation procedures may further increase reliability and ease of maintenance. For example, a permanent conduit may be installed under the road, leaving both ends open and accessible. The sensor may then be fed under the road through the conduit, avoiding lane closures. These detectors cannot measure occupancy, as they only sense the passage of vehicles, not the presence. They are used in combination with IR detectors on the Bay Bridge to provide vehicle counts, with the IR detectors measuring occupancy.

- Infrared Detector:
  (Labell et al., 1989): These detectors can be mounted overhead or on the side of the road. They can provide a measure of occupancy, and are well-suited for operation in tunnels and other situations with mostly uniform lighting. Changes in light and weather will cause scattering of the beam. The lens is sensitive to water and environmental effects. Measurement reliability is questionable in high-flow situations. IR detectors are not capable of providing vehicle counts, which is

[6]Installation of these may be very similar to installation of the discrete magnetic marker.

a major drawback.

- Ultrasonic Detector:
  (Labell et al., 1989): This reference considers only pulsed ultrasonic detectors, as this type can act as a presence detector. These operate by emitting 20 - 50 kHz bursts around 25 times per second. The vehicle interrupts the signal and the echo in the conical detection zone is registered. The sensors are typically mounted overhead, work well for all types of pavement and grades, and are insensitive to vehicle direction. However, the conical detection zone may miss some vehicles, and is only applicable for a single lane. Certain size and shape vehicles may cause inaccuracies. Stopped vehicles are not easily detected. The detectors are sensitive to noise and environmental conditions. Caltrans has found them unreliable in conditions of extreme heat. Others have had trouble controlling the conical detection zone. Finally, salt on the road can alter the signal.
- Microwave/Radar Detector:
  (Labell et al., 1989): These sensors can be either side or overhead mounted. They are far easier to install and maintain than inductive loops. According to the authors, such sensors had not yet been able to give occupancy measurements, or to detect a stopped vehicle. Newer models may alleviate this, but had not been field-tested. Unit costs are high, but manufacturers claim that the lifelong costs will be comparable to inductive loops.
- Lasers:
  (Labell et al., 1989): According to the authors, tests to date have been in the areas of range finding and distance measurement. Specific applications for vehicle detection are not discussed.

• Maintenance

  - Automatic Detection and Notification of Need for Maintenance
  - Use of Lane Control Systems for Lane Closure
  - Use of General AVCS Technology for Automating Maintenance Procedures.
  - Highway Speed Inspection of Facilities
  - Highway Speed Repair/Replacement of Some Systems
  - Maintenance of Changeable Message Signs for TMS
  - Maintenance of Traffic Controllers for ATMS:
    (Haver and Tarnoff, 1991)
  - Use of ATIS to warn travelers of construction and maintenance
  - Use of ATMS for dynamic route guidance to reroute vehicles around construction and maintenance sites
  - Maintenance of CVO facilities, such as Weigh-in-Motion and AVI equipment:
    (Deacon, Pigman and Jacobs, 1991)

• Alternative Infrastructure

- Pallet System:
  (Bender, 1991)
  (Womack, 1974)
- Electrified Highways:
  (Wang and Sperling, 1989)
- Inductive Power Transfer to Vehicles:
  (Choudhury et al., 1989): The system discussed in this reference uses an open E-core transformer. The design presented has been shown to be technically feasible by meeting a set of reasonable specifications and guidelines for automobiles. There are problems associated with high frequency excitation and the large (5 cm) airgap, which requires a high magnetizing current for effective power transfer.
- Reversible AHS Lane:
  (FHWA, 1994): This concept is similar to the reversible HOV lanes used currently in some areas. It will require barriers and exclusive AHS ramps.

References

Akiyama, T., Saeki, H., Satonaka, M., and Tohfuku, K. (1992). Chip in Glass Fluorescent Indicator Panel with a 128 x 32 dot matrix. In *Electronic Display Technology and Information Systems*, pages 9 14. Society of Automotive Engineers.

Akiyama, T., Yamamoto, J., Saeki, H., Sera, K., Okumura, F., Asada, H., and Kaneko, S. (1991). Poly-Si TFT active matrix fluorescent indicator panel. In *Vehicle Information Systems & Electronic Display Technology*, pages 87 92. Society of Automotive Engineers.

Andrews, D. A. (1992). Theoretical and empirical analysis of PATH magnetic lane tracking for the Intelligent Vehicle Highway System. Technical Report UCB-ITS-PRR-92-9, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Ayres, J. A. (1993). Multipe guage analog projection heads-up-display. In *Automotive Display Systems and IVHS*, pages 71 75. Society of Automotive Engineers.

Bender, J. (1991). An overview of systems studies of Automated Highway Systems. *IEEE Transactions on Vehicular Technology*, 40(1):82 99.

Bulkeley, D. (1993). The quest for collision-free travel. *Design News*.

Catling, I. and de Beek, F. O. (1991). SOCRATES: System of Cellular RAdio for Traffic Effeciency and Safety. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 147 150. Society of Automotive Engineers.

Chang, K. S., Li, W., Devlin, P., Shaikhbahai, A., Varaiya, P., Hedrick, J. K., McMahon, D., Narendran, V., Swaroop, D., and Olds, J. (1991). Experimentation with a vehicle platoon control system. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 1117 1124. Society of Automotive Engineers.

Chen, L. and May, A. D. (1987). Inductive loop detection: Errors and diagnostics. Technical Report UCB-ITS-WP-87-10, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Choudhury, P., Dawson, G. E., Eastham, A. R., John, V. I., and Parker, J. H. (1989). Inductive power transfer to highway vehicles. In *Vehicle/Highway Automation: Technology and Policy Issues*, pages 51 60. Society of Automotive Engineers.

Clemence, G. T. and Hurlbut, G. (1983). The application of acoustic ranging to the automatic control of ground vehicles. *IEEE Transactions on Vehicular Technology*, 32(3).

Corsi, K. M. and Sattler, W. J. (1989). Reconfigurable displays used as primary automotive instrumentation. In *Automotive Information Systems and Electronic Displays: Recent Developments*, pages 13 18. Society of Automotive Engineers.

Davis, R. J., Shinya, S., Hiraga, M., and Ikuta, Y. (1992). Color shift vacuum fluorescent display system. In *Electronic Display Technology and Information Systems*, pages 57 63. Society of Automotive Engineers.

Deacon, J. A., Pigman, J. G., and Jacobs, T. H. (1991). Implementing IVHS technology: The ADVANTAGE I-75 approach. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 355 363. Society of Automotive Engineers.

Egan, P. (1983). Lean machine: Logic and substance from the dreamer's workshop. *Road & Track*, 34:80B 80D.

Enderby, C. M. and Wood, S. T. (1992). Head-up display in automotive/aircraft applications. In *Electronic Display Technology and Information Systems*, pages 39 48. Society of Automotive Engineers.

Fenton, R. and Mayhan, R. (1991). Automated highway studies at The Ohio State University an overview. *IEEE Transactions on Vehicular Technology*, 40(1):100 113.

FHWA (1992). Precursor systems analyses of Automated Highway Systems. FHWA RFP Number DTFH-61-93-R-00047.

FHWA (1994). Automated Highway Systems Workshop. Washington, D.C., Sponsored by Federal Highway Administration, BRW, Inc., and Battelle Memorial Institute.

Frank, A. A., Liu, S. J., and Liang, S. C. (1989). Longitudinal control concepts for automated automobiles and trucks operating on a cooperative highway. In *Vehicle/Highway Automation: Technology and Policy Issues*, pages 61 68. Society of Automotive Engineers.

Fujioka, T., Yoshimoto, K., and Takaba, S. (1993). A case study on an automated driving highway system in Japan. In *Transportation Research Board 72nd Annual Meeting*. Session No. 94B.

Furukawa, Y. (1992). The direction of future automotive safety technology. In *Vehicle Electronics Meeting Society's Needs: Energy, Environment, Safety*, pages 95 102. Society of Automotive Engineers.

Galijan, R. C. (1993). Personal communication. SRI International.

Garrison, W. L. and Pitstick, M. E. (1990). Lean machines: Preliminary investigations. Technical Report UCB-ITS-PRR-90-4, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Garrison, W. L. and Pitstick, M. E. (1990). Lean vehicles: Strategies for introduction emphasizing adjustments to parking and road facilities. In *Automated Highway/Intelligent Vehicle Systems: Technology and Socioeconomic Aspects*, pages 17 33. Society of Automotive Engineers.

Getting, I. A. (1993). The Global Positioning System. *IEEE Spectrum*, 30(12):36 47.

Gris, A. E. (1991). Evaluation of potential hybrid electric vehicle applications, volume i. Technical Report UCB-ITS-PRR-91-4, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Gumkowski, G. T. and Shaout, A. (1993). Reconfigurable automotive display system. In *Automotive Display Systems and IVHS*, pages 13 19. Society of Automotive Engineers.

Hashimoto, K. et al. (1992). An image processing architecture and a motion control method for an autonomous vehicle. In *IEEE Intelligent Vehicles '92*.

Haver, D. A. and Tarnoff, P. J. (1991). Future directions for traffic management systems. *IEEE Transactions on Vehicular Technology*, 40(1):4 10.

Hessburg, T., Peng, H., Tomizuka, M., and Zhang, W.-B. (1991). An experimental study on lateral control of a vehicle. Technical Report UCB-ITS-PRR-91-17, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Hessburg, T. and Tomizuka, M. (1991). A fuzzy rule-based controller for automotive vehicle guidance. Technical Report UCB-ITS-PRR-91-18, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Hitchcock, A. (1994). Intelligent Vehicle/Highway System safety: Multiple collisions in automated highway systems. Preprint of paper presented at session 'Progress in Automating Highway Systems' at the Transportation Research Board 73rd Annual Meeting, Jan. 9-13, 1994, Washington, D.C.

Ishizuka, M. and Saeki, H. (1992). Chip in Glass Fluorescent Indicator Panel having functions of keyboard scan and dimming for automotive application. In *Electronic Display Technology and Information Systems*, pages 107 112. Society of Automotive Engineers.

IVHS AMERICA (1992). Strategic plan for Intelligent Vehicle-Highway Systems in the United States. Technical Report IVHS-AMER-ATMS-92-3, IVHS AMERICA.

Iwase, H., Tateyoshi, S., Tsunesumi, S., Slupek, C., Saunders, M., and Yano, K. (1992). Single vacuum fluorescent display, full featured cluster panel. In *Electronic Display Technology and Information Systems*, pages 1 7. Society of Automotive Engineers.

Johnston, A. R., Assefi, J., and Lai, J. Y. (1979). Automated vehicle guidance using discrete reference markers. *IEEE Transactions on Vehicular Technology*, 28(1).

Kamimura, M., Shima, N., Fujiwara, K., and Fujita, Y. (1993). Millimeter-wave automotive radar using digital signal processing. In *Automotive Display Systems and IVHS*, pages 91 98. Society of Automotive Engineers.

Kanemitsu, H., Saito, T., Shima, J., and Tanaka, Y. (1991). Automobile navigation using individual communication beacon. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 241 245. Society of Automotive Engineers.

Kao, W.-W. (1991). Integration of GPS and dead-reckoning navigation systems. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 635 643. Society of Automotive Engineers.

Kato, H., Ito, H., Shima, J., Imaizumi, M., and Shibata, H. (1992). Development of hologram head-up display. In *Electronic Display Technology and Information Systems*, pages 21 27. Society of Automotive Engineers.

Kornhauser, A. L. (1991). Neural network approaches for lateral control of autonomous highway vehicles. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 1143 1151. Society of Automotive Engineers.

Labell, L. N., Spencer, M., Skabardonis, A., and May, A. D. (1989). Detectors for freeway surveillance and control. Technical Report UCB-ITS-PWP-89-1, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Lowrie, P. R. (1992). SCATS Sydney Co-Ordinated Adaptive Traffic System: A traffic responsive method of controlling urban traffic. Roads and Traffic Authority, Sydney, NSW Australia.

Lubin, J. M., Huber, E. C., Gilbert, S. A., and Kornhauser, A. L. (1992). Analysis of a neural network lateral controller for an autonomous road vehicle. In *IVHS Issues and Technology*, pages 23 44. Society of Automotive Engineers.

Marhrt, R. (1971). Principle of automatic guidance of vehicles on a lane by means of permanent magnetic nails and on board computer control. In *22nd Annual Conference of the IEEE Vehicular Technology Group*, Washington D.C.

Markatos, L. D. and Nixon, T. R. (1991). Design considerations for the implementation of an automotive dot matrix display subsystem. In *Vehicle Information Systems & Electronic Display Technology*, pages 23 29. Society of Automotive Engineers.

Martin Marietta (1993). Precursor system analyses of Automated Highway Systems representative system configurations, draft. Available on the IVHS AMERICA Information Clearinghouse AHS Precursor System Analysis Forum. MMC-93-AHS-01.

Mayhan, R. J. and Bishel, R. A. (1982). A two-frequency radar for vehicle automatic lateral control. *IEEE Transactions on Vehicular Technology*, 31(1).

McLellan, D. R., Ryan, J. P., Browalsky, E. S., and Heinricy, J. W. (1992). Increasing the safe driving envelope ABS, traction control and beyond. In *Vehicle Electronics Meeting Society's Needs: Energy, Environment, Safety*, pages 103 124. Society of Automotive Engineers.

Miller, E. and Keel, J. (1993). An introduction to Gatelink its uses and benefits. In *Symposium on Worldwide Communications, Navigation, and Surveillance*.

Nauman, M. (1992). Smart buses, vans are making streets safer and life easier. *San Jose Mercury News*.

Ohara, K., Matsumoto, T., and Fraser, S. (1992). VHC LCD technology for use in an automotive instrument display application. In *Electronic Display Technology and Information Systems*, pages 65 72. Society of Automotive Engineers.

Olsen, D. L. (1991). Federal radionavigation policy and the land transportation user. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 627 634. Society of Automotive Engineers.

Olsen, K. W. (1977). Wire-reference configurations in vehicle lateral control. *IEEE Transactions on Vehicular Technology*, 26(2).

Palm, G. E. (1982). The art of detection a system concept. *IMSA Journal*.

Parsons, R. E. and Zhang, W.-B. (1988). Lateral guidance system requirements definition. Technical Report UCB-ITS-PRR-88-1, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Peng, H. and Tomizuka, M. (1990). Lateral control of front-wheel-steering rubber-tire vehicles. Technical Report UCB-ITS-PRR-90-5, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Peng, H. and Tomizuka, M. (1991a). Optimal preview control for vehicle lateral guidance. Technical Report UCB-ITS-PRR-91-16, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Peng, H. and Tomizuka, M. (1991b). Preview control for vehicle lateral guidance in highway automation. In *American Control Conference*, Boston, MA.

Peng, H., Zhang, W.-B., Arai, A., Lin, Y., Hessburg, T., Devlin, P., Tomizuka, M., and Shladover, S. (1992). Experimental automatic lateral control system for an automobile. Technical Report UCB-ITS-PRR-92-11, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Peng, H., Zhang, W., Shladover, S., and Tomizuka, M. (1993). Magnetic-marker-based lane keeping: A robustness experimental study. In *Automotive Display Systems and IVHS*, pages 127 132. Society of Automotive Engineers.

Pikula, M. S. and Calvas, G. (1991). Using variable reluctance sensors for differential odometer applications. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 441 450. Society of Automotive Engineers.

Pitstick, M. E. and Garrison, W. L. (1991). Restructuring the automobile/highway system for lean vehicles: The Scaled Precedence Activity Network (SPAN) approach. Technical Report UCB-ITS-PRR-91-7, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Polydoros, A. (1993). Vehicle to roadside communications study. Technical Report UCB-ITS-PRR-93-4, University of Southern California. Contributors: K. Dessouky and J. M. N. Pereira, C.-m. Sun and K-c. Lee and T. D. Papavassiliou and V. O. K. Li.

Rao, B. S. Y. and Varaiya, P. (1994). Potential benefits of roadside intelligence for flow control in an IVHS. Preprint of paper presented at session 'Progress in Automating Highway Systems' at the Transportation Research Board 73rd Annual Meeting, Jan. 9-13, 1994, Washington, D.C.

Scapinakis, D. A. and Garrison, W. L. (1991). Studies of the adoption and use of location and communication technologies by the trucking industry. Technical Report UCB-ITS-PRR-91-2, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Sheikholeslam, S. and Desoer, C. A. (1991a). Indirect adaptive control of a class of interconnected nonlinear dynamical systems. Technical Report PATH Technical Memorandum 91-1, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Sheikholeslam, S. and Desoer, C. A. (1991b). Longitudinal control of a platoon of vehicles with no communication of lead vehicle information: A system-level study. Technical Report PATH Technical Memorandum 91-2, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Sheikholeslam, S. and Desoer, C. A. (1991c). Combined longitudinal and lateral control of a platoon of vehicles: A system-level study. Technical Report PATH Technical Memorandum 91-3, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Sheikholeslam, S. and Desoer, C. A. (1992). Design of decentralized adaptive controllers for a class of interconnected nonlinear dynamical systems: Part I. Technical Report PATH Technical Memorandum 92-1, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Shirley, P. A. (1989). An introduction to ultrasonic sensing. *Sensors*, 6(11).

Shladover, S., Desoer, C., Hedrick, J. K., Tomizuka, M., Walrand, J., Zhang, W.-B., McMahon, D. H., Peng, H., Sheikholeslam, S., and McKeown, N. (1991). Automatic Vehicle Control developments in the PATH program. *IEEE Transactions on Vehicular Technology*, 40(1):114 130.

Sprague, D. and Woo, A. (1993). Global Position System (GPS) fundamentals. Scout GPS Application Note 2, Trimble Navigation, LTD.

Stevens, W. B. (1993). The Automated Highway System (AHS) Concept Analysis. Technical Report MTR 93W0000123, MITRE Corporation.

Tsumura, T. and Komatsu, N. (1989). Proposed position and heading measurement system of automobile on freeway using laser beams. In *Vehicle/Highway Automation: Technology and Policy Issues*, pages 19 25. Society of Automotive Engineers.

Varaiya, P. (1993). Smart cars on smart roads: Problems of control. *IEEE Transactions on Automatic Control*, 38(2):195 207.

Wang, Q. and Sperling, D. (1989). Highway electrification: An exploration of energy supply implications. Technical Report UCB-ITS-PWP-87-4, Program on Advanced Technology for the Highway, Institute of Transportation Studies, University of California at Berkeley.

Weber, L. and Tiwari, A. (1993). Performance of an FM sub-carrier (RDS) based DGPS system. Differential Corrections, Inc.

Weihrauch, M., Meloeny, G. G., and Goesch, T. C. (1989). The first head up display introduced by general motors. In *Automotive Information Systems and Electronic Displays: Recent Developments*, pages 55 62. Society of Automotive Engineers.

Womack, W. C. (1974). Status report on dual-mode concept development. In *Proceeding of the First International Conference on Dual-Mode Transportation*, Washington DC.

Yanagisawa, T., Yamamoto, K., and Kubota, Y. (1992). Development of a laser radar system for automobiles. In *Electronic Display Technology and Information Systems*, pages 73 85. Society of Automotive Engineers.

Zhang, W.-B. (1991). A roadway information system for vehicle guidance/control. In *Vehicle Navigation & Information Systems Conference Proceedings*, pages 1111 1116. Society of Automotive Engineers.

Appendix A

Distinguishing Characteristics of an AHS

Four categories are identified by the FHWA RFP (FHWA, 1992) as the distinguishing characteristics of an AHS:

- Infrastructure Impact
- Traffic Synchronization
- Instrumentation Distribution
- Operating Speed

A set of eight baseline assumptions are also given in the RFP. The selection of Representative System Configurations (RSC) should be based upon these categories and assumptions. Our approach, using the above classification, appears to represent a different approach than that taken by other contractors, but we should ensure that our results are still in line with the RFP constraints. At the end of our RSC selection, we should rate the resulting configurations in terms of these categories, and verify that the configurations do not violate any of the baseline assumptions. For our work, we believe that the most important categories are infrastructure impact and instrumentation distribution. In fact, we believe that these two categories are not completely independent. Operating speed will also have some impact, in the case that we are attempting to perform highway speed inspection, repair, and/or replacement.

In terms of implementation strategy, the following criteria are identified in (Bender, 1991):

- level of investment required by individual user
- level of investment required by system owner
- degree of interagency cooperation required

- risks assumed by user
- risks assumed by operator
- risks assumed by owner
- risks assumed by general public
- cost to user
- cost to general public
- size of potential market
- disruption to non-AHS users during construction
- disruption to non-AHS users during operation
- political feasibility

These are also important criteria to keep in mind in the RSC selection process. Bender uses a different set of general characteristics to classify an AHS concept, which is much closer to what we are doing in our group technology classification:

- Operational
  - Vehicle entrainment policy
  - System fleet mixture
  - Network type and control functions
  - Guideway lane separation requirements
- Structural
  - Intelligence distribution (vehicle/infrastructure)
  - Control/data equipment used in the infrastructure
  - Traveling unit configuration
  - Structural and equipment considerations in vehicle
- Vehicle Subsystem Technology
  - Body and chassis subsystems
  - Propulsion and brake systems
  - Vehicle control

We believe that this information is incorporated in a detailed fashion into the current group technology classification. The results of the analysis discussed in Bender's paper led to a recommended system. This system includes a smart vehicle with self-contained power operating on a passive guideway, in part to minimize liability of the system owner. Bender also recommended the use of a detachable electronics package so that vehicle owners would not have to purchase the AHS electronic systems for their vehicle.

Appendix B

Characteristics of Some Forms of Vehicle-to-Vehicle Communication for AHS

- Ultrasonic
  - Characteristics: Low frequency, directional.
  - Advantages: Directional.
  - Disadvantages: Low data rate.
- Radio
  - Characteristics: High frequency, non-directional.
  - Advantages: High data rate.
  - Disadvantages: Non-directional.
- Infrared
  - High frequency, directional.
  - Advantages: High data rate, directional.
  - Disadvantages: Sensitive to transmitter/receiver alignment.

Appendix C

Characteristics of Some Sensors for AVCS

- Absolute Vehicle Location
  - GPS
    - Characteristics: Vehicle-intensive.
    - Advantages: Negligible infrastructure impact.
    - Disadvantages: Currently low accuracy, slow, subject to blockage by bridges, tunnels, etc., subject to loss of satellite lock.
  - Triangulation w. Roadside Beacons
    - Characteristics: Infrastructure intensive.
    - Advantages: Accurate relative to GPS.
    - Disadvantages: Requires installation of many beacons in infrastructure. Possible bandwidth problems.
- Headway Measurement
  - Microwave Radar
    - Advantages: Insensitive to weather conditions.
  - Laser
    - Advantages: Fairly inexpensive solution.
    - Disadvantages: Sensitive to fog and rain.
  - Ultrasonic Sensing
    - Advantages: No electromagnetic emissions.
    - Disadvantages: Thermal sensitivity, susceptibility to background noise, turbulence, and convection currents, rapid attenuation, low range.
- Headway Closing Rate

- Doppler Radar
    - Disadvantages: Cannot give accurate measurement of vehicle separation.
- Laser with Differentiation
    - Disadvantages: Possibly noise sensitive due to differentiation.

- Vehicle Lateral Position
  - Embedded Wire with EMF Sensor in Vehicle
    - Disadvantages: Maintenance and reliability can be a real problem, especially with active wire. A passive wire may not be sufficient.
  - Side Radar Detecting Barriers
    - Advantages: Minimal investment in the vehicle.
    - Disadvantages: Requires barrier installation. Cost-effective if this is needed for other reasons, such as safety, but costly if solely for measurement purposes.
  - Discrete Magnetic Markers with Magnetometer in Vehicle
    - Advantages: Allows encoding of roadway information so that controllers can take predictive action.
    - Disadvantages: May be costly to install and maintain. Possibility of interference from rebar, etc., although this appears to be no problem (Peng et al., 1993). Significant investment in infrastructure.
  - GPS
    - Advantages: No infrastructure modification is needed, so it can be used throughout system.
    - Disadvantages: Low accuracy, slow, subject to blockage, subject to loss of satellite lock. May require a secondary system for use on bridges and in tunnels.
  - Vision System to Detect Lane Markers
    - Advantages: Minimal infrastructure requirements. Just need to maintain (sometimes install) consistent lane markers.
    - Disadvantages: High cost in vehicle, currently requires far too much processing power, may not be feasible to achieve necessary frames per second using cost-effective system. Also, subject to weather and lighting conditions.
  - Triangulation w. Roadside Beacons
    - Advantages: Minimal in-vehicle cost.
    - Disadvantages: Requires installation of many beacons in infrastructure. Possible bandwidth problems. May not be accurate enough for lateral control.

- Vehicle Yaw Rate
  - Gyroscope

- GPS with Two Antennas
  * Advantages: Allows high accuracy angular measurement.
  * Disadvantages: Expensive.

- Vehicle Speed
  - Standard Digital Speedometer
    * Advantages: Currently in use in most new vehicles, so requires minimal redesign and retrofit.
    * Disadvantages: May not be accurate enough.
  - Timing of Discrete Magnetic Marker Pulses
    * Advantages: Increases value of infrastructure investment. May be used as a redundant measure to backup other systems.
    * Disadvantages: Subject to accuracy of marker placement. Again, only useful if magnets are used for lateral control. Obviously this technique won't work where magnets are not installed.
  - Wheel Encoder or Resolver Differentiation
    * Advantages: High accuracy.
    * Disadvantages: Requires installation of additional (possibly expensive) vehicle hardware, and is subject to differentiation noise.

- Obstacle Detection
  - Infrared Detector
    * Advantages: Detects "soft" obstacles, such as humans and animals.

- Steering Angle
  - Potentiometer
    * Advantages: Inexpensive.
    * Disadvantages: Noisy.
  - Encoder
    * Advantages: Accurate, minimal noise problems.
    * Disadvantages: Expensive.

- Throttle Position or Fuel Flow Rate
  - Potentiometer
    * Advantages: Cheap.
    * Disadvantages: Gives measure of valve position, but may not accurately reflect flow. Also subject to noise.
  - Flow Meter

    * Advantages: Actual measure of flow.

- Vehicle Acceleration
  - Accelerometer
    * Advantages: Direct acceleration measurement.
    * Disadvantages: Cost of additional sensors.
  - Differentiation of Velocity Measurement
    * Advantages: Dual use of installed velocity sensor.
    * Disadvantages: Subject to differentiation noise.

Appendix D

IVHS Services/Applications

- ATIS[1]
  - Traveler Advisory
  - Traveler Information (Yellow Pages)
  - Position Location
  - Route Guidance
  - In-Vehicle Signing
  - Mayday
  - Misc, including: Visitor Attractions, Restaurants, Events, Hotels, Gas
- ATMS
  - AVI/Toll Collection
  - Flow Monitoring and Control
  - Incident Detection and Management
  - Work Zone Management
  - Hazard Warning
  - Parking Management
- Freight/Fleet Management (CVO)
  - Route Planning and Scheduling
  - Vehicle and Cargo Tracking
  - HAZMAT Monitoring
  - Automatic Fee Payment

[1] The information in this appendix is taken directly from (Polydoros, 1993). It is repeated here for completeness.

  - Law Enforcement and Regulatory Support

- APTS
  - Planning and Scheduling
  - Vehicle Tracking and Monitoring
  - Time of Arrivals
  - Automatic Payment
  - Trip Planning and Ride Sharing
  - Emergency Services Systems Management
  - Signal Preemption Traffic Control

- AVCS
  - Intelligent Cruise Control
  - Platooning
  - Cooperative Driving

Appendix E

Functional Areas and Communications Technologies

Table 3.1 on page 49 of (Polydoros, 1993) looks at the various IVHS functional areas and a variety of proposed communications technologies, and provides a matrix of applicability. The communications technologies listed include:

- Subcarrier FM
- SAP signals (a currently unused portion of the TV broadcast bandwidth)
- Highway Advisory Radio (530 kHz and 1610 kHz)
- Leaky cable
- Satellites (LEO and GEO)
- Beacons (IR and Microwave)
- 2-way wide area radio
- Cellular systems
- Inductive loops
- HF
- Personal Communication Services
- Microcellular
- Meteor Burst