Automated Highway System Approach

1 of 4 AHS Model Deployment Initiatives Funded by FHWA

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I. Executive Summary

The Virginia Tech Center for Transportation Research is developing a concept for a cooperative vehicle/infrastructure based automated management approach referred to in this proposal as a “Cooperative Infrastructure Managed System (CIMS).” There are many possible AHS concepts and we believe that each one has its individual strengths and weaknesses. The “Cooperative Infrastructure Managed System (CIMS)” builds on the various strengths of several systems in a cooperative fashion. The CIMS system is neither a totally vehicle-based system nor a totally infrastructure-based system. It relies on cooperation between processors on the roadside and on the vehicle and shares command decisions between the vehicle and the infrastructure. The concept uses communications to integrate the vehicle with the roadside. In addition, this system does not need complex roadside sensors to detect and manage the vehicles. Instead, it uses cooperation between the vehicle and roadside infrastructure to determine the best path for each vehicle on the road based on a global knowledge of location of all the vehicles in an area. Through this cooperation the tasks best suited for the vehicle are performed on the vehicle and the tasks best suited for the infrastructure are performed at the roadside.

The system fuses together the multiple sources of sensory data from both the vehicles and infrastructure into a layered management algorithm designed to optimize the safety of the system while maintaining a designed throughput potential. The use of a new solid state ultra-wideband communications system is proposed for precise vehicle and roadside waypoint location and simultaneous information sharing. The location from this sensor can be fused with on-board sensors to provide an accurate picture of the surroundings in which to develop an integrated control strategy.

This design approach attempts to fully exploit the opportunity of cooperation between the roadway and the vehicles to simplify the sensors and processing required for autonomous vehicle operation. By taking some of the bulk of the processing and sensing load off the vehicle and distributing it throughout the infrastructure, added vehicle costs are minimized with little added infrastructure. All sensory input the vehicle has to offer can be communicated to the infrastructure and integrated with the global information set.
II. Concept Description

1.0 TECHNICAL SUMMARY OF CIMS AHS CONCEPT

Highway system security and passenger safety has been a significant consideration in this technology approach. Today, over 90% of all crashes are caused, or contributed to, by human error. The accuracy of this system allows for updating the vehicle position and updating the vehicle control commands 100 to 1000 times per second. Also, all the vehicles can synchronize their response to a given situation.

While the flow capacity of manually controlled vehicles is roughly 2200 vehicles/lane/hour, it has been estimated (1) that sustainable lane capacities of the order of 5500 vehicles/lane/hour are feasible with an AHS system, a large improvement over existing capacities. With our field separation approach even higher throughputs are possible. (See the throughput analysis section.) The final deployment of this approach, therefore, significantly lessens the land use requirements of highways and reduces the need for new roadways, leading to substantial reductions in federal and state highway costs.

It is expected that use of the AHS will improve fuel efficiency, reduce congestion and improve commercial vehicle operations.

To date, the enabling technologies for the AHS have been machine vision (image processing), optical laser radars, RF detectors, acoustic sensors and magnetic sensors. Much of this work has been centered on installing these sensors on vehicles; in effect having "Smart Cars". Some systems, like PATHs, magnetic nails, are taking advantage of the fact that the roadway and vehicles can cooperate to simplify the sensors required to control the vehicle. Results from the PATH Program have shown that in order to maintain stability in a close platooning situation that inter-vehicle communications are required. Therefore, the car of the future must not be seen as operating on its own. In addition, many of these sensors and detectors contain a high degree of complexity and sophistication. This may be partially due to the Department of Defense origin of many of these products.

1.1 DESIGN APPROACH - Cooperative/Distributed Infrastructure

This design approach fully exploits the opportunity of cooperation between the roadway and the vehicles to simplify the sensors and processing required for autonomous vehicle operation.

By taking the bulk of the processing and sensing load off the vehicle and distributing it throughout the infrastructure, the vehicle costs are minimized with little
added infrastructure. Any sensory input the vehicle has to offer can still be communicated to the infrastructure and integrated with the global information set.

1.2 PHASED DEPLOYMENT

The CIMS concept uses a hybrid deployment strategy that arrives at a dedicated automated highway system through an evolutionary friendly mixed mode at early stages. This achieves the eventual high throughput potential of a fully dedicated automated highway system at final stages while focusing on safety and societal acceptance at early stages.

During the first years of deployment the system would gradually allow vehicle to enter a semi-automated mode in the presence of manually operated vehicles on slightly augmented conventional roadways. In this way, no significant investment in infrastructure has to be made before some level of automation can be achieved. The users will see enormous safety and mobility benefits, but, will not see significant changes in throughput.

Later, as more users become equipped with automation, the rational can be made to invest in dedicated infrastructure by dedicating lanes or dedicating whole facilities. Since vehicles can enter automation in mixed traffic easily, the need for special entry exit facilities and transition lanes are significantly reduced. With these dedicated facilities will come the increased throughput desired in congested urban areas and the shorter more reliable travel times desired in rural inter city travel.

The section on evolution describes the factors that contribute to this type of deployment strategy. Also, the throughput analysis shows why either mixed or dedicated lanes alone does not achieve the desired system characteristics and objectives.

1.3 THE ARCHITECTURE

The layered Berkeley AHS architecture will be used to describe the CIMS control structure. The key to the functionality of the CIMS is in the distribution of control between the vehicle and the infrastructure. This can be implemented in a number of different ways. As in many other approaches, the network and link layers will be carried out in the infrastructure and the physical layer will be in the vehicle. However, depending on how the CIMS system is designed, the control in the regulation and planning layers could be vehicle based, infrastructure based or some combination. The main discriminant is that some measure of vehicle management is initiated from the
infrastructure. This could be as little as desired speeds for the links to actual control commands sent to the vehicle processor. The detailed realization of a preferred system configuration and other possible system configurations within this framework will be defined by further study. See the controller section for more details.

1.4 THE VEHICLE

The basic instrumentation on the vehicle will consist of the actuators required to control the steering, acceleration and braking, the transponder/communications between the vehicle and the roadway, vehicle based sensors, the user interface and the self-diagnostic equipment. All this equipment is controlled by the vehicle processor (see Figure 1 below). These components are already available and only need slight modification to be integrated into this system. The major functional subsystems are outlined below. When installed on vehicles, some additional hardware for improving the reliability of the system through fault tolerance will also be present. Thus, a candidate architecture for the actual system may feature a self-diagnostic microprocessor installed in a “Triple Modular Redundancy” (TMR) configuration. Such a system possesses 3 identical processors executing the same actions in parallel, with a separate “voter” processing element deciding the correct output. The technology for a self-diagnostic microprocessor has already been developed (2). Hardware peripheral to the processor can be developed using CAD tools specially developed (3) for CMOS VLSI design of automotive electronic components.
The on-board sensors are designed for non-cooperative obstacle detection within the path of each vehicle. The transponder sensors are designed for situational awareness of other cooperative systems, i.e. other cars and the infrastructure. When combined these sensors can complete the whole control sensing task. Each type of sensor needs the other to function properly. Otherwise, the complexity of sensor solution would be too great. A system with only non-cooperative sensors would require sophisticated detection and identification with very fine resolution. Also, the system could not see beyond adjacent objects unless cooperative communications were conducted anyway. Conversely, a system with only cooperative sensing would require all possible obstacles be equipped sufficiently to prevent an inadvertent obstruction from hindering the free flow of traffic. This would involve putting a tag on every man, animal or object that may find its way into the path of traffic. Obviously, this is not possible. Therefore, the fusion of sensors makes the most sense.

1.4.1 Transponder/Communication

The vehicle will maintain a two way communications link with the roadside at all times through the main transponder. If the main transponder fails, then transition to a back-up transponder can be made or a controlled shutdown of the vehicle can be
performed by the vehicle processor. This system augments the existing vehicle sensors with a simple transponder type system that, in addition to performing the vehicle/roadside communications, will be used to accurately locate the vehicle in the roadside receivers or from other vehicles. The transponder system will be designed to locate and track the vehicle both laterally and longitudinally to better than 10 cm. The transponder also will be used to receive navigation instructions from the roadside sensors. Combining the communication and vehicle positioning system simplifies the vehicle design while providing very accurate positional information that the other detection systems are not even close to achieving. In addition, transponders similar to these already are being used in automatic toll collection and vehicle identification. To obtain the required accuracies, the use of an Ultra-wideband impulse radar of non-sinusoidal technology can be instituted. These systems are solid state, which leads to low cost with large quantities and can easily meet the specifications of the system. We discuss this more later in the Transmitter/Receiver section and in the Ultra-wideband section. The vehicle will transmit information such as diagnostic status, user requests, and vehicle ID. The roadside will transmit various information such as vehicle position, weather/road conditions, ETA and request responses. The information received by the main transponder is forwarded to the command input buffer through the demultiplexer.

1.4.2 Vehicle Sensors

It is assumed that earlier stages of deployment will make on-board vehicle sensors for adaptive cruise control and obstacle detection standard on all vehicles. These sensors will be combined with the Ultra-wideband sensor in a fusion process to give the vehicle and the roadside the necessary information it needs to manage the vehicles in the system. Other sensor on-board the vehicle will be used for carrying out the vehicle feedback controller operations. Wheel slip, engine torque, vehicle attitude, throttle angle, steering angle, etc. all are inputs to the control of the vehicle actuators. The on-board sensors must be monitored at all times and system diagnostics must be performed to insure these values are reliable.

1.4.3 Command Input Buffer

As the name suggests, this component consists of a Random Access Memory (RAM) that acts as a temporary storage point for the commands received from the roadside.
1.4.4 Vehicle Processor

The vehicle processor responds to the commands stored in the command input buffer by sending the appropriate feedback to the actuators that control steering, acceleration, braking, etc. In addition, it can forward data from sensors on the vehicle to the infrastructure. It, also, manages driver/infrastructure interaction by delivering data to, and accepting user commands from the user interface unit. In addition, the processor also performs a number of “house-keeping” functions. For safe operation on an Automated Highway System and to reduce the incidence of vehicle failure on an AHS, a certain degree of self-diagnostics must be maintained. A few operating cycles per second will be reserved for these operations. In addition to monitoring the major systems on the vehicle, the processor will keep a log of the steering, acceleration and braking responsiveness at different velocities based upon the navigation command vs. the actual motion of the vehicle. Also, routine maintenance performed on the vehicle such as tire changes, oil changes and break maintenance will be entered into the processor. When vehicle responses become too sluggish or the time comes for routine maintenance, the driver will be instructed to have the vehicle serviced. If the driver does not respond, he will not be allowed to enter automated mode.

1.4.5 Actuators

Many studies have designed actuators to control the vehicle functions. The key elements to examine in the actuator design are the update rate at which the vehicle functions can be controlled and the size of the incremental adjustments that can be made. In the past, developers have tried to emulate the capabilities of a person in their actuator designs. However, in order to get the increased performance required and the comfort expected from an AHS the responses in the actuators must be at least an order of magnitude better than that of a person. The safety of a system will be directly proportional to the rate at which the vehicle commands are updated. It has been shown (10) that the “safegap” (distance at which collision velocity drops to zero) for a vehicle following another one can drop to a third of its original value when system lag time drops to a tenth of its initial value, depending on the original spacing between vehicles. Thus, a system that can respond to a situation in a fraction of a second will be safer than one that takes a second or longer to respond. We are looking at updating the navigation commands at a 100 to 1,000 Hz rate with mechanically integrated controls to allow for smooth steering, acceleration and braking controls rather than incremental adjustments. The net result will be a smoother ride with a faster response time and better lane following. At present, processing requirements of other sensor systems like machine vision systems can not achieve these update rates.
1.4.6 User Interface

The user interface will look different depending on which stage of deployment is envisioned. Initially the user interface will be the same as current systems. Buttons that set the cruise control will set lateral and longitudinal cruise control with the actual processing transparent to the user. This will be possible due to the mixed mode of traffic at early stages of deployment. However, as the systems evolve and dedicated facilities are starting to appear then the vehicle displays will become more sophisticated. Users will be able to set way points for their trip to stop for gas or specify desired exit locations. Audible traveler information systems will be common to vehicles and drivers in automated mode will have more and more time to look at visual displays. One vision of a user interface is of an audio-based system with a visually-based back-up. The system would verbally give instructions to the user and use speech recognition to receive responses. If a driver does not prefer verbal interaction, he or she would also be given the option of reading the same instructions on an LCD screen. Also, driver responses may be communicated to the processor via touchpad on a hand-held unit depending on driver preferences. Figure 2 below shows the User Interface Unit.
This system would not require any changes to the dashboard of the vehicle. However, these user interface functions also could be incorporated into an existing Advanced Traveler Information Systems (ATIS) interface.

1.5 TRANSMITTER/RECEIVERS

This AHS architecture design consists of a series of transmitters and receivers that are highly overlapped and locally controlled by a series of networked processors. It contains three times the number of transmitters, receivers and processors that are needed for minimal operation. This is done to allow graceful degradation of the system.
as various components fail and to allow for even greater performance when all components are working. This approach uses a "multi-static" transmitter/receiver layout where the transmitters and receiver are not necessarily co-located. There are multiple receivers for each transmitter and each receiver can process the returns from multiple transmitters. This allows the system to overcome the line-of-sight problem or shadowing problem inherent in many systems by being able to see the vehicle from many directions.

The transmitters are omni-directional to excite the vehicle transponders on all sides and of sufficient power to cover approximately a 300m radius reliably in all weather conditions. Since the vehicle transponders are active devices, the transmitter does not have to be very powerful. Transmitters are spaced approximately 100m apart and transmit coded pulses to identify from which transmitter the pulse emanated.

Conventional X-band radar has been used for detecting vehicle locations with accuracies of the order of 10 feet every 1.7 seconds (4). However, in order to know the precise location of vehicles at all times, the distance measuring equipment should be capable of resolving distances of the order of 10 cm. or less. To achieve these accuracies, conventional radar would need to operate in the higher frequency ranges (>40GHz), where its operation is susceptible to weather conditions. To meet the critical requirements of AHS, we propose the use of an “Impulse Radar (or Impulse Radio) System”. This is a new type of Ultra Wide Band (UWB) radar system that transmits pulses or monocycles of extremely short duration (less than a nanosecond) over an extremely wide frequency band (several GHz wide). This may be sinusoidal or non-sinusoidal in nature. This type of technology has been used before in ground probing radar by the military (5). It has been estimated (5) that a range resolution of 7.5 cm. can be achieved with an impulse radar system operating over a 1 GHz bandwidth.

Commercial vendors and a system developed under an ARPA project report that they have already achieved and demonstrated accuracies down to less than 5 cm. Since these systems are solid state, they can be manufactured in large numbers at low cost. A detailed description of this technology is provided in the Ultra-wideband technology section and the related Appendix sections. (Please contact Robert James for copies of this material.)

The impulse radar system can also be used to carry the low data rate communication from the roadside to the vehicle by using a Pulse Position Modulation (PPM) scheme. The low data rate communication typically consists of commands from the roadside to manage independent vehicle responses. Assume that a non-sinusoidal impulse radio system is used for distance resolution purposes. Now, trains of pulses may be used to convey information to individual vehicles. Consecutive pulses can represent “flags” that control the operation of each of the vehicle actuators. Each flag sequence will be preceded by a vehicle ID sequence, much like a telephone number.
Alternatively, the ID sequence could be superimposed on the flag information itself. Information is imposed on the pulses by varying the time interval between consecutive pulses. For example, an increase in the interval over the default value may cause an actuator to incrementally increase acceleration or braking. As vehicle commands will be updated at between a 100 to 1000 times per second, we feel that the desired degree of vehicle management and cooperation will be achieved. As the energy is spread over an extremely wide bandwidth, the power density is low, and hence this system can co-exist with other radio systems operating in the same electromagnetic spectrum. A time-hopping multiple access scheme using impulse modulation has been proposed by Scholtz (9). This system has been found to possess excellent time resolution, thus allowing easy resolution of propagation paths with differential delays on the order of a nanosecond. It has been claimed that the degrading effects of multipath delay can be easily countered using this scheme with a simple receiver. This is an attractive feature for the proposed AHS system in a dense traffic scenario. For carrying the high data rate voice communication, a conventional cellular radio system can be used. A different approach to the issue of simultaneous range finding and communications has been taken in the “Spread Spectrum Communications Radar” using photodetectors reported by (6). While this system can achieve a transmission rate of 12.6 kbps, its range resolution is of the order of 1 m, and hence further work would be needed to make it suitable for use in the proposed AHS system.

In addition to the increased range resolution over conventional radar, this system also possesses a number of features beneficial to AHS. For instance, the upper limit of the bandwidth required to obtain the desired levels of accuracy is well below the onset of severe atmospheric absorption (7). High bandwidth impulse signals occupying the 0.5-10 GHz band are susceptible to minimum atmospheric distortion (8). This suggests “All-Weather” operation of the system. Also, it is felt (7) that the solid state components that will be used for generating these signals will be much smaller in size than those used in waveguide radar. This allows each element of the transmitting array to have its own transmitter. This in turn provides a simple alternative to complex beam-steering equipment. However, many technical issues need to be resolved before this technology can be transferred from the laboratory onto the roadside.

Regardless of where a vehicle is positioned on the road, there will be one set of receivers positioned to receive pulses longitudinally along the roadway, and another set positioned to receive pulses laterally. Since the receivers are spatially distributed, receivers of both types contain both lateral and longitudinal information. The local processor is able to optimally extract this information. The sensors are co-located with the transmitters along the roadway. (see Figure 3).
The receivers measure the time difference between the arrival of the transponder pulse and the arrival of the transmitter pulse. This time difference and the transponder pulse level is tagged with the vehicle ID, the transmitter ID, the receiver ID and any other ancillary information and sent to the local processor. The processor calculates the vehicle position and determines any navigation adjustment the vehicle should make. These navigation adjustments and any other information are sent to the transmitter to encode and send to the vehicle. One similar system is the LORAN Navigation System which is easy to use, has an inexpensive processor and provides high accuracy data. Other localization techniques have been used in various sonobuoy systems.

1.5.1 Local Computer Processor System

The bulk of the decision making and calculations are performed in a distributed network of interconnected local processors. Two advantages of a distributed architecture are: 1) the computational load on each processor is low; bringing the cost down, 2) the system can randomly lose 30% or greater of the processors and still function, and 3) individual processors can be replaced or upgraded without bringing the system to a halt. Each processor maintains communication with local sensors; performs vehicle tracking and management; maintains area map; services requests; maintains inter-processor communications; and communicates with a central Advanced Traffic Management System (ATMS) controller. The sensor communications, vehicle tracking and vehicle management tasks make up the processing plow for each update cycle. Other processing is done on a scheduled basis around the regular updates. Figure 4 shows the operations required during each update cycle.
Following is a description of the processor functions:

a. **Sensor Communications**

Each processor controls one transmitter and has access to 6-12 receivers. Access to the receivers is overlapped such that each processor uses 2/3 of the receivers that an adjacent processor uses and 1/3 new receivers. The processor receives the time differences, signal level and identification information from the receivers and sends positional update commands to the transmitter at a 100-1000 Hz rate. Other communications with the vehicles are also scheduled by the processor.

b. **Area Map Maintenance**

The processors contain a local map that specifies the edges of the roadway relative to the sensors. This is a high accuracy (~10-20 cm) map of approximately 500 meters of roadway closest to each processor. These maps can be programmed into the processors after they are deployed by running a training beacon along the edges of the roadway. If a portion of the road need routine maintenance the perimeter of the roadway can be redefined by running a training along the new roadway edges. With this information and the current flow rate, the processor can determine the optimal vehicle spacing in its area of coverage. Vehicles do not need to travel down fixed sized lanes. If traffic flow is low, a safer configuration would be one lane of traffic. When flow increases, one may want to increase to two, three or more lanes to handle the flow. There is very little reason to tightly pack cars together when it isn't needed.

c. **Vehicle Location**
The localization algorithm uses the time differences of arrival between multiple receiver positions. The time difference between each pair of receivers defines a hyperbola with the two receivers as foci. When multiple hyperbolas are combined from different receiver pairs they cross at the source of the transmitted energy, i.e. the vehicle. We have shown in simulation a number of approaches at solving the localization problem given the time differences of arrival. Since each arrival time may have some slight error the actual hyperbolas do not cross at a single point. Therefore there is no closed form solution to the multiple hyperbola crossings. We explored three methods to solve the localization problem.

First, we calculated each pair of hyperbola crossings and centroided on crossings within a certain proximity. This allowed us to throw out the second solution to the crossing equations and localize the remaining points. One problem, however, is that certain configurations of hyperbola crossings can yield significant errors. With multiple crossings and good spatial diversity of receivers this problem is minimized.

Second, we did a linear approximation in a least squares sense of the solution to the hyperbolic crossings. This allowed us to simultaneously integrate the time differences of N>4 receivers into a least squares solution of the linear approximation. With vehicle positions contained within a perimeter of receivers this method gave good approximations, however, with vehicle positions outside the receiver perimeter the results became systematically erroneous.

Finally, we explored a neural net technique to localize the vehicle based upon the receiver time differences. We randomly generated a large number of positions within the region of the receivers, calculated the actual time differences at the receivers and introduced some error in the signals. The neural net was then trained with these values and evaluated.

The net result was that all three localization schemes produced similar results. Measurement errors on each receiver of 10 cm produced location errors of 20 cm to 30 cm. Similarly, measurement errors of 1 cm produced location errors of 2 cm to 4 cm. All algorithms performed better when the receivers showed good spatial diversity and when locations were contained within the perimeter of receivers.

Another way to localize the position of the vehicles is to have the vehicles prompted by the roadside to echo back a pulse. The algorithms associated with this technique involve ellipse crossings with the transmitter and receiver as foci. The ellipses from multiple receivers all cross at the vehicle location. (See Figure 5)

Algorithms have been developed (such as the LORAN System) to use the ellipse crossing points to find the vehicle position and define an area of uncertainty (i.e., lateral and longitudinal errors). While the algorithms are much simpler with this technique the
hardware requirements of the system are more pronounced. The transponders on all the vehicles must be able to echo the trigger pulse from the roadside at a very consistent interval. The echo can be delayed by a constant interval as long as that delay is known and constant. Since we are dealing with sub-nanosecond differences aligning the transponders may be difficult. Therefore, we only did analysis with hyperbolas which do not have this problem. The hyperbolas do need a periodic signal from the infrastructure in order to provide a common relative marker from which to compare time differences. However, since the relative location of the roadside receivers is known and is constant the exact timing of the marker pulse is not important.

This positional information can be put into a standard tracker to update the track file. When all tracks are updated, tests will be run to verify all vehicles are accounted for and updated.

Each vehicle has different response characteristics (a truck will not stop like a car). These characteristics, as well as size and shape of the car, will be combined with the current and desired vehicle spacings to determine a managed response for each vehicle in the region of coverage. This way a big deviation in one vehicle can be compensated for by a smaller correction in that vehicle and the surrounding vehicles. Detection of significant deviations can be dealt with by adjusting surrounding vehicles and a controlled shutdown of that vehicle, if necessary. Details of the controller are provided in the controller section.

**Figure 5: Vehicle Location Using Ellipse Crossing**
e. **Servicing Requests**

The processor also must schedule time to service requests from all sources. For example, 1) What actions should be taken if detections for a track are lost? Increase spacing? Notify vehicle to start back-up transponder? 2) If all tracks are lost, shut down this processor, re-route services and notify ATMS controller of failure, 3) Is a transmitter or receiver not functioning? Notify ATMS controller, 4) The vehicle may request some service such as change the desired exit or a mechanical problem may have been found. How severe is the problem? A detailed malfunction management routine on the vehicle and roadside should take into account all possible situations requiring a response and optimize this response with all possible resources.

f. **Inter-Processor Communications**

In order to efficiently transfer vehicle information from processor to processor, the processors must be networked together and the appropriate handshaking performed. To allow for failures, the design networks at least three processors forward and at least three behind. Information to be passed between processors includes:

1) Vehicle Code lists for hand-off
2) Previous track information
3) Vehicle specific information
4) Track verification for transition

If a processor goes down, lists and tracks are re-routed to the next computer. All these inter-processor communications need to be scheduled on the timeline. **Figure 6** shows the architecture of the system.

The inter-processor communications can be compared to a cellular network. Much of the protocol and handshaking used to transfer control of a channel from one cell site to another can be used to describe the interaction between the roadside processors. The time critical nature of the cellular transfer is closely related to that of the vehicle management. Further study should use the example of the cellular system to define much of the interchange between AHS processors.
1.5.2 Fault Tolerance For AHS Roadside Transmitters, Receivers and Processors

For the communication layout discussed above, we consider 3 types of failure scenarios. These represent worst-case situations where overall system failure is possible. For smaller defects, the system performance would be degraded, but the system would not fail. Thus, the proposed system is a kind of “fail-soft” system. The three scenarios are outlined below (see Figure 7).

1) 3 adjacent transmitters fail, or
2) at least 4 out of 7 receivers do not receive transponder signal, or
3) 3 adjacent processors fail.

We assume random failures and define the following terms:

$$\bar{t}_{tf} = \text{Transmitter mean time between failures (assumed as 6 months)}.$$

$$\bar{t}_{rp} = \text{Receiver mean time between failures (assumed as 6 months)}.$$

$$\bar{t}_{pf} = \text{Processor mean time between failures (assumed as 1 year)}.$$

Substituting the assumed values from parentheses, we obtain the individual failure rates (in Hz) as:

$$\frac{1}{\bar{t}_{tf}} = 6.3 \times 10^{-8}.$$
Each of the three failure scenarios is examined separately below:

Transmitter Failure:

Assume that the system were to be deployed on all of the National Highway System (NHS) consisting of 250,000 Km of highway. Let N denote the total number of transmitters deployed along the highway system. Assuming that transmitters have been deployed along the entire highway system with a deployment rate of 10 transmitters per Km. of highway, N equals $2.5 \times 10^6$. 

\[
\frac{1}{L_x} = 6.3 \times 10^{-8}.
\]

\[
\frac{1}{L_y} = 3.2 \times 10^{-8}.
\]
Thus, the probability of 3 adjacent transmitters failing is

\[ P_{tf} = \frac{N-2}{t_{t}} = 6.25 \times 10^{-15}. \]

This works out to an interval of 5.07 x 10^7 years between failures.

**Processor Failure:**

Proceeding as before, the failure probability for this case is:

\[ P_{pf} = \frac{1}{N-2} \quad \rightarrow \quad 4.06 \times 10^8 \text{ years between failures.} \]

**Receiver Failure:**

The probability of 4 out of 7 receivers not receiving the transponder signal is calculated as:

\[ P_{rf} = \left(\frac{1}{8}\right) \left[ N/t_{r} \right] + \left(1/2\right) \left[ N/t_{r}^{2} \right] + \left[ N/t_{r}^{3} \right] \]

In the worst case one receiver is masked (the transmitter/transponder/receiver path is close to the direct transmitter/receiver path), causing the second and third terms in the above equation to drop to zero. This reduces to an interval of 4.06 x 10^8 between failures.

Combining the three cases above, the cumulative interval between failures is given by

\[ \frac{1}{P_{t} + P_{r} + P_{p}} = 4.05 \times 10^7 \text{ years.} \]

It is seen that the failure probabilities are small enough to ensure safe operation of the AHS system as proposed.
1.6 SAFETY AND DRIVER COMFORT: Primary Design Goals

The AHS system design proposed here places heavy emphasis on driver safety. This is evident from the following factors:

1. The system is able to maximize vehicle spacing within the available road surface, while maintaining the necessary throughput based on traffic density. The processors on the side of the road contain algorithms that synchronize the activity of all the vehicles based upon individual vehicle response capability and traffic density. Also, the spacing can be made variable based upon individual vehicle response capabilities. For example, trucks and cars with flat tires would be given a greater proportionate headway than normal cars. When density is high this system will still be able to maintain the close headways found in a "platoon". This ability to adjust headway spacing at the network level provides the system with greater flexibility to respond to potentially dangerous situations.

2. The proposed system involves communication between the vehicle and the roadside in a feedback loop. Thus, the system can be configured as a closed loop control system. A closed loop system can be designed in general, to be a stable system through feedback (11).

3. The failure probability of the overall system is extremely small. This is seen from the probability calculations from the earlier section.

4. Since vehicle data is acquired by the roadside processors between 100-1000 times a second, the system response time represents a quantum improvement over manual response time. It has been shown (10) that while the average human reaction time is 1 second, automated vehicle response time of only 0.1 second can achieve enormous safety benefits.

The advantages of the proposed approach not only increase the safety of the system when not operating at maximum capacity but allow for a much better transition for the user. A key to the success of an AHS program will depend on user acceptance. A system that asks users that have been used to multi-car length separations between vehicles to suddenly accept 3 feet spacings will experience a great deal for criticism. However, a system that begins new users with more separation than they are used to having between vehicles and gradually over the course of years brings the spacing down as traffic density increases will be well received by the driving public.

1.7 ATMS CONTROLLER INTERFACE

The AHS system described here is can also be examined in the context of the five-layer hierarchical architecture proposed by Varaiya (12). The ATMS layer of the proposed system is responsible for routing and flow control at the network and link levels and thus broadly corresponds to the network and link layers mentioned by Varaiya. The roadside processors work with each other and with the vehicle-based
actuators to manage individual vehicle positions. The roadside and vehicle processors perform the functions of planning, regulation and physical layers. One big advantage the ATMS Manager will find when transition is made to the AHS is that he will have more responsive control over the road network. This will serve to adjust flow controls on arterials well in advance of changing environments to optimally handle upcoming situations. The controller will be linked to each processor and constantly be advised of any maintenance needs or emergency situations to automatically direct help as needed. The ATMS controller also will be in charge of the entrances and exits to the AHS. The controller will provide the processors with any needed information such as road and weather conditions.

1.8 CONCLUSIONS

The approach we are proposing has merits as well as drawbacks. Like the platoon approach cited in (12), the proposed system avoids the enormous computation and communication costs of a centralized controller-based system and also avoids the need for highly sophisticated technology on-board the vehicle in the autonomous vehicle case. However, a fair amount of redundancy needs to be built into the infrastructure to ensure its resilience to failures. The system described can be made very safe due to synchronized vehicle management and the closed loop nature of the system. The spacing of the vehicles can be maximized based upon the density of the traffic. Vehicles do not have to travel in close proximity platoons until traffic densities exceed current roadway capacities. A system that gradually reduced vehicle proximities over years as the traffic densities increased would be received much better than a system that required immediate close proximities. Best of all, much of the crucial range-finding technology has already been developed by ARPA and private vendors. In view of the strengths of this approach, we feel that it deserves further systematic analysis and development.
2.0 DEFINITION BASED UPON REPRESENTATIVE SYSTEM CONFIGURATIONS

The CIMS concept cannot fully be described based upon the six primary representative system configuration (RSC) areas used by the consortium. However, some comparisons can be made to the six categories. Following we will attempt to place the CIMS concept in the framework established by the consortium and point out key differences.

2.1 Distribution of Intelligence

Although no definition of the various categories exactly matches the description of the CIMS concept and the fact that the exact embodiment of the concept has yet to be determined, the infrastructure managed category best fits the concept we describe in this report. However, there have been many instances of generalizations made about this and other categories that may not be applicable to this concept. As we have said, the CIMS concept is evolutionary and seeks at each stage of deployment to fully utilize the existing resources on the vehicles and the infrastructure. Therefore, the concept may reside in more than one category at various stages of its evolution.

Key areas to note are the location of sensory equipment and the level of control. The initial sensory equipment resides exclusively on the vehicle. The vehicle will provide non-cooperative obstacle detection and warning. In some situations the vehicle may provide some non-cooperative obstacle avoidance through braking alone. As time progresses the cooperative ultra-wideband sensor can provide additional information and coordination. In addition, this will allow for exchange of information between the vehicle and roadside to provide lane keeping. The infrastructure participation in this process at early stages will be limited. However, as time advances the infrastructure will provide a greater degree of coordination between vehicles and finally manage the intervehicle spacing in a global sense. The high rate regulation control will still reside on the vehicle based upon the onboard sensory information.

2.2 Separation Policy

The separation policy planned for the CIMS concept is neither free agent or platooning, but, contains some of the characteristics of both. (The separation policy is described in detail in the section on management and spacing strategy.) As described, the separation policy is at a later stage of deployment. The system is highly coordinated, yet, each agent seeks to maximize its safety. Since the vehicles are tied
into the infrastructure they have access to the sensory data of all the vehicles in the region, as well as, site specific information provided from the infrastructure. The intervehicle spacing is dynamic based upon real time road conditions, relative vehicle dynamics and measured uncertainties. **The system separation is designed to never have a collision between vehicles.** In fact, during non-capacity operation the separation between vehicles increases further reducing the cumulative probability of an incident. Increases in highway capacity are made possible through reduced reaction time and adaptive spacing based upon pairwise vehicle dynamics comparisons. Later techniques such as adaptive segregation of vehicles can further increase the throughput. (Analysis shows capacities of 6000 to 8000 vehicles/lane/hour are possible. See the throughput analysis section for more details.) The potential field separation policy is very fluid and flexible in its design and can be adapted to a wide range of operational scenarios. It should be noted that the separation policy used is not a one dimensional solution. It simultaneously uses lateral and longitudinal movements to adapt to a given situation. For example, if a front vehicle is stopping rapidly then the following vehicles will take the path of least resistance including changing lanes if necessary. However, the spacing used in the system will allow all vehicles to come to a full stop at maximum braking without colliding.

### 2.3 Mixing of AHS and Non-AHS Vehicles

Due to our phased deployment strategy AHS vehicles will be capable of full mixing at any stage of the game. Even in later dedicated lane scenarios, the AHS vehicles will be able to operate with a manual vehicle in the dedicated lanes. This situation would only reduce local capabilities of that lane to the mixed mode case. If only safety and capacity were at issue then there would not be a need for dedicated lanes. (See the throughput analysis for reasoning.) However, for reduced trip time during non-capacity periods there may be advantages to dedicated lanes. However, dedicated lanes will not be seen until later stages of deployment when significant percentages of vehicles are AHS capable. In most cases no barriers will be required since whole roadways will be redesignated as AHS only roads. The remainder of the highways will be fully mixed. Again, a rogue non-AHS vehicle in a designated AHS roadway would not effect the safety of the system.

### 2.4 Mixing of Vehicle Classes in a Lane

Operationally, we see no way to separate cars and trucks on different roads when AHS is deployed. Instead our separation policy takes into account the wide range of vehicle dynamics differences between cars and trucks and adapts to them in much
the same way a human would, only faster. However, there are techniques to segregate
the vehicle classes adaptively over the existing highway real estate. The more agile
vehicles can be given a tendency towards the left most lanes and the more bulky
vehicles can be given a tendency towards the right most lanes. In this way the capacity
can be increased slightly.

2.5 Entry/Exit

The CIMS concept requires no special entry or exit. Any AHS equipped vehicle
within range of the local roadside communications equipment will have a link
established whether they are in automated mode or not. Vehicles enter automation
much the way we enter cruise control currently. Users can exit automation at any time
by regaining control of the steering or braking. Automatic safety monitoring will be
conducted to monitor the drivers ability to regain control. Most of this will be transparent
to the driver and will reduce as the driver proves reliable and the event was not
determined to be inadvertent. Any roadway that increases its capacity either through
conventional approaches such as adding lanes or through AHS will need to expand the
entry exit points to accept the higher capacities. Since the CIMS approach will
gradually increase capacity as more AHS vehicles are purchased then the modification
of the entry and exit points can be incorporated into the transportation planning process.

2.6 Obstacle Detection and Avoidance

There are cooperative obstacles (other cars, the roadway, fixed objects, etc.) and
there are non-cooperative obstacles (pedestrians, animals, fallen objects, etc.) that the
AHS vehicle must detect and avoid. Obstacle detection and avoidance evolves with the
CIMS concept. Early systems have obstacle detection and warning onboard the
vehicle. Some vehicle systems may have obstacle avoidance through braking alone.
As the CIMS concept progresses then the infrastructure assists in co-operative obstacle
detection and begins to carryout two dimensional obstacle avoidance. The sensory
equipment on the infrastructure is very inexpensive and does not significantly contribute
to the infrastructure costs. Another advantage is that once an object has been detected
by one vehicle the information is shared with all the other vehicles which makes
subsequent detection easier.
3.0 ULTRA-WIDEBAND TECHNOLOGY DESCRIPTION

3.1 INTRODUCTION

Ultra-wideband technology is a new field of communications and radar that uses ultra-short pulses of energy and complex pulse trains for location and communication. Ultra-wideband signals are characterized by the ratio of their bandwidth to their center frequency. Normal narrowband signals have bandwidth-to-center-frequency ratios that are 0.01 or less. Wideband and spread spectrum signals have bandwidth-to-center-frequency ratios that are 0.01 to 0.25. However, ultra-wideband signals have bandwidth-to-center-frequency ratios that are 0.25 to 2.0. Since the bandwidth is so large these signals lose their sinusoidal nature and take on a whole new set of properties. An ultra-wideband signal is produced by generating an ultra-short pulse that is in many cases less than a nanosecond in duration. This makes the pulse duration on the same order as the RF cycle. To some, the pulses are so different than conventional RF that they are referred to as non-sinusoidal impulse technology. However, without some kind of variation in the signal it cannot be radiated from an antenna. Work is currently underway to develop a large current radiator that will not require oscillations.

In addition to the short duration pulses, these devices can be made with very high pulse repetition frequencies (prf). The pulses can be repeated on the order of microseconds. With very fine variations of the spacings of these trains of pulses, sophisticated messages can be communicated with the device. With correlation technology, a significant quantity of information can be transmitted. Therefore, these devices can be joined together to communicate as well as co-locate each other.

With current technology, these capabilities are possible with solid state electronics. Low cost chips can be made to perform a wide range of applications. UWB offers accurate location and sophisticated communication at a very low price.

3.2 FEATURES OF UWB TECHNOLOGY

3.2.1 Range Finding

The initial intended application for UWB technology was for range finding. UWB has been used for many years to measure water content and depth in ground probing devices. The wideband nature of the signal allows it to penetrate many solids with various degrees of penetration. Water and metals offer the greatest reflection for these signals. The short pulses allow the devices to give location accuracies of better than a centimeter over several meters of range.
When it was discovered that similar pulses could be generated with solid state devices to propagate over open space the possibilities expanded significantly. Many military applications opened up in a desire to obtain better accuracies over longer ranges with less power. UWB chips offer all these advantages. To obtain centimeter accuracies with conventional techniques requires at least millimeter wave transmitters. However, the atmospheric absorption at those frequencies are much higher and cause the signal to attenuate much more rapidly. The short duty cycle of the UWB pulse makes the average power of the device very low. The only limitation is being able to generate a strong enough pulse to obtain the ranges that are of interest. The existing chip technology can get sub-centimeter accuracies with ranges in the tens of feet with hundreds of feet ranges possible with correlation integration. (1) These devices use microwatts of power. With cooperative ranging, difference in arrival times of 50 picoseconds or less are possible yielding accuracies of a fraction of a centimeter. With non-chip or breadboard technology even better performance has been shown. Miliwatts of power have enabled ranges of a kilometer or better. Research is attempting to increase the upper bounds of chip technology and expand its capabilities.

3.2.2 Multiple Access Communications

A number of vendors are developing UWB devices that are capable of multiple access communications. A time hopping scheme has been developed to vary the timing of the pulses within a pulse train to encode information into the transmission. (2) This analysis shows the feasibility of operating a large number of simultaneous channels with this technology. The high pulse resolution provides a natural ability to reject multipath transmissions from cars, buildings, bridges, etc. Path differences of greater than 4 cm are easily rejected with UWB technology. Pulson Communications has demonstrated data transmission rates of megabits per second over ranges of just a few meters to multiple kilometers. (3) One of their tests showed transmission of 125 kbps at a range in excess of 7 km with a raw BER of 10^{-3}. The effective isotropic radiated power was below 100 milliwatts.

The correlation capabilities of UWB technology are enormous. The system could be used in a warehouse setting to monitor the individual packages. If a chip were placed on each package in the warehouse and there were a million packages, the UWB device would be able to precisely locate any one package. In a crowded traffic environment this form of signal separation is vital.

3.2.3 Interoperability
A key area to the success of the UWB device is its ability to operate in a crowded RF environment and not interfere with or be interfered with by other narrowband communications or other similar devices. The communications for the UWB device is carried out by a train of sub-nanosecond pulses separated by less than a microsecond in some cases. In order to prevent these train of pulses from interfering with narrowband communications the timing of the pulses will be varied with a pseudo-random code. The pseudo-random code serves to spread the pulse train energy over the broad spectrum so that spikes will not form. Many unique pseudo-random codes can be generated based upon the size of the pulse train and the number of unique spacings that can be obtained between pulses. This allows the opportunity to channelize a large number of devices to operate in the same region without interference. Also, this provides the means for communicating a large amount of information with each device. As techniques are developed to better control the spacing of the pulses the amount of information that can be communicated will increase.

### 3.2.4 Spectrum Issues

As was said previously, each UWB pulse is spread over a very wide bandwidth. Also, a train of pulses will have pseudo-random codes applied to ensure that the energy remains spread over a broad band. However, since the UWB region of operation overlaps many licensed regions of spectrum there is a justified concern that ambient noise levels will be raised and signal-to-noise ratio will be degraded. This is something that must go through FCC and NTIA approval processes before any operational systems can be deployed. The arguments that UWB supporters will make are that the power levels of the devices are so low (microwatts) due to their low duty cycle (~0.1%) and that the energy is spread over GHz of bandwidth. (A 1 GHz UWB signal would be 13 dB down from a similar 50 MHz signal.) Therefore, while there is potential for interference, this interference would only be significant within a few feet of the device. Opponents will argue that if these devices are allowed then much higher power UWB devices could be made, especially for military applications. Also, these devices could become very popular for a large number of applications and pose a concern due to their numbers.

While both sides have valid concerns there is quite a bit of momentum for these devices. Contacts at FCC have indicated that a ruling on these devices is possible in the coming years and that the FCC is likely to modify Part 15 devices to include UWB with some power limitations.

### 3.3 BACKGROUND
There are a number of efforts across the country to develop UWB into marketable devices. The low cost and the wide range of applications make the likelihood of UWB products becoming commonplace very high. The following are some current efforts that are underway:

Some would say that the founder of non-sinusoidal impulse technology was Dr. Henning Harmuth. He was with Catholic University in Washington, D.C. for many years until he retired a few years ago. Many of the original papers like (4) on UWB technology were penned by Dr. Harmuth. He is still working on his own with researchers from Russia to develop a large current device to make UWB devices capable of transmitting powers on the order of watts or greater.

Merrill Skolnik, known to many by his industry defining Radar Handbook, is still the head of radar for the Naval Research Lab. In about 1980 he became interested in UWB radar for military applications. In addition to authoring papers on the subject (5) he has pursued UWB as a personal area of interest. What progress has been made in military circles is probably classified, but indications are that work continues.

In 1993 former Colonel James Taylor edited a compilation of works to publish the first UWB Radar book. (6) Top researchers in the field from many universities and corporations all contributed to the book. Mr. Taylor currently is seeking to publish a second book on the applications of UWB technology.

Lawrence Livermore Labs made quite a few ripples in the commercial sensor industry when it announced last year that it had successfully completed development of its radar on a chip. They are seeking to sell non-exclusive licenses to the technology for any application for $100,000 each. They have released specifications for a wide range of chips with a wide array of applications. The specifications are included in the Appendix. (1) They have listed potential applications of medical; speech; security; energy conservation; residential, commercial and industrial automation; transportation; entertainment; material evaluation; tools; communications; underground detection; buried mine and ordnance detection; military; and a radar camera to name a few. The current devices are listed as costing about $10 with sufficient production quantities. With a cost this low devices like IR sensors and ultra sonic sensors definitely have some competition.

Some of the most advanced work being done currently on cooperative UWB location and communication has been done by Aetherwire & Location, Inc. based in California. With ARPA funds and venture capital they are almost ready to release a chip that can co-locate other chips with centimeter accuracy as well as conduct communication over the device. These device will be capable of much longer ranges than the Lawrence Livermore devices by using cooperative ranging and a one way
travel path. Also, they have implemented a sophisticated front end to carry out a large amount of correlation to further extend the range capabilities of the system. Indications from the company are that the devices can be made for $20 in quantity. As the system is released more information will be made available to the public.

Pulson Communications is a small company that has a number of patents on UWB technology as it related to communications. They have shown breadboard type demonstrations of the ability of UWB to communicate over long ranges. (3) One demonstration showed sending music over a link separated by several kilometers. Also, they have worked with Professor R. A. Scholtz from the University of Southern California to show the multiple access communications capabilities of UWB technology. (2) Included in the Appendix is a brief description of Ultra-wideband technology prepared by Pulson Communications. The description provides a good tutorial on the basics of ultra-wideband transmission, generation and application.

At last years ITS America Annual meeting authors from the Virginia Tech Center for Transportation Research (CTR) published a paper on the use of Ultra-wideband devices for an Cooperative Infrastructure Managed Automated Highway System. (7)

3.4 ITS APPLICATIONS OF UWB TECHNOLOGY

3.4.1 Automatic Vehicle Identification (AVI)

Existing automatic vehicle identification systems use wireless technologies to extract a vehicle ID from a vehicle passing through a beam. Many of these systems are narrowband systems operating around 902 MHz or 2.4 GHz. These devices are used in both highway and rail systems to identify vehicles passing a specific site. The processing they employ is complex in order to prevent mis-identification from any one of a number of interference sources. Also, transportation agencies deploying these systems have desired to make these devices readable and writeable to allow for future applications.

The UWB device would easily be able to carryout the function of these AVI devices. Their low susceptibility to interference, low power requirements, low cost, location capability, and correlation capability not only make them ideal for this application but even better for future applications.

As said previously, the UWB device can easily reject sources of interference. Multipath is not a problem because of the short pulse resolution. The correlator rejects interference from other UWB devices and sources of narrowband interference are reduced by 13 dB or greater. Also, the location capability of the system allows spatial
interference rejection, as well as the ability to track the device from site to site. This will provide accurate link travel time estimates for the probe vehicles with these devices and an ability to continuously track vehicles with sufficient roadside receivers. If all cars were equipped with a UWB device then the Traffic Managers would be able to carry out dynamic traffic assignment at a microscopic level.

3.4.2 Advanced Traveler Information Systems (ATIS)

Not only could these devices be used for vehicle to roadside communications, but they can be used for roadside to vehicle communications, as well. The toll devices can receive from the roadside the exact amount to be debited from the AVI users account to give the user more confidence in the system. Also, a wide range to traveler information can be provided to the users. Devices with a simple LCD display or a simulated voice could inform travelers of coming traffic jams, dangerous road conditions, or where the available parking spaces are located in a central business district. The low cost and wide bandwidth of information that can be conveyed with the devices makes them attractive candidates for site specific forms of traveler information. Their wide range of uses makes deployability more feasible.

3.4.3 Advanced Traffic Management Systems (ATMS)

As said previously, these devices can be used to effectively measure link travel time from one point to another. The vehicle ID can be extracted with a vehicle equipped with the device and later segments of the roadway can look for that ID to determine the time needed to traverse the link. Other applications are necessary to achieve a sufficient number of probe vehicles to statistically represent the activities on any one portion of roadway. With enough roadside devices the exact track of the vehicle can be monitored throughout its trip for a better indication of a specific location of an incident. Lane changes and decelerations can be monitored to give more information to the traffic management system.

3.4.4 Transportation Planning

The Origin Destination (OD) matrix is a valuable tool in transportation planning. These devices can, also, be used in an OD matrix collection project to effectively track a percentage of probe vehicles distributed through the system. The spending of millions of dollars of construction hinges on the accurate modeling of the traffic within a region. Often only vehicle counts are used to estimate OD matrix values. Exact OD paths
would be a much more reliable source of information provided a sufficient number of probe vehicles were deployed. In the past this has been done through traveler interviews. Interviews are costly and time consuming. Randomly equipping vehicles in a region with a UWB device or using devices already deployed for AVI or some other application is a cost effective way to collect accurate OD information.

There are a number of traffic surveillance devices deployed for counting traffic flows and monitoring traffic activities. Most of these devices have been inductive loops imbedded in the roadway. However, the high cost of maintaining these systems have led to the development of a number of new technologies both in the road and above the road. UWB offers a possible replacement of loops by its ability to penetrate solids, its ability to do rangefinding, its low cost, and its communications capability. These devices can be imbedded in the pavement and still monitor the presence of a vehicle above. A single chip can be imbedded an inch or so in a pavement and still be able get the reflection of a metallic object a few feet above the roadway. Also, the device could communicate counts to a roadside site periodically.

### 3.4.5 Concealed Detectors

Other forms of concealed detectors can be used in ITS applications. One big concern with deployment of technology is making the technology vandal proof. Many devices in the open are subject to vandalism and other forms of environmental deterioration. The ability of UWB to penetrate concrete and drywall make its application in high foot traffic areas more reasonable. Raytheon is looking at the UWB technology as a possible sensor technology for determining space availability in the Med Tech Corridor operational test in Johnson City, TN. The exact extent of penetration for different substances and the effect changing mediums on the signal must have further research before a device can be developed.

### 3.4.6 Ground Probing

The oldest use of UWB technology is for ground probing ranging. Traditionally this was used for detecting metallic objects like mines and ordnance. However, it can be just as effective in measuring depths of pavement layers and water pockets. This ability can be used to monitor the life of pavement and estimate the frequency and costs of repairs and resurfacing. Dr. Al-Qadi from the Civil Engineering Dept. at Virginia Tech is currently researching this area. The technology offers the potential to save millions of dollars in highway maintenance costs.
3.4.7 Collision Avoidance

An obvious ITS application of the MIR chip from Lawrence Livermore Labs is that of collision avoidance. The current chips have perfect specifications for finding the range to an object near a car. The detection range available now can be used for driver warning while backing the vehicle as well as blind spot detection. Future chips can have ranges capable of warning of forward objects. Again, the low cost make warning systems on the vehicle an affordable aftermarket accessory for the automobile manufactures.

3.4.8 Automated Highway Systems (AHS)

AHS was the application area that brought researchers here at the CTR into ultra-wideband technology. CTR researchers were looking for a technology that could provide the centimeter accuracies required to safely manage the vehicles, update rates that would allow a system to respond orders of magnitude faster than a human driver, and an ability to communicate between vehicles and the roadside. Frequencies above 40 GHz were the first to be looked at in order to achieve the desired bandwidths. However, atmospheric absorption and the cost of devices in this frequency range limit the usefulness of such a system. The UWB technology was first noticed in its use in impulse radar, but a cooperative communications system was also needed. Then it was noticed that there was an ARPA project being developed to use ultra-wideband signals for location and communication. This seemed to be the answer. Not only could this device get centimeter accuracies, but it also could communicate information and used solid state electronics. It was later found out that numerous other projects were developing aspects of UWB and that it was a mature technology. At last years ITS America annual meeting authors from the CTR published a paper that described one way to apply UWB technology to AHS. (7)

The UWB technology can be used for a wide range of AHS concepts and can be used, through sensor fusion, with a wide range of other sensor technologies. Almost all AHS concepts have some need for vehicle to vehicle or vehicle to roadside communications or for both. Following is a discussion of the application of UWB to these to areas.

3.4.8.1 Vehicle to Vehicle Communications
A number of AHS concepts have suggested using some form of vehicle to vehicle communications to stabilize the control of vehicles within a platoon. If vehicles within a platoon were informed by the head of a platoon when it planned on initiating a maneuver, the controller on the following vehicles could begin responding sooner to the maneuver. The head vehicle could provide both its intended velocity and acceleration, as well as, passively provide its location. This would allow for a greater stability, in effect closing the loop on the system. However, finding a system that would not become crowded, could provide reliable point to point communications, and not need line of sight is a difficult task. The UWB technology could provide the correlation capability to uniquely identify signals, reject interference, and see through objects. In addition, the location capability can be used along with other sensors to determine relative headway, velocity, acceleration, jerk, etc.

3.4.8.2 Roadside to Vehicle Communications

In many AHS concepts some form of advisory signal is transmitted from the roadside to the vehicles. At one extreme, this communications can be used to set a desired vehicle speed, desired headway, desired platoon size, etc. At the other extreme, this can be used in the regulatory control loop to control each vehicle actuators. Regardless of whether megabytes per second or bytes per second are to be communicated, it is within the capabilities of the UWB device to serve this purpose. Again, if the vehicles would like to use wayside markers to control their path or if the roadside determines the location of all the vehicles, the dual use of the technology can benefit any AHS approach.

The CIMS concept can effectively use the UWB device to simultaneously locate each of the vehicles in a section of roadway and communicate with those vehicles.

3.5 CONCLUSIONS

Ultra-wideband communications and radar location is an exciting new technology with a wide range of application areas. ITS is an exciting range of applications looking for the right technology, and UWB technology does offer some interesting possibilities for a number of ITS applications. Those developing various ITS applications should explore the UWB technology for their transportation needs. FCC rulings and large scale production of UWB devices will make the technology more popular in years to come. It is not unreasonable to see a day where every car and every mile of highway are equipped with at least one UWB device.
4.0 MANAGEMENT AND SPACING STRATEGY
4.1. INTRODUCTION

This section describes the preliminary control design for the Cooperative Infrastructure Managed System (CIMS) concept for Automated Highway Systems (AHS). This control design is based on emphasizing safety in platoon formation and on semi global optimization. The intelligence is distributed among the infrastructure and the vehicles, with infrastructure supervising the overall behavior.

CIMS is a flexible concept of infrastructure managed AHS, where various degrees of control could be asserted by the infrastructure depending on the particular design. The concept also is evolutionary in the sense that the degree of control would evolve as time progresses in the deployment of AHS. This paper discusses just one specific control design which could be used in CIMS.

4.2. SYSTEM DESCRIPTION

The CIMS control performs three distinct tasks: estimation of the decoupled, linearized and reduced vehicle/road dynamics, solution of potential field equilibrium, and production of the control commands. This structure is shown in Figure 1.

![Figure 1: CIMS Tasks](image)

4.3 ESTIMATION OF THE DECOUPLED, LINEARIZED AND REDUCED VEHICLE/ROAD DYNAMICS

The response of a vehicle to an input actuation command (throttle, brakes and steering) is dependent upon the dynamics of the vehicle and the dynamics of the
interaction of the vehicle with the road surface and the environment, such as wind. The dynamics are highly nonlinear, time varying, and contain uncertainties [1-9]. In this approach, these dynamics are first decoupled into longitudinal and lateral dynamics. Then those dynamics are linearized about an operating point, and the Linear Time Invariant (model) thus produced is written in a transfer function form, with poles and zeroes. For safety purposes we are interested in the slowest poles of the system, for they characterize the response of the system. After looking at the transfer function of the system, we obtain a reduced order model, which we use in estimation utilizing the real time input output data available to the infrastructure.

4.3.1 System Dynamics

Free body diagram of the vehicle model is shown in Figure 2. The nonlinear bicycle model of the vehicle, described here, is adopted from Taheri [1]. This model has five degrees of freedom: longitudinal and lateral velocities, yaw rate, and rotational velocities for the front and rear wheels. Although this model is described for the acceleration case only, it can be easily modified for the deceleration case. Since, Taheri and Law's description in [1] is concise and suits for the purpose of the present study, Appendix A in [1] is inserted below, with the addition of wind disturbance.

![Figure 2 Schematic diagram of the vehicle model for longitudinal and lateral control](image)
The lateral components of the forces of the roads on the tires are $F_{yf}$ and $F_{yr}$, the longitudinal components are $F_{xf}$ and $F_{xr}$, where the f and r subscripts refer to front and rear, respectively. The longitudinal wind thrust is $F_{wx}$, and the lateral wind thrust is $F_{wy}$. The effects of camber and self aligning moments are neglected.

Summing the lateral forces along the body y axis leads to

$$F_{yf} \cos \delta_f + F_{xf} \sin \delta_f + F_{yr} \cos \delta_r + F_{xr} \sin \delta_r + F_{wy} = M_v (v_y + v_{xr})$$  \hspace{1cm} (1)$$

where, $M_v$ is the vehicle mass, $v_x$ and $v_y$ are the longitudinal and lateral components (on body axis) of the vehicle velocity, and $r$ is the yaw rate. The angles $\delta_f$ and $\delta_r$ are the front and rear wheel steering angles.

Summing the longitudinal forces along the body x axis gives

$$F_{xf} \cos \delta_f - F_{yf} \sin \delta_f + F_{xr} \cos \delta_r - F_{yr} \sin \delta_r - F_{wx} = M_v (v_x - v_{yr})$$  \hspace{1cm} (2)$$

The sum of the yaw moments about the center of gravity of the vehicle yields

$$L_f (F_{yf} \cos \delta_f + F_{xf} \sin \delta_f) - L_r (F_{yr} \cos \delta_r + F_{xr} \sin \delta_r) = I \dot{r}$$  \hspace{1cm} (3)$$

where, $I$ is the yaw moment of inertia of the vehicle.

For the front and rear wheels, the sum of torques about the axle results in

$$T_f - F_{xf} R_w = I_{wf} \dot{\omega}_f$$  \hspace{1cm} (4)$$

$$T_r - F_{xr} R_w = I_{wr} \dot{\omega}_r$$  \hspace{1cm} (5)$$

where, $\omega_f$ and $\omega_r$ are the angular velocities of the front and rear wheels, $I_{wf}$ is the inertia of the front wheels about the axle, $I_{wr}$ is the inertia of the rear wheels about the axle, $R_w$ is the wheel radius, and $T_f$ and $T_r$ are the applied torques for the front and rear, respectively.

The forces predicted by the tire model depend on the instantaneous value of the road's normal force on the tire. The normal forces change due to the longitudinal acceleration. For the model used, the effects of the suspension system are neglected. Thus, the normal forces on the front and rear tires are obtained by summing moments about the two contact patches. The resulting equations for the total normal reaction for the front tires, $N_f$, and the total normal reaction for the rear tires, $N_r$, are

$$N_f = \frac{L_f M_v g}{(L_f + L_r)}$$  \hspace{1cm} (6)$$
The nonlinear tire forces are evaluated using the slip angle and the longitudinal slip for each tire. The side slip angle \( \delta \), is the angle between the vehicle centerline and the velocity vector of the vehicle center of gravity. The tire slip angles are

\[
\alpha_f = \delta_f - \tan^{-1}\left[\frac{v_y + L_f r}{v_x}\right]
\]

and,

\[
\alpha_r = \delta_r - \tan^{-1}\left[\frac{v_y - L_r r}{v_x}\right]
\]

The values of the longitudinal slip are

\[
\lambda_f = \frac{\omega_f R_w - V_{wf}}{\omega_f R_w}
\]

\[
\lambda_r = \frac{\omega_r R_w - V_{wr}}{\omega_r R_w}
\]

where \( V_{wf} \) and \( V_{wr} \) are the longitudinal components of the velocity of the front and rear axles, respectively,

\[
V_{wf} = v_f \cos \alpha_f
\]

\[
V_{wr} = v_r \cos \alpha_r
\]

and the magnitudes of the velocities of the front and rear axles, \( v_f \) and \( v_r \) are

\[
v_f = \left[\left(\frac{v_y + L_f r}{v_x}\right)^2 + v_x^2\right]^{1/2}
\]

\[
v_r = \left[\left(\frac{v_y - L_r r}{v_x}\right)^2 + v_x^2\right]^{1/2}
\]

When the characteristics of the tire (tire pressure, road and tire surface condition, temperature, etc.) are fixed, the traction and turning forces generated from the tire are solely determined by the tire slip angle and the wheel slip (tire slip ratio). The longitudinal tire adhesion coefficient is defined as the ratio of longitudinal tire force and the normal force on the same tire. Similarly, the lateral tire adhesion coefficient is defined as the ratio of the lateral tire force and the normal force on the same tire. These adhesion coefficients are nonlinear functions of slip angle and slip ratio. The longitudinal adhesion coefficient versus the slip ratio curve looks like a serpentine curve which gets flatter and flatter for increasing values of slip angle. On the other hand, the lateral adhesion coefficient versus the slip ratio curve resembles a Gaussian curve which gets flatter for decreasing slip angle values. Typical adhesion coefficients versus slip ratio curves are shown in Figure 3 for various slip angle values. Since the adhesion coefficients are functions of slip ratio and slip angle, they can be represented by three dimensional curves. Figure 4 shows the longitudinal adhesion coefficient on the z-axis,
while slip ratio and slip angle are plotted on the x and y axes, respectively. Figure 5 shows the lateral adhesion coefficient on the z-axis, while slip ratio and slip angle are on the x and y axes, respectively. These plots were drawn by using approximate analytical functions for the adhesion coefficient versus wheel slip curves. A mathematical serpentine function was used for the longitudinal adhesion coefficient and a Gaussian function was used for lateral adhesion.

Figure 3  Longitudinal and lateral adhesion coefficient versus slip ratio and slip angle
Figure 4  Longitudinal adhesion coefficient versus slip ratio and slip angle
4.3.2 Decoupled Longitudinal Vehicle Dynamics

In this section, the decoupled longitudinal vehicle dynamics are derived. The vehicle model identifies five state variables and two input variables to complete the nominal model. Three of the state variables in this model are associated with one-wheel rotational dynamics and linear vehicle dynamics and the other two are associated with the engine and actuator dynamics. The wheel dynamics and vehicle dynamics are derived by applying Newton’s law. The engine dynamics are a simplified model of a continuous four stroke spark ignition engine and the actuator dynamics are derived from the braking system and the throttle characteristics of the vehicle. These dynamics are decoupled form of the dynamics of section 2.1.1.

4.3.2.1 Wheel dynamics

The dynamic equation for the angular motion of the wheel is

$$\dot{\omega}_w = \frac{\left[ T_e - T_b - R_w (F_t - F_w) \right]}{J_w} \tag{16}$$

where $J_w$ is the moment of inertia of the wheel, $\omega_w$ is the angular velocity of the wheel, the over dot indicates differentiation with respect to time, and the other quantities are as defined in Table 1. The total torque acting on the wheel divided by the moment of inertia of the wheel equals the wheel angular acceleration. The total torque consists of shaft torque from the engine, which is opposed by the brake torque and the torque components due to the tire tractive force and the wheel viscous friction force. The wheel viscous friction force is the friction force, which is a function of the wheel angular velocity, developed on the tire-road contact surface. The tractive force developed on the tire-road contact surface is dependent on the wheel slip, the difference between the vehicle speed and the wheel speed, normalized by the vehicle speed for braking and the wheel speed for acceleration. The engine torque and the effective moment of inertia of the driving wheel depend on the transmission gear shifts.

| $R_w$ | Radius of the wheel |
Table 1  Wheel Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_v )</td>
<td>Normal reaction force from the ground</td>
</tr>
<tr>
<td>( T_e )</td>
<td>Shaft torque from the engine</td>
</tr>
<tr>
<td>( T_b )</td>
<td>Brake torque</td>
</tr>
<tr>
<td>( F_t )</td>
<td>Tractive force</td>
</tr>
<tr>
<td>( F_w )</td>
<td>Wheel viscous friction</td>
</tr>
</tbody>
</table>

Applying a driving torque or a braking torque to a pneumatic tire produces tractive force at the tire-ground contact patch\cite{2-4}. The driving torque produces compression at the tire tread in front of and within the contact patch. Consequently, the tire travels less distance than it would if it were free rolling. In the same way, when a braking torque is applied, it produces tension at the tire tread within the contact patch and at the front. Because of this tension, the tire travels more distance than it would if it were free rolling. This phenomenon is referred to as the deformation slip or wheel slip. The adhesion coefficient \( m(l) \) is a function of wheel slip. Mathematically, wheel slip is defined as

\[
\lambda = \frac{\omega_w - \omega_v}{\omega_v}
\]

where, \( \omega_v \) is vehicle angular velocity defined as

\[
\omega_v = \frac{V}{R_w}
\]

which is equal to the linear vehicle velocity, \( V \), divided by the radius of the wheel. The variable \( \omega \) is defined as

\[
\omega = \max(\omega_w, \omega_v) = \begin{cases} 
\omega_w & \text{for } \omega_w \geq \omega_v \\
\omega_v & \text{for } \omega_w < \omega_v 
\end{cases}
\]

which is the maximum of vehicle angular velocity and wheel angular velocity.

The tire tractive force is given by

\[
F_t = \mu(\lambda) N_v
\]

where the normal tire force \( N_v \), depends on vehicle parameters such as the mass of the vehicle, location of the center of gravity of the vehicle, and the steering and suspension dynamics. The adhesion coefficient, which is the ratio between the tractive force and
the normal load, depends on the road-tire conditions and the value of the wheel slip[2-7]. For various road conditions, the curves have different peak values and slopes, as shown in Figure 6. The adhesion coefficient-slip characteristics are influenced by operational parameters like speed and vertical load. The average peak values for various road surface conditions are shown in Table 2.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Average Peak Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt and concrete (dry)</td>
<td>0.8-0.9</td>
</tr>
<tr>
<td>Asphalt (wet)</td>
<td>0.5-0.6</td>
</tr>
<tr>
<td>Concrete (wet)</td>
<td>0.8</td>
</tr>
<tr>
<td>Earth road (dry)</td>
<td>0.68</td>
</tr>
<tr>
<td>Earth road (wet)</td>
<td>0.55</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.6</td>
</tr>
<tr>
<td>Ice</td>
<td>0.1</td>
</tr>
<tr>
<td>Snow (hard packed)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Table 2 Average peak values for friction coefficient.**

The model for wheel dynamics is shown in Figure 7. The parameters in this figure are defined in Table 1. The figure shows the acceleration case for which the tractive force and wheel viscous friction force are directed toward the motion. The wheel is rotating in the clockwise motion and slipping against the ground, i.e. $\omega_w \geq \omega_v$. The slipping produces the tractive force towards right causing the vehicle to accelerate towards right. In the case of deceleration, the wheel still rotates in the clockwise motion but skids against the ground, i.e. $\omega_w < \omega_v$. The skidding produces the tractive force towards left causing the vehicle to decelerate.
4.3.2.2 Vehicle dynamics

The vehicle model considered for the system dynamics is shown in Figure 8. The parameters in the figure are defined as:

\( F_v \): Wind drag force (function of vehicle velocity)

\( M_v \): Vehicle mass

\( N_w \): Number of driving wheels (during acceleration) or the total number of wheels (during braking).

The linear acceleration of the vehicle is governed by the tractive forces from the wheels and the aerodynamic friction force. The tractive force \( F_t \), is the average friction force of the driving wheels for acceleration and the average friction force of all wheels
for deceleration. The dynamic equation for the vehicle motion is

\[ \ddot{V} = \left[ N_w F_t - F_v \right] / M_v \]  

(21)

The linear acceleration of the vehicle is equal to the difference between the total tractive force available at the tire-road contact and the aerodynamic drag on the vehicle, divided by the mass of the vehicle. The total tractive force is equal to the product of the average friction force, \( F_t \) and the number of relevant wheels, \( N_w \). The aerodynamic drag is a nonlinear function of the vehicle velocity and is highly dependent on weather conditions. It is usually proportional to the square of the vehicle velocity.

4.3.2.3 Engine dynamics

The engine is a self-contained power unit which converts the heat energy of the fuel into mechanical energy for moving the vehicle. In the IC (Internal Combustion) engine, an air-fuel mixture is introduced into a closed cylinder where it is compressed and then ignited. The combustion of the fuel causes a rapid rise in cylinder pressure which is converted to useful mechanical energy by the piston and crank-shaft. The four strokes of the IC engine are shown in fig. The four-stroke sequence is repeated continually, with power delivered to the crank-shaft on only one of the four strokes-the combustion stroke. Figure 9 shown below is adapted from reference 14.

![Four stroke engine diagram](image-url)

Figure 9. Four stroke engine

The fuel stored in the fuel tank is fed into the carburetor through a pump. The carburetor mixes the fuel and filtered air, and the vaporized mixture is sent
into the inlet manifold. The throttle valve controls the amount of fuel-air mixture entering the inlet manifold, which then directs it into the cylinders. Typically, the air-fuel ratio, by mass, varies in the range 12:1 to 17:1. The throttle valve angle is controlled by the throttle pedal, which when at a vertical position, directs the full volume of the air-fuel mixture to produce maximum engine power.

The mass continuity equation for the inlet manifold is

\[ n\dot{Y}_a = n\dot{Y}_{ai} - n\dot{Y}_{ao} \]  \hspace{1cm} (22)

The mass flow rate of air from the carburetor into the inlet manifold through the throttle valve is

\[ n\dot{Y}_{ai} = k_1 TC(\alpha)f_1(P_M) \]  \hspace{1cm} (23)

The mass flow rate of air from the inlet manifold into the cylinder is

\[ n\dot{Y}_{ao} = f_2(m_a, \omega_e) \]  \hspace{1cm} (24)

where \( n\dot{Y}_{ai} \) and \( n\dot{Y}_{ao} \) are the mass flow rate into and out of the inlet manifold respectively, \( k_1 \) is a constant related to the geometry of the manifold, \( TC(\alpha) \) is an invertible throttle characteristic, \( f_1(P_M) \) is a non-linear function of the ratio of the pressure in the inlet manifold to the atmospheric pressure and \( f_2(m_a, \omega_e) \) is a function of the mass of air and the rotational speed of the engine. Combining (7), (8) and (9) we get

\[ n\dot{Y}_a = c_1 TC(\alpha) - c_2 \omega_e m_a \]  \hspace{1cm} (25)

where \( c_1 \) and \( c_2 \) are constants used to approximate the model.

### 4.3.2.4 Actuator Dynamics

The dynamics involved in the throttle actuators are very fast. Therefore, it has been assumed that there is no lag between the change in angle of the accelerator pedal and the corresponding angle change in the throttle valve mechanism. But, the modeling of the brake torque has not been done as simplistically as the throttle actuator. Instead, it has been modeled as a first-order lag model described by

\[ t\dot{Y}_b = t_1 t_b + t_2 t_{bc} \]  \hspace{1cm} (26)
where $t_b$ is the brake torque, $t_1$ and $t_2$ are constants that depend on the maximum brake torque time constant, and $t_{bc}$ is the commanded brake torque.

### 4.3.2.5 Combined system

The dynamic equations for the whole system can be written in state variable form by defining convenient state variables as follows:

\[
x_1 = \frac{V}{R_w} \tag{27}
\]
\[
x_2 = \omega_w \tag{28}
\]
\[
x_3 = s \tag{29}
\]
\[
x_4 = m_a \tag{30}
\]
\[
x_5 = t_b \tag{31}
\]

Here $s$ denotes the longitudinal distance of the vehicle from a fixed frame of reference. The dynamics of the combined system can be represented by

\[
\dot{x}_1 = -f_1(x_1) + b_1 \mu(\lambda) \tag{32}
\]
\[
\dot{x}_2 = -f_2(x_2) - b_2 \mu(\lambda) + b_3 T \tag{33}
\]
\[
\dot{x}_3 = x_1 \tag{34}
\]
\[
\dot{x}_4 = -c_2 x_2 x_3 + c_1 T C(\alpha) \tag{35}
\]
\[
\dot{x}_5 = t_1 x_5 + t_2 t_{bc} \tag{36}
\]

where

\[
T = t_e - t_b = c_3 x_4 - t_b \tag{37}
\]
\[
\lambda = (x_2 - x_1) / x \tag{38}
\]
\[
f_1'(x_1) = \frac{[F_v(R_w x_1)]}{(M_v R_w)} \tag{39}
\]
\[
b_1 = N_v N_w / (M_v R_w) \tag{40}
\]
\[
f_2'(x_2) = \frac{F_w(x_2)}{J_w} \tag{41}
\]
\[ b_2 = \frac{R_w N_v}{J_w} \]  \hspace{1cm} (42)
\[ b_3 = \frac{1}{J_w} \]  \hspace{1cm} (43)
\[ x = \max(x_1, x_2) \]  \hspace{1cm} (44)

### 4.3.3 Decoupled Linearized Longitudinal Vehicle Dynamics

A nonlinear lumped parameter dynamic system can be linearized about an operating point by performing the first order variation using Taylor's series approximation [10]. A system \( \dot{\mathbf{Y}} = f(\mathbf{x}, \mathbf{u}) \) can be linearized about the operating point \([\mathbf{x}_0, \mathbf{u}_0]\) by writing the first order variation as

\[
\delta \dot{\mathbf{Y}} = \frac{\partial}{\partial \mathbf{x}} f(\mathbf{x}, \mathbf{u}) \bigg|_{\mathbf{x}_0, \mathbf{u}_0} \delta \mathbf{x} + \frac{\partial}{\partial \mathbf{u}} f(\mathbf{x}, \mathbf{u}) \bigg|_{\mathbf{x}_0, \mathbf{u}_0} \delta \mathbf{u} \]  \hspace{1cm} (45)

This is a Linear Time Invariant (LTI) differential equation. By linearizing in the same fashion the decoupled longitudinal vehicle dynamics given by equations (32)-(36), we obtain the structure of the LTI as:

\[
\begin{bmatrix}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4 \\
    x_5
\end{bmatrix}
= \begin{bmatrix}
    0 & 1 & 0 & 0 & 0 \\
    0 & a_{22} & a_{23} & 0 & 0 \\
    0 & a_{32} & a_{33} & a_{34} & a_{35} \\
    0 & 0 & a_{43} & a_{44} & 0 \\
    0 & 0 & 0 & 0 & a_{55}
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4 \\
    x_5
\end{bmatrix}
+ \begin{bmatrix}
    0 \\
    0 \\
    0 \\
    b_{41} \\
    0
\end{bmatrix} \begin{bmatrix}
    TC \\
    t_{bc}
\end{bmatrix} \]  \hspace{1cm} (46)

### 4.3.4 Decoupled Linearized Lateral Vehicle Dynamics

The model for lateral control includes only the lateral and the yaw motions of the mass center of the vehicle. The derivation of the linearized model, described below, is adapted from the model used by Matsumoto and Tomizuka in [2]. For the sake of linearization, it is assumed that the steering angles are small, so that (1) and (3) can be replaced by

\[
\dot{v}_y = \frac{[F_{yf} + F_{xf} \delta_f + F_{yr} + F_{xr} \delta_r + F_{wy}] M_y - v_x r}{M_v} \]  \hspace{1cm} (47)
\[
\dot{r} = \frac{[L_f(F_{yf} + F_{xf} \delta_f) - L_r(F_{yr} + F_{xr} \delta_r)]}{I} \]  \hspace{1cm} (48)
The lateral tire forces \( F_{yf} \) and \( F_{yr} \) are functions of the lateral road-tire adhesion coefficients \( \mu_{yf} \) and \( \mu_{yr} \), respectively so that

\[
F_{yf} = \mu_{yf}N_f \tag{49}
\]
\[
F_{yr} = \mu_{yr}N_r \tag{50}
\]

Lateral road-tire friction is dependent on the road-tire condition and the slip ratio \( \lambda_f \) and \( \lambda_r \) as shown in Figure 3 and Figure 5. Furthermore, \( \mu_{yf} \) and \( \mu_{yr} \) are approximately proportional to the wheel slip angles \( \alpha_f \) and \( \alpha_r \), respectively. Thus, \( \mu_{yf} \) and \( \mu_{yr} \) can be described as

\[
\mu_f \approx f_f(\lambda_f)\alpha_f \tag{51}
\]
\[
\mu_r \approx f_r(\lambda_r)\alpha_r \tag{52}
\]

where, \( f_f \) and \( f_r \) are nonlinear functions which depend on the road-tire condition. Hence, the lateral tire forces can be rewritten as

\[
F_{yf} = C_f\alpha_f \tag{53}
\]
\[
F_{yr} = C_r\alpha_r \tag{54}
\]

with the cornering stiffnesses originally defined as [3]

\[
C_s = \frac{ZF_y}{Z\alpha}|_{\alpha = 0} \tag{55}
\]

given here by

\[
C_f = f_f(\lambda_f)N_f \tag{56}
\]
\[
C_r = f_r(\lambda_r)N_r \tag{57}
\]

For linearization, the slip angles defined by (8) and (9) can be approximated as

\[
\alpha_f = \delta_f - \left[ \frac{(v_y + L_f r)}{v_x} \right] \tag{58}
\]
\[
\alpha_r = \delta_r - \left[ \frac{(v_y - L_r r)}{v_x} \right] \tag{59}
\]

The lateral tire forces can now be written as

\[
F_{yf} = C_f(\delta_f - \left[ \frac{(v_y + L_f r)}{v_x} \right]) \tag{60}
\]
\[
F_{yr} = C_r(\delta_r - \left[ \frac{(v_y - L_r r)}{v_x} \right]) \tag{61}
\]
Substituting these in (16) and (17), we obtain the following linear lateral model of the vehicle.

\[
\frac{d}{dt} \begin{bmatrix} v_y \\ r \end{bmatrix} = A \begin{bmatrix} v_y \\ r \end{bmatrix} + B \begin{bmatrix} \delta_f \\ \delta_r \end{bmatrix}
\]

(62)

\[
A = \begin{bmatrix} \frac{-P_1}{M_v} & \frac{-P_2}{M_v} - v_x \\ \frac{-P_2}{I} & \frac{-P_3}{I} \end{bmatrix}
\]

\[
B = \begin{bmatrix} \frac{Q_f}{M_v} & \frac{Q_r}{M_v} \\ \frac{L_f Q_f}{I} & -\frac{L_r Q_r}{I} \end{bmatrix}
\]

where, \( P_1 \) and \( Q_i \) are

\[
P_1 = \frac{C_f + C_r}{v_x}, \quad P_2 = \frac{C_f L_f - C_r L_r}{v_x}, \quad P_3 = \frac{C_f L_f^2 + C_r L_r^2}{v_x}
\]

\[
Q_f = C_f + F_{xf}, \quad Q_r = C_r + F_{xr}
\]

If we consider only front wheel steering and take lateral deviation and yaw angles also as state variables, then we get

\[
\frac{d}{dt} \begin{bmatrix} y \\ v_y \\ r \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & c_{22} & c_{23} & c_{24} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} y \\ v_y \\ r \end{bmatrix} + \begin{bmatrix} 0 \\ b_2 \\ 0 \end{bmatrix} \delta
\]

(63)

**4.3.5 Transfer function representations**

The transfer functions from the throttle and brake inputs to the longitudinal positions are:

\[
\frac{X(s)}{TC(s)} = \frac{b_4 a_{32} a_{34} (s - a_{55})}{\det(sI - A_L)}
\]

(64)

\[
\frac{X(s)}{BP(s)} = \frac{b_5 a_{32} a_{34} (s - a_{44})}{\det(sI - A_L)}
\]

(65)

where
Similarly the transfer functions from the steering input to lateral deviation and yaw angle are:

\[
\frac{Y(s)}{\delta(s)} = \frac{b_2 s^2 + (b_4 c_{24} - b_2 c_{44}) s + b_4 a_{33} - b_2 a_{43}}{\det(sI - A_\ell)}
\]

\[
\frac{R(s)}{\delta(s)} = \frac{b_2 s^2 + (b_2 c_{42} - b_4 c_{22}) s}{\det(sI - A_\ell)}
\]

where

\[
A_\ell = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 \\
0 & c_{22} & c_{23} & c_{24} & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & c_{42} & c_{43} & c_{44} & 0 \\
\end{bmatrix}
\]

4.3.6 Reduced Order Models

In order to have an indication of safety, we are concerned with the time constant of the system. For that reason we use reduced order models for the system. The estimator then would estimate the parameters of the reduced order model from the input output data.

4.3.7 The Parameter Estimator

The parameter estimator essentially estimates the system parameters in order to calculate the real time response time of each car. The parameter is based on the transfer function representation of the reduced order linearized and decoupled longitudinal and lateral dynamics of the vehicles. The system is represented in linearly parametrizable form which is suitable for performing standard estimations like gradient, least square and least square with forgetting factor.
4.4 POTENTIAL FIELD VEHICLE SEPARATION POLICY

The application of artificial potential field to mobile robot path planning was first introduced by Khatib [14]. He stated the philosophy of the potential field approach as follows:

“The manipulator moves in a field of forces. The position to be reached is an attractive pole for the end effector and obstacles are repulsive surfaces for the manipulator parts.”

With this philosophy in mind, he developed the artificial potential field concept and applied for a real-time obstacle avoidance for manipulators and mobile robots. Once this field concept was introduced, it drew a great deal of attention from people in the field. Warren used this artificial field concept to plan the collision-free paths for multiple robots [15]. To do this, the robots are assigned priority. A path of the highest priority robot is planned to avoid the stationary obstacles first. Then, a trajectory for the next lower priority robot is planned so that it avoids both stationary obstacles and the higher priority robot which is treated as a moving obstacle. Tilove made an overview of the method of the artificial potential field, described the common variations in a unified framework and compared the performance of the different algorithms [16]. Chuang extended this potential field concept of three-dimensional workspace for path planning [17]. It was assumed that the workspace boundary is uniformly distributed with generalized charge. The potential at a distance from a point charge is inversely proportional to the distance to the power of an integer. He claimed that this approach completely eliminates the possibility of the collision between two objects. Masoud and Bayoumi extended this potential field concept to the Biharmonic potential fields which govern mechanical stress fields in homogeneous solids [18]. Keymeulen and Decuyper proposed a new method that generates a collision free-path from a vector field which is not necessarily the gradient of a potential function. Their approach consists of representing the robot’s work space as a pipe-system with a fluid pump installed at the robots’ initial position and an outlet at its destination. The robot is simulated as a fluid particle that moves through the pipe-system under the action of the pump [19]. Makita, Hagiwara and Nakagawa use this artificial potential field along with fuzzy rules to plan a collision-free path for a truck backing up problem [20]. Kitamura, Tanaka, Kishino and Yachida proposed that the robots and environments should be represented by using an octree without any distinction of movability of objects [21]. A potential field is generated for each cell of the octree. Thus, the potential field at any point in the environment is given by the maximum of the potentials due to individual cells. This prevents local maxima of the potential field from appearing in free space. Nam, Lee, and Ko proposed a unified method that incorporates the artificial potential field concept into view-time based motion planning, where the driving force is generated at every interval of the view-time. The view-time is defined as the time set from one sampling time instant to
Hennessey, Shankwitz and Donath proposed a 2-degree of freedom strategy based on the concept of a virtual bumper. Their approach is based on surrounding the perimeter of the vehicle with a sensor-based computer controlled bumper. As the bumper’s boundary is deflected, a virtual force proportional to the amount of deflection is generated. The vehicle controller responds to this virtual force in such a way as to return the bumper to its non-deflected state.

All this prior research has demonstrated the potential solution of collision-free path using the artificial potential field approach. All this previous work has motivated us to develop an artificial potential field approach to guide an automated vehicle with collision-free motion in our concept. The field will be generated by the infrastructure, with a field generator, for each vehicle and environment. The field generator uses the parameters from the estimator to generate fields for each vehicle. These fields in general will be nonlinear functions of these parameters. This field will be a dynamic, real-time field for each vehicle because it will be a function of the system dynamic parameters, the road-tire parameter, etc. The roadway and obstacles also generate fields as shown in Figure 10. When there is an emergency situation, this field will change in order to force the vehicle to respond in a particular way. The fields are generated so that the system is optimized for safety given the desired throughput and actual traffic. For instance, using the field generation and calculation, an initial configuration of Figure 11(a) will be converted to the one shown in Figure 11(b) which will be safer for emergency situations, and especially when there is not much traffic demand, this scenario will provide the same throughput also.

The artificial potential fields for generating the configurations for the vehicles are being developed. These fields should have the following properties:

1. The field function is continuous.

2. The strength of a field decreases as the distance to the object which generates that field increases. The strength of the field will also depend on other parameters. For example, the strength will depend on relative velocity so that a stopped vehicle will have a larger field strength than a moving vehicle.

3. Each vehicle will have a driving field to provide the desired velocity in the desired direction for that vehicle. This driving field will exert a force only on that vehicle in order to keep it moving forward. In other words, the vehicle will be affected by its own driving field, not by the other driving fields. This driving field can be overcome by the potential field of the obstacle, and thus the driving field will not drive a vehicle into an obstacle.

Initial analysis shows a nonlinear relationship based on ignoring vehicle dynamics and considering different deceleration capabilities of vehicles and different reaction times. The plots are shown in Figure 12.
The relationship is given by

\[ s_g = \frac{v_0^2(a_1 - a_2)}{2a_1a_2} + v_0 t_r \quad \text{for} \quad \frac{v_0}{a_1} \leq \frac{v_0}{a_2} + t_r \]

\[ s_g = \frac{t_r^2a_1a_2}{2(a_2 - a_1)} \quad \text{for} \quad \frac{v_0}{a_1} > \frac{v_0}{a_2} + t_r \]

where

\( s_g \) = safe gap

\( v_0 \) = initial velocity of both vehicles

\( t_r \) = reaction time of the second vehicle

\( a_1 \) = braking deceleration of the first vehicle

\( a_2 \) = braking deceleration of the second vehicle

Figure 10. Field Generation for a Scenario
Figure 11 (a) A constant spacing platoon (b) Spaced Vehicles Based on Relative Dynamics

Figure 12. Plots Showing Safegaps, Reaction Times, and Deceleration Rates

4.5 CONTROL COMMANDS

The commands for the longitudinal and lateral spacing of the vehicles are generated by solving the field equilibrium problem. The problem statement is: given an initial configuration, maximize the safety of the system by using minimum motion to...
produce the desired configuration state. These commands are then passed onto the vehicle controller, which processes them in its own feedback control to achieve the desired motion.

4.6. FUTURE RESEARCH

- Detailed development of the field generator and solver.
- Analysis and design of the outer infrastructure management loop and the vehicle control loop, which includes the effect of sampling time.
- Analysis and design which includes communication and sensing modeling.
- Detailed design of hybrid controllers and control of the degraded modes of operation in the layered architecture.
- Testing of the entire system in software (DYNAVIMTS), small scale hardware laboratory (FLASH), and full scale facility (Smart Road).
5.0 SYSTEM EVOLUTION

5.1 INTRODUCTION

Description of an evolutionary process that will end in a fully automated highway is a complex task. There are a large number of variables associated with this process. The process of building public knowledge of the system while maintaining public confidence is on its own a complex undertaking. In order for AHS to succeed, like any goal, it must be achievable and desirable. What we can do is to describe a potential scenario that is based upon observation of current trends and some assumptions about human nature.

It seems clear that the first implementation of AHS technologies will be in the form of Adaptive Cruise Control and Collision Warnings systems. These stand a good chance of acceptability since they are a relatively simple extension of current systems and can be made at a low cost to the user. While these systems will be key building blocks for future AHS implementation, they are a long way from "brain off" driving. Lateral control represents a major step towards AHS. Our belief is that initial lateral control will be a cruise control for the steering. This is the point we see the systems beginning to interact with the infrastructure. The infrastructure will not be the detailed distributed system required for full AHS, but, will provide cues to the vehicle to assist them in keeping in their lanes and preventing road run off’s. Deployment at this level will be based upon a system architecture that meets transportation agency needs while allowing for expansion for other services. For example, a DOT may deploy a series of infrastructure locators to drive unmanned maintenance vehicles, monitor traffic flows, provide travel information, provide in vehicle signing and provide electronic fare collection.

The next generation of cars manufactured could then begin to include a lane holding capability that potentially used a combination of infrastructure communications and onboard sensor information. When decisions begin to be made by the AHS system to manipulate vehicles relative to one another, such as lane changing, merging, passing, etc., the interaction with the infrastructure must become more sophisticated. The system then takes on command responsibility as well as liability.

At this level the system must be extremely robust and contain significantly more information and decision making capability than the human driver. Therefore, a fusion of all possible sensory information into a synchronized closed loop management system is desirable. As implied by this description we see mixed mode traffic as a strong likelihood until a significant percentage of the vehicles have reached the point of full AHS functionality. This form of evolution also gives the transportation agency time and resources to retrofit existing lanes. More than likely, initial highways to be instrumented
would be rural interstates connecting major cities. See the throughput analysis for a
detailed description of the rationale we used to arrive at some of these conclusions.

5.2 TRANSITION FROM CURRENT TECHNOLOGY

Automated Highway Systems (AHS) fact or fiction? The United States Congress in all its wisdom included in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 a provision to develop and prototype an AHS. Why in a time of shrinking budgets and growing National debt would our leaders spend taxpayers money on research that may seem to many like "Buck Rogers" type science fiction? The fact remains that we are reaching a crucial turning point for our nation's transportation system. The current infrastructure has begun to plateau in its ability to meet the operational requirements of highway transportation. This results in ever increasing congestion and increased safety risks. The previous solutions of building new roads and widening existing roads to adapt to the increasing flow demand can no longer be sustained. With the cost of a mile of urban freeway averaging $38 million, the prospect for building our way out of congestion is very dim. Also, Americans are beginning to realize that 40,000 lives per year is a steep price to pay for mobility. Safety belts and air bags are signs that Americans want to travel without the threat of death or serious injury looming over their heads. AHS offers the potential to increase safety, reduce congestion and improve the driving experience.

The idea of Automated Highways has been around for 30 years. What makes us think we can make AHS a reality now and not earlier? Yes, there have been strong AHS concepts developed for many years. However, not until this decade has the computational and communication equipment been available at a reasonable cost and size to accomplish the task.

The consensus in the AHS community is that AHS will evolve over a series of smaller steps in technology. Each step in technology will have its own benefits and be self sustaining. The final step to full automation will not be a dramatic leap, but, a logical outgrowth of previous development and deployment. Our vision of this evolution combines vehicle evolution with infrastructure evolution (1) (See Figure 1) The vision begins with modern cruise control and existing communications infrastructure, adds obstacle and headway warning and Automatic Vehicle Identification (AVI). After headway warning, vehicles will be equipped with automatic headway control and automatic braking or basically a "feet off" situation. Automatic headway control would work through the cruise control to adjust the throttle to maintain constant headways when traffic becomes too dense for normal cruise control. The individual driver will be able to adjust their headway to suit their comfort level. This can be referred to as
adaptive cruise control or intelligent cruise control. Automatic braking would automatically actuate the brakes when an obstacle is detected or vehicle headway changes rapidly. The detection would be performed by some form of forward looking sensor like the VORAD radar or a vision based sensor. While these features are being added to the vehicle the infrastructure will be expanding in its vehicle to roadside communications. Applications in ATIS, ATMS, APTS and cellular will desire more and more sophisticated vehicle location capabilities. In addition, the number of uses for vehicle to roadside communications will increase dramatically. The next step in evolution would be to provide lane departure warning or potential lane departure warning. This is a very attractive safety feature that could stand on its own given reasonable costs. Shortly behind this would be a lane holding feature added to the adaptive cruise feature. Automatic lane holding would allow the steering to be electronically actuated to keep the vehicle in the present lane. This feature would basically provide a "hands off"/"feet off" driving situation where the driver is still responsible for all command decisions in the vehicle and must be aware at all times of his surroundings. This step would either detect the lanes from the vehicle with onboard sensors, be provided with roadside reference data, or actually be given navigation commands from the roadside to maintain the lane. Because of the following steps of evolution we prefer the latter approach.
Until this point the driver has been in total control of the vehicle at all times. The driver has gained convenience and hopefully safety. The vehicles being automated have required nothing of the vehicles around them since the driver was in control. In order to gain any additional benefit of safety and efficiency the driver control must be removed as the primary source of command and control. This involves giving individual vehicle control to the individual vehicle or placing control in the infrastructure. Each approach has its advantages and disadvantages and should be explored. A cooperative approach where the control is shared between the vehicle and roadside can be made with the advantages of both extremes without the costs. There is a great deal of work being done that has the control on the vehicle and very little that has a
cooperative infrastructure management approach. Because of this discrepancy and the fact that the Smart Road is an excellent platform for this type of infrastructure based management, we believe the infrastructure based management is well suited for study under the Smart Road project.

When primary space management is given to the infrastructure the automation system becomes "hands off"/"feet off"/"brain off". For the system to accomplish this additional task it must not only have knowledge of forward obstacles and headways and lane positions but also it must know where the vehicles on all sides are and some idea of their intent. This requires accurately locating the position of all the vehicles in close proximity to the automated vehicle. This can be accomplished through side and rear sensors for adjacent vehicles and possibly inter vehicle communications to give an idea of what to expect beyond adjacent vehicles. Alternatively, with roadside management the roadside must have knowledge of the positions of the vehicles relative to fixed roadside reference points. The roadside must gather this knowledge either through vehicle based or roadside detection, through communication with the vehicle or a combination of both detection and communication. Vehicle location might be accomplished through a number of different approaches spanning from acoustic to microwave to optical. Whether it is generated from one of these approaches or a combination of these approaches, the location system must provide information from all surrounding vehicles and will very likely involve participation from these other vehicles and at later stages full cooperation.

Once the system has knowledge of the surrounding environment it can begin to make merging and passing decisions in addition to the headway control and lane keeping performed under driver control. It can also be made responsive to ATMS system flow control strategies on a macroscopic level. Full system optimization and higher efficiencies can then be obtained as the percentage of automated vehicles on the road increases.

Highways, as opposed to arterials, contain many characteristics that simplify the problem of automation. Automation on arterials will lag significantly behind automated highways. However, many safety measures can be taken on arterials using the equipment designed for the highway. Pre-crash restraint deployment will be commonplace and obstacle detection and warning will be operational on all roadways. The significant problem of intersection collision can be greatly reduced by activating the onboard warning systems and automatic braking systems with electronic signal lights in addition to the normal traffic signal. If the intersection detects a potential for a collision it can notify vehicles equipped with driver warning or deceleration actuation of the potential hazard. Some situations where this will improve safety are the driver of an equipped vehicle not noticing a change in the signal or an equipped vehicle approaching an intersection where another vehicle is preparing to cross against the
signal. It is very important that these benefits are enjoyed on more than just the freeways if we are to see significant reductions in fatalities and injuries. Eventually, full automation will be placed in all the major cities to relieve congestion. Also, full vehicle control from origin to destination will be possible.

5.3 VEHICLE BASED CHANGES

5.3.1 Cruise Control

Cruise control is one of the first stages of automation. Actually, earlier stages of automation relieved the driver of the responsibility to control the starting, choke and transmission in vehicles. Cruise control is, therefore, only a continuation in the automation of vehicles. Initial cruise control equipment was very erratic in its behavior. Much work has gone into making cruise controls have smoother transitions and having them maintain a fixed speed regardless of the slope of the ground. As more and more vehicle functions have been replaced with electronic controls the task of automation is becoming even easier. The average modern vehicle has as many as 12 processors performing various functions on the vehicle. While the vehicles are becoming more complex the tasks the drivers must maintain are being reduced. When cruise control was first developed there was much concern over the safety and user acceptance of this form of automation. However, cruise control has improved noticeably from initial prototypes and has become widely accepted and used. Any of us would become indignant if we were forced to crank a starter and many do not even know how to operate a manual transmission. Therefore, if we are to learn from history we will realize that technological advances of today, no matter how amazing they are, will become the expected minimum requirements of tomorrow.

5.3.2 Obstacle/Headway Warning

The first marketable products to arise out of the installation of external sensors are warning devices designed to alert the driver to potential collision situations. These warning sensors are already being deployed and tested in the field. The VORAD radar system has already been installed in all the Greyhound busses for over a year. Systems like these mark the beginning of a new era in situation awareness for vehicular technology. Vehicles now can not only protect a driver if a collision occurs, but also can prevent collisions from occurring.

The dominant issue to be addressed for driver warning systems is the trade-off between detection and false alarms. All detection systems have a threshold that must
be set to determine the sensitivity of the system. If the threshold is set high the number of false detections from noise and other interference will be reduced. However, this will cause obstacles producing low level signals to be missed. If the threshold is lowered then many of the obstacles can be found, but, many false detections will also occur. Ideally, the system design will provide a wide separation between the signals from obstacles and the noise. Even the best systems will have some missed detections and some false alarms. If the system is properly designed very few detections will be missed and the occurrence of false alarms can be made so infrequent that it will not be a problem. Figure 2 shows the detection distributions for a good system design and a bad system design. It must be recognized that the best system design might, also, be very expensive.

The systems used for obstacle detection and headway warning may not be the same. Detecting a large metallic vehicle and detecting a child or small animal may not be possible with a single system. Each has very different dynamics and characteristics. However, a warning system that detects one or the other can still be useful in that it is an improvement over having nothing.

Figure 2: System design considerations

5.3.3 Automatic Headway Control
Most of us have experienced the frustration of using cruise control in an increasingly dense traffic environment. We tend to want to stay in cruise for as long as possible without touching the brake pedal. Finally, when we get too close we resign to the fact that we must exit cruise control and re-enter it when the headway is clear. A number of vendors are preparing to release an "adaptive" cruise control to minimize this problem. "Adaptive" or "intelligent" cruise control will enable you to set the desired cruise speed of the vehicle and when the headways become too short it will slow down your vehicle to maintain a constant headway. When the headway is clear it will resume the initial cruise speed. This will allow us to stay in cruise control over a much wider range of traffic conditions.

Like early cruise control systems, the adaptive cruise control systems have a number of difficulties to work through. Some of these difficulties are related to system design and some are based on user preferences. One issue involving user preference is the varying temperaments among people. When driving is concerned, people can be characterized as either "hunters" or "creepers". The hunters are those that see their destinations as prey to be conquered. They press the limits of safety to achieve their goal of minimum travel time. Stopping for rest stops is a significant inconvenience. Half second headways or less are the norm in dense traffic environments. They can switch lanes with the grace of a gazelle. An adaptive cruise system with fixed headways may be perceived as sluggish and unresponsive. Another group of people can be characterized as creepers. The creepers see driving as an opportunity to relax and meditate on the concerns of life. Their purpose is to go from point A to point B with as little stress and concern as possible. Being constantly cut-off by the hunters may bother them at times but often they are absorbed in thought and may not even notice. Headways of 2, 3 or 4 seconds are common and even desired by the creepers. The perception of an adaptive cruise system to this group may be distracting and unnerving. While these may be extremes, they do reflect the array of user perceptions that must be addressed by an adaptive cruise control design. Allowing the user to set the desired headway may improve the perception of a system over a wider range of users.

For straight, continuous driving situations the adaptive cruise problem is relatively simple. However, there are a number of common traffic situations that make the job much more complicated. Some issues that must be addressed are **type of sensor to use, headway spacing, curve handling, merging vehicles, changing lanes and integration with steering and braking**.

One of the first decisions to make when designing an adaptive cruise control is what type of sensor to use to determine forward headway. The sensor must be evaluated based upon range, reliability, cost, accuracy, size, all weather capability and functionality. The maximum sensor range must be able to detect vehicles in sufficient
time to allow for a smooth adjustment in speed. The minimum sensor range must be considered to prevent the system from disengaging when needed most. Since the users will tend to rely on the system to slow them when approaching traffic, the system must have a higher standard of reliability than normal cruise control. Another safety related issue is operation in all weather conditions. They must be able to operate in rain, snow, fog, dust storms, electrical storms, etc. They must also be able to operate with various electro-magnetic interference sources. One area of particular concern is the location of the sensor. Since the sensor is forward looking it has an increased potential of being obstructed with some foreign matter. Also, some electro-magnetic sensors have shown significant difficulty operating through salt water. For northern latitudes this could be a serious limitation. Finally, size and cost of the sensor are significant for overall user acceptability of the system. The best sensor for the job is probably prohibitively expensive.

As discussed earlier, the choice of headway spacing in the system can significantly effect user perception of the system. Therefore, the system designer should take this into account when determining how to set the headway spacing. One and a half second headways may be a safe average to use in a system, but, may receive criticism from both extremes. Much consideration should be given to allowing the user to adjust the headway. However, for safety reasons the headway should not be adjustable down to zero seconds. A lower limit of half a second may be acceptable to all concerned.

A significant issue that has shown itself on early prototypes is the operation of adaptive cruise control on curves. To avoid being distracted by roadside objects many existing sensors employ a narrow beamwidth to detect only vehicle in front of them. However, when the vehicles in front enter a curve they may leave the beam of the sensor and cause the vehicle to speed up thinking there is no vehicle ahead. Also, a vehicle from another lane could be confused as being in front of the sensor and cause the system to make a rash response. Also, a rash response could be made if a roadside object is confused with a leading vehicle. Proposed solutions to these problems have been to use more sophisticated tracking algorithms and false alarm suppression algorithms with sensors that are more angularly discriminating. Also, feeding in information from the steering column to determine the present curve angle can be used to steer the beam along the curve. However, this presents a whole new set of predictive problems. At the very least solving these problems is going to increase the system cost.
Very similar to the problem of going around curves is that of vehicles merging in from other lanes. Control algorithms must be designed to handle sudden range changes from the sensor output. It must also be able to distinguish between a vehicle merging into the present lane and a vehicle in an adjacent lane entering a curve that puts it in the path of the sensor. Also, a sudden range change can occur when the vehicle equipped with adaptive cruise control itself changes lanes. However, the latter case should be able to be determined by monitoring the steering.

Integration of the steering and braking with the adaptive cruise control will not only improve the operability of the system but also pave the way for future evolution of vehicle automation. Earlier discussion explains how using the current steering angle can improve the algorithms used to control the vehicle headways. In addition, integrating the braking with the adaptive cruise control will allow operation under a wider range of scenarios. Not only will depressing the brake disable the cruise function and return manual control, but, the cruise function will be able to activate braking to perform faster deceleration. Throttle control can only provide minimal deceleration. This can be increased slightly with engine braking by down shifting the transmission. However, in extreme situations the brake must be employed or the system must rely on the driver. This will be discussed in more detail in the next section. The steps taken in integration of all maneuvering functions at earlier stages of development will make future centralized control of all vehicle function much easier. Full integration will only be obtained when steering, braking, throttle and transmission are all electronically controlled.

### 5.3.4 Automatic Braking

Closely related to the automated headway control is automated braking. While automated braking can be initiated by the adaptive cruise control system, it may be initiated from other sources. The main purpose of automatic braking is to obtain deceleration rates that are greater than those obtainable by throttle and transmission control. This requirement could be triggered from a number of sources:

1. The adaptive cruise control could detect a sudden deceleration from the leading vehicle and initiate brake actuation.
2. A second sensor system designed to detect closing objects could initiate the braking.
3. The leading vehicle could notify the following vehicle of its deceleration.
The infrastructure could send a deceleration request to the vehicle.

Regardless of the source of the deceleration request the braking control system must operate within safe parameters by not braking too quickly or too slowly.

The importance of integration was discussed previously. Using the braking in tandem with the other vehicle systems will improve the capabilities of other automated functions and make them responsive to a wider range of scenarios. Braking is an extreme function and should be used cautiously. It has the potential to make driving much safer. However, if not properly implemented it could cause serious problems. The vehicle must be very sure that there is an obstruction before braking is initiated. Also, knowledge of following vehicles would be helpful to prevent being rear-ended. Rate of deceleration is a factor for the driver safety.

Liability issues are very visible with this stage of evolution. A driver could argue that steering and acceleration would have been a better response in a given situation than braking. One way to deal with this situation is to provide enough braking to serve as an alert to the driver of a dangerous situation. Allowing the driver to override the braking with any maneuvering function would help limit liability. Another concern would arise if the drivers were very dependent on the system to stop for them and the system did not detect the obstacle. This is a good reason to have a second specialized detection system for obstacles. This system must be very intelligent and detect a wide variety of obstacles with very high probability of detection and very low false alarm rates.

Inter-vehicle communications and rear sensing capability both would help in determining when and to what degree to apply the brakes. However, at this point we are beginning to increase the vehicle costs by potentially doubling the sensor systems and communications for both forward and rearward application. This is where vehicle to roadside communications might serve to decrease the onboard vehicle requirements. There are a number of technologies for vehicle to roadside communications being developed for a variety of applications. Roadside supervisory systems could compile information from the available vehicles and from roadside equipment, determine potential conflicts and alert equipped vehicles to take corrective action. Following is a description of how the evolution of vehicle to roadside communications may expedite the evolution of AHS.

5.4 ROADSIDE BASED CHANGES

5.4.1 Cellular Communications
Since its introduction a few years ago, the boom in user demand for cellular communications has fueled a rapid expansion of the cellular network. The success of AHS evolution depends on linking the power of cellular communications and the emerging range of high-performance computers to the vehicle based developments that are ongoing. AHS evolution is expected to make significant demands on the information-carrying capacity of the communications network. However, the communications infrastructure will have been put in place with the deployment of other IVHS and communications user services. Therefore, the additional investment to deploy the AHS infrastructure will be relatively small.

A basic architecture depicting the direction of cellular communications is outlined below (2): The entire highway system is divided into a number of hexagonal "cells" that may range from 2 to 35 km. in diameter at early stages, and even smaller as demand increases. Each cell will contain a number of "nodes" or radio transceivers or beacons that will be linked together through a fiber optic Metropolitan Area Network (MAN). Each cell will be linked to the infrastructure through an interface. Each vehicle will be equipped with some kind of transceiver unit carrying a number of user services including telecommunications. Initially, this may consist of a simple beacon that may be modified to perform a range of functions as the AHS system evolves. The messages transmitted by each vehicle are received by several nodes and each node forwards its signals to a signal filter at the interface, which determines the best signal from each vehicle to be forwarded to the infrastructure. Also, there must be some overlap between the radio beams of the nodes, depending on the amount of redundancy desired.

In addition to the basic components shown above, other retransmission equipment may also be needed to provide radio reception in electromagnetic "shadow zones" (3). These zones are typically present in tunnels, underground parking areas, etc.
5.4.2 Automatic Vehicle Identification (AVI)

The first evolutionary AHS service that will reap the benefits of the communication infrastructure will be the automatic toll collection service using Automatic Vehicle Identification (AVI) technology. Drivers will be allowed to purchase electronic toll tags (ETT's) that will enable them to be automatically charged at toll booths. Also, these "smart cards" may be equipped with speakers or LCD displays to display other information from the infrastructure. The ETT's are thus converted into rudimentary "Traveler Information Systems" providing the traveler with information like gas, food, lodging, navigation, "yellow pages", current news casts or even services like stock quotes.

AVI may be implemented by requiring each vehicle to be equipped with an Electronic License Plate (ELP) in addition to its usual license plate. This will consist of a tiny computer chip with a radio beacon that can be queried by the infrastructure. This chip will be commercially produced for as little as $5. ELP will allow the infrastructure to find out the identity of any road vehicle by comparing its ELP signal with a database.

5.4.3 Automatic Vehicle Location (AVL)
The next step would be to provide a class of services using radiolocation to improve the driving environment. These services include the MADAY service, improved cellular communications, transit fleet tracking, commercial vehicle fleet tracking and stolen car recovery. As these services are utilized and deployed, a number of other services will be discovered.

The MAYDAY service will enable a vehicle equipped with a radiolocation beacon to send out distress signals in case of an accident. These signals could be driver-activated or automatically triggered. This enables better incident management by the infrastructure, i.e. quicker and more efficient deployment of emergency services in response to an incident. The infrastructure response to such incidents could later be made totally automated. This information may also be transmitted to other vehicles in the vicinity to inform them of the incident and to suggest diversion strategies. The communications network can be utilized to determine the locations of vehicles.

Vehicle location through cellular radio is already a reality. Use of radiolocation helps reject interference in cellular communications by directing beams adaptively towards the communication source. This allows for greatly increased reuse of frequencies. As shown by the OJ Simpson case, this technology is also being used by law enforcement authorities. This has raised the significant issue of privacy. While it may have negative repercussions on IVHS technologies, the capabilities offered to law enforcement may prove to be too desirable for them to ignore. However, recovery of stolen vehicles using radiolocation is an area of law enforcement that even the most staunch privacy advocates would have trouble disputing. Resolution of the privacy issue is the key to continued evolution of this technology.

The use of radiolocation for commercial vehicle and transit vehicle tracking has been well established and will continue to expand. The increase in efficiencies using AVL for these areas has been proven.

With all these technologies, there will be a need for improved accuracies and for refined and expanded services. As channel congestion increases the operation of these systems will be pushed to higher frequencies and require smaller operational cells.

5.4.4 Automated Vehicle Management

Through the AVI and AVL services already in place by this time, the infrastructure already possesses real-time information about the location of vehicles. The next step is to utilize this information to detect unusual traffic patterns, such as traffic jams, accidents, etc. This can be achieved through "smart" Electronic Toll Tags.
For instance, toll authorities in New York / New Jersey anticipated this application for their toll-tag technology and required tags to be capable of more advanced read / write capabilities so as to interact with the infrastructure.

It is expected that only a few vehicles will be equipped with AVL technologies initially. However, a Traffic Management Center (TMC) can effectively use a small percentage of vehicles as "probe" vehicles and base its decisions on the data that they send back. As more vehicles begin to possess communication and sensory capabilities, the quality of the decisions that are made by the TMC will improve. It has been found that within the first year of deployment toll tags have been used by as many as 30% of the vehicles equipped with this facility. The information gathered by the TMC may be used to provide drivers with real-time traffic information through road-side electronic displays and later, through Advanced Traveler Information Services (ATIS). Also, this information will be supplied to commercial vehicle operators to optimize their fleet deployment and improve arrival time reliability.

At a later time, when a large percentage of vehicles have been equipped with AVL technology, this information may also be used by the infrastructure to decide route guidance and trip planning strategies through dynamic traffic assignment.

5.4.5 Widespread Vehicle to Roadside Communications

It is seen that once the communications infrastructure has been set up and vehicles are equipped with electronic license plates, a large number of useful services can be introduced involving little cost to the driver. As the number of services increases, the demands on the communications infrastructure in terms of bandwidth will increase tremendously. Also, the demands on the network in terms of reliability and information update rates will multiply, requiring additional bandwidth. Already, the cellular networks in major cities are being used at their full capacity. Thus, new ways of increasing capacity on existing infrastructures will have to be found. One such way is to decrease the size of the cells to fit greater number of cells in a smaller area. This allows the same frequencies to be reused more efficiently. The current standard is 7 cells per cluster, but efforts are underway to incorporate 9 or 12 cells in the same cluster through better interference rejection. Adaptive beam steering will be a step in that direction. This helps accommodate more users within the same cell by concentrating the propagation of radio signals directly in the direction of the target vehicle to avoid interference problems with signals of other vehicles. Another way to increase channel utilization is through more efficient multiple access (spread spectrum) schemes. Spread spectrum can use separated frequency bands selectively to increase
the system capacity. In addition, the wide range of frequencies associated with spread spectrum techniques will increase the accuracy of radiolocation capabilities.

New portions of the radio spectrum are increasingly being explored in the search for higher capacity and performance. Currently, the bands around 900 MHz are the standard for cellular communications and electronic toll tags. However, vendors have developed systems for operation at 2.4 GHz and expansion to the 5.8 GHz band is expected when low cost chips are developed at that frequency. The Federal Communications Commission (FCC), in coordination with the International Telecommunications Union (ITU) is now looking at ways to harness the 5-20+ GHz band which offers better directional capabilities for critical AHS applications such as AVI, AVL and Automated Collision Avoidance.

An important class of services that will be provided are the Advanced Traveler Information Services (ATIS). This system may be implemented in the form of an LCD screen/speaker combination near the dashboard, initially, and with a Heads Up Display, later on. The system will be capable of receiving information from the infrastructure. Initially, this system will be used to provide "dumb" information such as street maps, travel advisories, etc. They will also serve as "bulletin boards" for ridesharing (carpooling) information. Once TMC services have been implemented, it will be a relatively simple matter to provide timely information on accidents, alternate routes, event schedules and weather information to drivers through ATIS.

Many services will develop on a local basis and not require direct access to the TMC but using the same channels of communication. These services will employ distributed information network system that will collect and distribute local information. ATIS will be used to provide quick access to local travel-related information such as auto-repair, hospitals, etc. through an on-line "yellow pages" directory. In addition, ATIS may be used by the system to provide data regarding speed, heading, etc. from in-vehicle sensors on a nearby "probe" vehicle. Information about congestion, fog, road hazards, and road geometry will also be provided. Local interface units will eventually be deployed every few hundred feet along the highways. It is expected that ATIS will gradually become the primary interface between the driver and the infrastructure.

As the ATIS interface becomes standard on new cars, the systems will be tied into the vehicle processors to inform drivers of vehicle maintenance requirements. Also, the adaptive cruise control and driver warning sensors can be tied into the ATIS interface. The categories of services that ATIS will provide to the driver will continue to get "smarter" as the AHS system evolves.

5.5 LANE DEPARTURE WARNING
The next step in the AHS evolution would be the introduction of systems that warn drivers of lane departures. The information regarding the current trajectory of the vehicle could be obtained by the onboard sensors or with the information from the infrastructure. The infrastructure AVL systems will be accurate enough to determine vehicle position relative to the roadway and vehicle speed. The infrastructure can provide this information to the vehicle and allow it to decide if a warning is necessary. Also, the infrastructure could decide that a vehicle is in danger and provide a warning.

Lane departure warning will be initially deployed at places that they are needed the most: dangerous curves and steep gradients. The first stages of deployment will be characterized by roadside variable message signs that will be later supplemented through communication with the in-vehicle auditory or visual systems. For commercial vehicles, information warning them of tipping potential on nearby ramps may also be provided along with lane departure information. Once this system has proven its usefulness, it can be extended to all portions of the highway system. It is important to note that as envisioned, the lane departure warning will one of many services offered in the local distributed network ATIS.

Another feature that may be provided is driver performance monitoring. This is especially important on long stretches of roads that tend to make drivers drowsy and for night time driving. The lane following information that the infrastructure possesses may be used by it to monitor driver reaction times to various road features so as to judge the alertness of the driver. If these reaction times are found to be too slow, appropriate warnings (audio or video) may be given to the driver through ATIS.

5.6 LANE HOLDING

At this point, the infrastructure already knows the exact location of each vehicle, possesses information regarding its lane holding and is also in two-way cellular communication with the vehicle through ATIS. Thus, the stage is set for the creation of a lane holding system. This requires additional equipment on-board the vehicle in the form of steering mechanism that can respond to commands from the infrastructure. The infrastructure will not need any further changes except to provide access to the relative lane position determined with lane departure warning service. The infrastructure can provide this information in the form of a lateral acceleration command necessary to return the vehicle to center lane. Transitional versions of this service may provide some lateral collision avoidance through integrated on-board side sensors and infrastructure information process. In this case the infrastructure could adjust the acceleration command to account for vehicles merging in from adjacent lanes.
The effect of this service will be to lessen driver fatigue on long drives by providing feet-off operation. The driver is still in charge of all command driving functions at this time, but he or she can switch on/off the lane holding system at any time, much in the same way as we switch on/off the cruise control on our cars today.

5.7 AUTOMATIC VEHICLE CONTROL (AVC)

This represents a major step for the driver conceptually, as it implies removing the driver as the principal source of control in the vehicle. The driver is not only hands-off and feet-off, but is also brain-off. From a technology standpoint though, this is not a big step: The lane holding system has already placed steering control of the vehicle in the hands of the infrastructure and the infrastructure knows the precise location of the vehicle. Thus, the driver will not be required to make additional investments. The only modifications that will be necessary will be those in the infrastructure in that the communications facilities will be called upon to provide a higher bandwidth and computational power.

Also, all vehicles may not be equipped with this technology right away. Hence, AVC and non-AVC vehicles will have to coexist for some time. For this purpose, the infrastructure will need to know the locations of the non-AVC vehicles. This information may be conveniently determined from the vehicle’s cellular, ATIS, Electronic Toll Tag (ETT) or electronic license plate.

This technology will require extremely accurate knowledge of the vehicle location at all times on the part of the infrastructure. Since the driver no longer has the command, functional reliability of the information network is critical. We propose an update rate of 100-1000 times a second with 10 cm. accuracy to provide the desired high level of safety. This is expected to improve driver safety as the system is essentially 500 times faster than the driver in responding to dangerous situations. Another benefit of this system is the increase in traffic throughput that it will allow: even for mixed vehicle traffic, it is expected to boost capacity by 50 % or more.

5.8 PARTIAL CONTROL ON ARTERIALS

The deployment of AHS technologies on arterials is expected to lag behind that on highways. Part of the problem is the presence of intersections, complicating the issues of lane following and control.

Initially, AHS deployment on arterials may be in the form of intersection collision avoidance systems. These systems will use data collected from the AVL and AVM to
warn drivers about imminent collisions while approaching intersections. The system may also use the ATIS capability existing on most vehicles by this time to advise drivers regarding right of way in ambiguous situations. Other useful features may also be incorporated by upgrading the intelligent cruise control mechanism: The infrastructure could gather data regarding the status (red/green) of the next traffic signal so as to optimize the speed of the vehicle to arrive when it is green. The same data can allow automatic stopping at red lights.

Once the proportion of vehicles equipped with AVC becomes large, the infrastructure can use its AVL and AVC capabilities to perform Lane Holding and Intelligent Intersection Control (IIC), i.e. allow cooperative longitudinal control between vehicles at cross-roads to harmonize their speed.

Another problem in AHS deployment on arterials is the need to integrate the movement of highway vehicles with cyclists and motorcyclists. Just as other vehicles have been equipped with an Electronic License Plate, these vehicles too could be equipped with a similar device to allow the infrastructure to monitor their location at all times.

However, the problem of pedestrians and animals makes the arterial problem more difficult. That is why sensor integration from multiple sources is essential to automated operation on all roadways.

### 5.9 Optimized AHS

The gains in throughput that accrue from applying AVC technology will be vastly improved when the majority of vehicles possess AVC capability. The reason for this is that it will now be possible to reserve many highways for use by AVC-capable vehicles alone. On these highways, vehicle headway spacing will be initially set to driver preferences. As the traffic density grows, intervehicle spacing will decrease, leading to increased capacity. The key to this is that short headways will gradually develop over years as traffic density increases. This will maintain maximum safety and yet be able to adjust to increased capacity requirements. Also, this approach is much more attractive from a user comfort standpoint. While users may not accept very close headways given today's experiences, if they were given years to adjust to gradually decreasing spacings the final close headways would be more readily acceptable. Maximum capacity may be 300+% above today's traffic. See the throughput analysis for more detail on the evolution of highway capacities.
5.10 FULL AUTOMATIC CONTROL ON HIGHWAYS AND ARTERIALS

In this case, the driver will be provided with a hands-off / feet-off / brain-off environment for the whole journey. All that he or she needs to do is inform the infrastructure through the ATIS system of the desired destination and the system will utilize information that it has acquired through AVL and AVM to select the best route to the destination. Many drivers may want to include additional criteria with appropriate weights attached to each criterion in the route selection [5]. This can also be accomplished by the infrastructure at no extra expense to the driver.

Once the route has been selected, the infrastructure utilizes AVC to guide the vehicle, while constantly updating the routing strategy based on current traffic characteristics obtained through AVM. Once the vehicle arrives at the destination, it may be automatically parked in a spot that has been reserved in advance by the driver through ATIS.

5.11 CONCLUSION

It is thus seen that AHS will evolve in a series of small steps, with the cumulative result being a 200+% increase in traffic capacity of the highway system with much higher safety rates. Each stage will call upon the communications network to meet higher demands in terms of bandwidth and accuracy. Each phase of AHS will require higher levels of reliability and consequently redundancy. The computational power available to the infrastructure to process data from multiple inputs will thus need to grow rapidly as well.

Each stage will build upon the successes of the earlier stage and will involve little investment on the part of the driver - most of the investment will be in upgrading the infrastructure. Much of the infrastructure investment can be carried by private industry since the basis will be communications and highly beneficial user services. Individual AHS services may be combined in various ways at the infrastructure to provide additional services. We feel that this aspect of AHS - huge benefits for minimum driver investment - will make it very attractive to most drivers, allowing it to evolve from concept to reality. Also, this kind of phased introduction will be preferred by most drivers, instead of a sudden, full-scale deployment. It will also allow time for each AHS subsystem to be fine-tuned for reliability and efficiency - an essential ingredient for the success of AHS.
6.0 MALFUNCTION MANAGEMENT - (This is an initial outline of the work that
must be done to fully define the malfunction management of the CIMS concept.
As work proceeds on the concept this section will be expanded to address the
whole malfunction management problem.)

6.1 INTRODUCTION

In order to insure a reliable automated highway there must be a significant level
of detail given to address every possible malfunction or situation that could affect the
safe and continuous operation of the system. A good system design can mitigate a
large percentage of potential hazards before they become a danger. However, the
automated system has a greater responsibility to maintain safety since it has assumed
the drivers role of command and control of the vehicle. Therefore, even if subsystem
failure rates are extremely low the overall system must have contingency plans to deal
with the situation. The system must not only be able to have a reasonable solution, but,
first it must detect the problem that is occurring. It is not always necessary to know the
exact problem that is occurring. Often it is sufficient to know the nature of the problem
and its potential implications on the safety of the vehicles occupants. Classes of
problems often have the same solution.

Following are the various parts of the system that could have a problem that
requires some type of action to be taken by the system:

-External Impedances
-End User
-Man Machine Interface
-Vehicle Processor
-Vehicle Mechanical
-Vehicle Communications
-Roadside Communications
-Roadside Processors
-Processor Networking
-ATMS Interface
-ATMS Control
The exact detection and solution to any given problem is a function of what stage of deployment the vehicle and the roadway have achieved. When the vehicles are operating in dedicated lanes there are a number of areas that have been optimized to increase the capacity of traffic and the operating speeds. Therefore, if a vehicle is forced to stop in this situation they may not be allowed to regain manual control of their vehicle. However, if they are in mixed mode then a vehicle that is expelled from automation may still be able to resume their trip in manual mode.

Most problems that could occur in the system can usually be corrected without the user even noticing. However, there are levels of solution that effect the occupants to various degrees. Following is a list of levels of severity of a problem:

1) Normal operational mode - Self correcting - driver unaware

2) Use of redundant system - graceful degradation - level of service not effected - user or ATMS notified to replace faulty subsystem

3) Use of redundant system - some reduction in level of service - user or ATMS notified of problem - user must correct problem before next automated session

4) Minor vehicle subsystem failure - user is advised of problem and is taken to next exit - may not re-enter automation until corrected

5) Major vehicle subsystem failure - user is advised of problem and is brought to stop ASAP - automatic emergency assistance summoned

6) Minor infrastructure subsystem failure - management functions re-routed - maintenance crews dispatched - limited system entry possible

7) Major infrastructure subsystem failure - vehicles brought to a stop and manual flow resumed - maintenance crews dispatched - no system entry possible

Following is the beginnings of a list of possible system problems. The actual list of malfunctions will include hundreds of possible problems specific to the type of components and their interaction. However, some general problems can be identified that are not a function of the individual hardware. As time goes on this list will be expanded as decisions are made about the exact technologies and algorithms to be used. Each problem will be rated by its severity level as stated above. At some point an attempt will be made to determine the rate of occurrence of each potential problem to determine the total rate of occurrence of each level of severity. As more is known about the system the accuracy of these estimates will improve.
### 6.2 EXTERNAL IMPEDANCES

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>Weather sensors locally or at least feedback from ATMS</td>
<td>Adjust speed and spacing according to condition</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Roadside/vehicle sensors monitor vehicle responses for slip</td>
<td>Limit highway entry</td>
<td>3</td>
</tr>
<tr>
<td>Obstacles on or near roadway</td>
<td>Detection with vehicle/roadside sensors.</td>
<td>Alter vehicle paths and notify ATMS for removal.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Maintenance crews and emergency vehicles would be required to wear a transponder.</td>
<td>Reprogram road during maintenance.</td>
<td>1</td>
</tr>
<tr>
<td>Pot holes/road hazards</td>
<td>Roadside/vehicle sensors monitor vehicle responses to look for changes in track. Detect hazards early before they become severe.</td>
<td>Alter vehicle paths and notify ATMS.</td>
<td>1</td>
</tr>
<tr>
<td>Manual vehicles</td>
<td>Vehicle sensors on other vehicles Transponder required on all vehicles whether automated or not</td>
<td>Adjust automated vehicles to limit the chance of an accident. Spacing is based on uncertainty.</td>
<td>1</td>
</tr>
</tbody>
</table>

### 6.3 END USER

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>User emergency (medical problems, user jitters, etc.)</td>
<td>User notifies ATMS (panic button)</td>
<td>Immediate: Pull car in to mixed mode lanes (if not already). Then driver can regain manual control at any time. Notify ATMS. Notify user of options. &lt;br&gt; 1. Reenter AHS &lt;br&gt; 2. Voice communication with ATMS for assistance</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short Term Response: Allow for exit at next exit. (Give feedback to user for time to next exit and what facilities are available.) Also, inform where closest hospital is located. Voice communication with ATMS if needed.</td>
<td>1</td>
</tr>
</tbody>
</table>
### User redirection

- **User notifies ATMS**
- **Routine redirection function in system with choices for user. (Bathroom, food, lodging, gas, change in destination, other ATIS features.):**

### User not prepared to regain control of vehicle

- **Roadside/vehicle sensors monitor vehicle to determine whether driver has taken control**
- **Give a wake-up call five minutes before exit.**
- **Pull vehicle into a waiting station at exit.**
- **Charge them for time on roadway.**

### Inadvertent manual initiation

- **Roadside/vehicle sensors monitor vehicle to determine whether driver has taken control**
- **Take back control of vehicle**

### 6.4 MAN-MACHINE INTERFACE

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Deployment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>User doesn't know how to use the system or are uncomfortable using the</td>
<td>Determined by user</td>
<td>System is exactly like current cruise control. User decides when to enter by setting speed and exits when the steering or brake is adjusted.</td>
<td>1</td>
</tr>
<tr>
<td>system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Final Deployment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>User doesn't know how to use the system or are uncomfortable using the</td>
<td>Determined by user</td>
<td>Only cruise control level of difficulty required to enter automation.</td>
<td>1</td>
</tr>
<tr>
<td>system</td>
<td></td>
<td>Initial training for more advanced system settings. Repeating choices.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>More detailed description of choices.</td>
<td></td>
</tr>
<tr>
<td>They don't like voice interaction</td>
<td>Determined by user</td>
<td>Remote hand-held back-up device for entering choices.</td>
<td>1</td>
</tr>
<tr>
<td>Problem with voice recognition</td>
<td>User notices commands are not</td>
<td>Hand-held or dashboard backup with multi-language capability.</td>
<td>2</td>
</tr>
<tr>
<td>received</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Made a wrong choice</td>
<td>Determined by user</td>
<td>Feedback to user.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Allowance for redirection.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Confirmation/reconfirmation of major choices.</td>
<td></td>
</tr>
<tr>
<td>Electronic interface failure</td>
<td>User notices commands are not</td>
<td>Redundant interface voice/keypad. Emergency override (panic button) can be on a separate electronic pathway.</td>
<td>2-4</td>
</tr>
</tbody>
</table>
### 6.5 VEHICLE PROCESSOR

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor failure</td>
<td>Self diagnostic.</td>
<td>High reliability components.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Global system shows unresponsive vehicle.</td>
<td>Partial failure - Transfer vehicle to manual operation, notify ATMS, and notify user (to service vehicle)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full failure - Surrounding vehicles react to avoid vehicle. Default vehicle shutdown. Notify ATMS and user.</td>
<td>3-5</td>
</tr>
<tr>
<td>Communications failure in vehicle processor</td>
<td>Self-diagnostic/periodic polling.</td>
<td>Loss of incoming messages: Notify ATMS &amp; user and use predetermined shutdown trajectory and vehicle sensors until vehicle transfers to manual operation</td>
<td>3-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of outgoing messages: Roadside system notifies vehicle of failure. Re-start attempted. Vehicle brought to exit and instructed to be serviced</td>
<td>2-5</td>
</tr>
</tbody>
</table>

### 6.6 VEHICLE MECHANICAL FAILURE

<p>| Problems         | Detection                                      | Solutions                                                      | Lvl |
|------------------|------------------------------------------------|                                                               |-----|
| Brake failure    | Maintain and look for deviations in the response curves. | Down shift and coast to stop.                                  | 5   |
|                  | Early warning through self-diagnostics and routine maintenance requirements. |                                                           |     |
| Steering failure | Maintain and look for deviations in the response curves. | Pull to a stop. Use road curvature or what little steering you do have. | 5   |
|                  | Early warning through self-diagnostics and routine maintenance requirements. |                                                           |     |</p>
<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration failure</td>
<td>Maintain and look for deviations in the response curves.</td>
<td>Sticks - put in neutral and pull to a stop.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Early warning through self-diagnostics and routine maintenance requirements.</td>
<td>Unresponsive - pull to a stop.</td>
<td></td>
</tr>
<tr>
<td>Transmission failure</td>
<td>Maintain and look for deviations in the response curves.</td>
<td>Routine maintenance.</td>
<td>4-5</td>
</tr>
<tr>
<td></td>
<td>Early warning will detect slippage.</td>
<td>Pull to next exit in most cases.</td>
<td></td>
</tr>
<tr>
<td>Flat tire</td>
<td>Maintain and look for deviations in the response curves.</td>
<td>Increase steering acceleration commands to compensate.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pull vehicle to shoulder.</td>
<td></td>
</tr>
<tr>
<td>Power loss/stalling</td>
<td>Maintain and look for deviations in the response curves.</td>
<td>Pull to stop.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Self-diagnostic.</td>
<td>Communicate with ATMS Manager.</td>
<td></td>
</tr>
<tr>
<td>Other vehicle problems</td>
<td>Self-diagnostic or determined by user</td>
<td>Minor problem - Notify user. Course of actions TDB by user.</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Major problem - Notify user and ATMS. Pull to stop.</td>
<td>5</td>
</tr>
</tbody>
</table>

### 6.7 VEHICLE COMMUNICATIONS

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little or no transmitter power</td>
<td>Roadside would be losing echo pulses (more than likely from multiple receivers). Low signal-to-noise ratio.</td>
<td>Notify vehicle to switch to back-up transponder.</td>
<td>2-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If location is lost, use other vehicles’ sensors to fix location and transfer vehicle to manual operation. Notify ATMS &amp; user to service vehicle.</td>
<td></td>
</tr>
<tr>
<td>Not receiving roadside commands</td>
<td>Lack of polling queues.</td>
<td>Switch to back-up transponder.</td>
<td>2-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Notify ATMS &amp; user and use predetermined shutdown trajectory or vehicle sensors to transfer vehicle to manual operation</td>
<td></td>
</tr>
</tbody>
</table>
## 6.8 ROADSIDE COMMUNICATIONS

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little or no signal from one receiver</td>
<td>Low signal-to-noise ratio.</td>
<td>Built in roadside redundancy can handle multiple roadside system failures.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>No contribution from receiver to vehicle track.</td>
<td>Turn off receiver.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Notify ATMS.</td>
<td></td>
</tr>
<tr>
<td>High error rate from transmitter</td>
<td>Lack of polling to multiple vehicles.</td>
<td>Retransmit messages.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Parity checks, etc.</td>
<td>System can lose many commands before reducing system performance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintain error logs.</td>
<td>Notify other end of link to start diagnostics.</td>
<td></td>
</tr>
<tr>
<td>High noise levels on one receiver</td>
<td>Periodic checking of noise statistics to determine source</td>
<td>Monitor receiver</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ignore receiver inputs until noise within a reasonable range</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Notify ATMS if problem continues</td>
<td></td>
</tr>
<tr>
<td>High noise levels on multiple receivers</td>
<td>Periodic checking of noise statistics on multiple receivers shows noise increase</td>
<td>Increase power of transmitter</td>
<td>6-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If at max power signals are lost, initiate highway shutdown and notify ATMS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>If noise levels fall then restart system</td>
<td></td>
</tr>
<tr>
<td>Transmitters or receivers lose power</td>
<td>1. Monitoring power supply</td>
<td>1. Uninterruptable power supply - battery backup</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2. Roadside processor detects signal loss</td>
<td>2. Use other receivers, notify ATMS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Feedback from vehicles that they are not receiving transmissions</td>
<td>3. Increase transmitter power, reroute transmitter functions, and notify ATMS</td>
<td></td>
</tr>
</tbody>
</table>

## 6.9 ROADSIDE PROCESSORS
## Problems

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory failure</td>
<td>Self diagnostic: a few cycles per second reserved for memory checks</td>
<td>If possible reallocate memory, otherwise schedule maintenance and reroute processor functions based on severity of memory failure</td>
<td>2</td>
</tr>
<tr>
<td>Processor failure</td>
<td>Self diagnostics</td>
<td>Built in roadside redundancy</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Adjacent processors perform parallel processing and compare results</td>
<td>Shutdown processor and reroute functions</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Notify ATMS</td>
<td></td>
</tr>
</tbody>
</table>

## 6.10 PROCESSOR NETWORKING (2,6-7)

Many of the malfunction management techniques will be dependent upon the type of network used. The system design calls for being able to reroute the functions between processors. However, if three consecutive processors are down or cannot communicate the highway system must be shutdown. As a backup, the WAN between the processors and the ATMS could be used as an alternative path for the processor handshaking. This would have to be designed into the networking and remains to be determined.

## 6.11 ATMS INTERFACE

<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAN fails</td>
<td>Processor monitoring ceases</td>
<td>Emergency communications can be passed along the LANs until it reaches a check-in/check-out terminal</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All non-emergency user services can be discontinued</td>
<td></td>
</tr>
</tbody>
</table>

## 6.12 ATMS CONTROL
<table>
<thead>
<tr>
<th>Problems</th>
<th>Detection</th>
<th>Solutions</th>
<th>Lvl</th>
</tr>
</thead>
</table>
7.0 THROUGHPUT ANALYSIS

The focus of this analysis is on the effects that deployment strategy and separation policy have on the capacity of the CIMS. This analysis will compare a few different deployment strategies to see how the capacity of the highway changes as the automated vehicle market penetration increases. It will also look at how the safegap headway strategy affects capacity. This part will first discuss the mixed mode and dedicated lane strategies. Then, a hybrid strategy, which is the evolutionary deployment used for the CIMS, will be introduced. A summary of the capacity analyses used for these three strategies is then presented. Finally, the results of these analyses and some conclusions drawn from them will discussed.

7.1 Deployment Strategies for AHS

Mixed Mode

In the mixed mode strategy, all lanes are able to handle both automated and manual traffic simultaneously. Thus, mixed mode systems are more likely to require fewer modifications to existing roadways and, therefore, lend themselves more to an evolutionary deployment. Mixed mode lanes do not have the problem of underutilization that dedicated lanes (such as HOV lanes) experience in the initial stages of deployment. Also, they are relatively transparent to the user. However, some drawbacks of mixed mode systems are that they may need to be more complex and that some of the capabilities of automation are not fully exploited because the manual traffic will limit the overall system performance.

Dedicated Lane

In the dedicated lane strategy, some lanes will carry only automated traffic and others will carry only manual traffic. As the number of automated vehicles grows, the manual lanes will be modified to automated lanes one-by-one. This strategy allows automated lanes to reach their full potential since there will be no manual cars to limit performance. It also allows for shorter trip times when higher speeds are used. Also, the system may possibly be less complex since the added burden of dealing with manual cars has been removed. However, in a failure scenario a dedicated lane system must also deal with manual cars, and thus the complexity difference might not be as great. Dedicated lane systems are likely to require more modifications to existing roadways (such as transition lanes and entry/exit locations) and are, therefore, less conducive to an evolutionary deployment. Also, in the initial stages of deployment,
which are the most critical from a public acceptance point of view, dedicated lanes will be underutilized and will reduce the overall capacity.

A variant of the dedicated lane strategy is the dedicated roadway strategy. In this case, entire highways are one-by-one converted to automated highways. This strategy will have the same advantages and disadvantages as the dedicated lane strategy. Also this strategy could potentially require less civil infrastructure than a dedicated lane strategy, but there must be alternate routes for the remaining manual vehicles. The analysis of this strategy is similar to that for the dedicated lane strategy when an average is taken over a number of highways with similar routes. Because of these reasons, this strategy will not be analyzed separately.

Hybrid

As one can see, some of the capacity advantages of the mixed mode strategy are also disadvantages of the dedicated lane strategy and vice versa. Therefore, it is reasonable to assume that a combination of the two strategies could have superior capacity characteristics. This hybrid strategy would be the same as the dedicated lane strategy except that the manual lanes would now be mixed mode lanes. This is the evolutionary deployment strategy used for the CIMS and allows for a more graceful evolution to a dedicated lane strategy. This will solve the problem of automated lane underutilization that the dedicated lane strategy experiences initially while still having the shorter trip time advantages of dedicated lanes.

7.2 Analysis Assumptions

1. Each analysis determines the capacity per lane, \(c\), in vehicles/lane/hr, of a four lane highway (one direction).

2. The average speed of automated vehicles in dedicated lanes, \(v_a\) in mph, is a parameter that can vary depending on the design of the actual system. However, when they are in manual or mixed mode lanes, they are assumed to be limited to the speed of manual traffic.
3. For the dedicated lane and hybrid strategies, as the percent of automated vehicles increases, the capacity of the current configuration is compared to the possible capacity with one more automated lane. If an increase in capacity is possible, then another automated lane is dedicated. The exception to this rule is that for the dedicated lane analysis where the first automated lane is dedicated as soon as there are automated vehicles to use it. Therefore, its capacity growth curve will only have a discontinuity at this initial dedication.

4. If the automated lanes have reached their capacity, then the remaining automated vehicles must travel in the manual or mixed mode lanes. In manual lanes they must operate manually, but in mixed mode lanes they can be automated.

5. Transition lanes are assumed to have negligible throughput and to require negligible roadway. This is because the aim of this analysis is to determine the capacity of the major traffic-handling lanes in terms of vehicles/hr. However, in an analysis which looks at the capacity in terms of right-of-way width, these factors may tend to be balanced by such things as narrower dedicated lanes and use of shoulders.

6. Manual lanes are assumed to have a capacity, $c_m$, of 2200 vehicles/lane/hr at an average speed, $v_m$, of 60 mph. These numbers represent typical numbers for multilane freeways as stated in the Highway Capacity Manual. [1] Using these numbers, the average distance headway for manual vehicles, $h_m$, is 43.9 m (at 60 mph). This was obtained using the fact that $h_m$ is given by $1609.344v_m/c_m$. Therefore, this headway is used for a manual vehicle following another manual vehicle or following an automated vehicle (See Figure 1).

![Figure 1 - Situations where $h_m$ is used](image)
7. The average distance headway for automated vehicles following manual vehicles (See Figure 2), $h_{am}$, is assumed to be 30 m (at 60 mph). This value is significantly more than is needed for an automated vehicle. This is so that manual vehicle drivers in front will not experience the uncomfortable headways that an automated vehicle could handle. This value was chosen using the composite model of headway distribution presented in May. [2] Thus, this value approximately corresponds to the 20th percentile of the distribution and represents an aggressive but not overly aggressive headway. For most situations this spacing is in excess of the safegap described in the next assumption.

![Figure 2 - Situations where $h_{am}$ is used](image)

8. The average distance headway for automated cars following automated cars (See Figure 3), $h_{aa}$, is determined by the vehicles' braking capabilities. The “safegap” (sg), the minimum distance a vehicle must maintain behind another vehicle in order to prevent an accident, is given by

$$s_g = \begin{cases} \frac{v_a^2 (a_1 - a_2)}{2a_1a_2} + v_o t_r, & \frac{v_o}{a_1} \leq \frac{v_o}{a_2} + t_r \\ \frac{a_1a_2 t_r^2}{2(a_2 - a_1)}, & \frac{v_o}{a_1} > \frac{v_o}{a_2} + t_r \end{cases}$$

(1)

where $a_1$ and $a_2$ are the maximum braking accelerations of the front vehicle and following vehicle respectively, $t_r$ (assumed to be 0.1s for automated vehicles) is the
reaction time of the following vehicle, and \( v_0 \) is the initial speed of the two vehicles. It is assumed that the controller has accurate knowledge of (or tight bounds on) all the vehicles braking capabilities, and can thus calculate the needed safegap. The accuracy of the braking information (or the tightness of the bounds) will have a strong effect on the performance of the system since inaccurate information will cause the controller to chose conservative safegaps in order to prevent accidents. To calculate \( h_{aa} \), a distribution of braking capabilities was determined using the values in Table 1. The distribution of vehicle type was developed from data from [3] and [4]. The distribution of car braking capabilities was estimated using data from Car and Driver tests. The best and worst performers from 1989-1994 (see January issues) were used to approximate the 3-sigma points of the distribution. The distributions of truck braking capabilities was determined using data from [5]. The "typical ranges" were used to set the 2-sigma points of the distributions. In order to go from vehicle spacing to vehicle headway, the average vehicle lengths were assumed to be 5 m for cars and 15 m for heavy duty vehicles. Figure 4 shows the combined probability density function for all vehicles.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Distribution (a in g's)</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>Normal: ( m=0.83, s=0.08 )</td>
<td>92.0</td>
</tr>
<tr>
<td>Bus</td>
<td>Normal: ( m=0.575, s=0.0125 )</td>
<td>0.2</td>
</tr>
<tr>
<td>Loaded Tractor Trailer</td>
<td>Normal: ( m=0.49, s=0.03 )</td>
<td>2.8</td>
</tr>
<tr>
<td>Loaded Truck</td>
<td>Normal: ( m=0.395, s=0.0275 )</td>
<td>4.2</td>
</tr>
<tr>
<td>Unloaded Trucks and Tractor Trailers</td>
<td>Normal: ( m=0.34, s=0.025 )</td>
<td>0.7</td>
</tr>
<tr>
<td>&quot;Bobtail&quot; Tractors</td>
<td>Normal: ( m=0.31, s=0.035 )</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 1 - Table of distributions for different vehicle types
7.3 Deployment Algorithms

Mixed Mode Strategy

As the percent of automated vehicles increases, only the average headway will change for mixed mode traffic. Assuming that the probability that a vehicle is automated is independent from the probability that the vehicle in front of it is automated, then the average headway in m will be

\[ h = p_a^2 h_{aa} + p_a (1 - p_a)(h_{am} + h_m) + (1 - p_a)^2 h_m \]  

where \( p_a \) is the fraction of automated vehicles. Once \( h \) is calculated, then the capacity is given by

\[ c = 1609.344 \frac{v_m}{h}. \]
Dedicated Lane Strategy

\( T_a \) and \( T_m \), the throughputs in vehicles/hr for the automated and manual lanes respectively, are needed to find the capacity for a given configuration. However, in order to calculate \( T_a \) and \( T_m \) for a given configuration, it must be determined whether the automated lanes have reached their capacity. To do this the \( T_a \)'s from both case 1 and case 2 below are compared. If the \( T_a \) from case 1 is less than that from case 2, then case 1 applies which means that the automated lanes are below their capacity. Otherwise the automated lanes are at their capacity and case 2 applies. Once \( T_a \) and \( T_m \) are calculated, then the capacity is given by

\[
c = \frac{T_a + T_m}{l_a + l_m}
\]

(4)

where \( l_m \) is the number of manual lanes and \( l_a \) is the number of automated lanes.

**Case 1 - The automated lanes have not reached their capacity**

\[
T_m = c_m l_m
\]

(5)

\[
T_a = v_a \left( \frac{p_a}{1 - p_a} \right) \left( \frac{c_m l_m}{v_m} \right)
\]

(6)

The second factor in (5) is the ratio of automated vehicles to manual vehicles, and the third factor is the number of manual vehicles/mi. The product of the two gives the number of automated vehicles/mi., and multiplying that by \( v_a \) gives \( T_a \). Also, as can be seen, \( T_m \) is at its maximum.

**Case 2 - The automated lanes have reached their capacity**

\[
T_m = c_m l_m
\]

(7)

\[
T_a = 1609.344 \frac{v_a l_a}{h_{aa}}
\]

(8)

As stated before, any additional automated vehicles which cannot fit in the automated lanes must operate manually in the manual lanes. Thus, when the automated lanes fill up, both the automated and manual lanes will be at their
capacity. This means that c will remain constant as the percent of automated vehicles increases until another automated lane is dedicated.

Hybrid Strategy

The hybrid analysis is similar to the dedicated lane analysis. The one difference comes in when there are no dedicated lanes or when the current dedicated lanes are full. These situations fall under case 2 of the dedicated lane analysis. The difference is that automated vehicles which cannot drive in the dedicated lanes do not have to operate manually like they would for the dedicated lane analysis. Below is a revised case 2 for the hybrid analysis.

Case 2 - The automated lanes have reached their capacity

Like before $T_a$ will be at its maximum and is given by (7). In order to find the throughput for the manual lanes (which are really mixed mode for the hybrid case), the number of automated vehicles in these lanes must be found. To do this, (5) is set equal to (7), and the result is solved for $p_a$. This $p_a$, which will be called $p_{aa}$, is the fraction of vehicles in the automated lanes. The fraction of vehicles in the manual lanes which are automated, $p_{am}$, is given by

$$p_{am} = \frac{p_a - p_{aa}}{1 - p_{aa}} = p_a - \frac{l_a h_m}{l_m h_{aa}} (1 - p_a).$$

(9)

$T_m$ is then given by $c l_m$ where c is given by (2) with $p_{am}$ taking the place of $p_a$.

7.4 Analysis Results

Figure 5 shows a plot of the capacity with 100% automation for different vehicle speeds. This plot shows how using the safegap strategy to determine vehicle spacings will affect the capacity. As can be seen, the capacity reaches a maximum (about 7500 vehicles/lane/hr) at around 60-65 mph. This is because the safegaps have a quadratic dependence on speed (which is stronger if the front vehicle has much better braking than the following vehicle), and this will
dominate the throughput at higher speeds. Thus, speeds higher than manual speeds will not improve throughput. Higher speeds do have other advantages such as lower trip times; so that if the highway is below capacity, higher speeds can be achieved. Since the maximum throughput is achieved near manual speeds, the analyses that follow will assume that the automated vehicles travel at manual speed. However, it will be shown later that there are ways of getting more capacity at higher speeds while using the safegap strategy.

Figure 6 is a plot of percent increase in capacity vs. percentage of automated vehicles for the three different deployment strategies. The percent increase in capacity is measured in reference to $c_m$. Figure 6 illustrates some points that have already been mentioned. It can be seen that the dedicated lane strategy does indeed lose capacity after the first automated lane is dedicated. This is because in the analysis it was assumed that the first automated lane is required as soon as there are automated vehicles and not when it will allow a capacity increase. This premise asserts that there will not be automated vehicles until there are roadways for them to drive on. This may or may not be a reasonable assumption since there could be major highways which will have lanes dedicated as soon as there are automated vehicles to use them or there could be highways that will not start to automate until there is a significant number of
automated vehicles. In any event, both the mixed mode and hybrid strategies avoid this problem entirely because they allow for immediate automation before any facilities are dedicated. Another advantage of the hybrid strategy that Figure 6 illustrates comes directly from the revised case 2 mentioned in the analysis section. In this situation, the throughput of the dedicated lane strategy remains fixed until the next lane is dedicated. However, since the hybrid strategy has mixed mode lanes, the throughput will be able to rise slowly until the next lane is dedicated.

Figure 6 also illustrates the advantages of dedicate lanes. Even at manual speeds the dedicated lane and hybrid strategies have higher capacities at certain points. This is because the dedicated lanes are effectively grouping similar (i.e., automated) vehicles together which will reduce the headways and increase the throughput. The dedicated lane and hybrid strategies also have the potential of achieve much higher capacities at higher speeds if the headway strategy allows it. It will be shown shortly that there are ways of getting the safegap strategy to yield higher capacities and higher speeds.
7.5 Capacity Over Time

The capacity advantages that the mixed mode and hybrid strategies have over the dedicated lane strategy are even more important when one considers how the number of automated vehicles will increase with respect to time. As with any new technology, there will be a long period at the beginning where the market penetration will rise very gradually. At a certain point when the majority of the public starts to adopt the new product, the market penetration will increase very rapidly. Also, there will always be a few people who will wait a long time or will refuse to by into a technology. Thus, at this point, the market penetration will again increase gradually as it slowly reaches its maximum value. In order to incorporate this effect into the previous plots, the x-axis of the plots must be expanded on both extremes and contracted in the middle. The log sigmoid function, which is given by \( f(x) = \frac{1}{1+e^{-x}} \) and is shown in Figure 7, was used to produce this nonlinear scaling to the x-axis. Figure 8 is a plot of the mixed mode, dedicated lane, and hybrid strategies with the log sigmoid scaling. In a sense, this scaling is an attempt to convert the percent of automated vehicles axis into a time axis.

From Figure 8, one can indeed see how this scaling emphasizes the throughput advantages of the mixed mode and hybrid strategies. Another important practical issue to consider is that in the early stages of automation, where the mixed mode and hybrid strategies are superior, is in fact a critical period from the point of view of public acceptance. If all that the public sees is that there are lanes being taken away from them and that congestion is increasing from lower overall throughput, then they will become very disenchanted quickly.
Figure 7 - The log sigmoid function, \( f(x) = \frac{1}{1 + e^{-x}} \).

Figure 8 - Mixed mode, dedicated lane, and hybrid strategies.
7.6 Higher Capacities Through Vehicle Segregation

As was mentioned above, the eventual capacity of the hybrid strategy could be increased with higher speeds depending upon the headway strategy. The reason that the safegap strategy yields a maximum throughput at manual speeds is the quadratic dependence on speed of the safegap. It can be seen from (1) that if the two vehicles have similar capabilities, then this quadratic dependence is lessened. Thus, an intuitive improvement to the safegap strategy would be to group vehicles with similar dynamics together. A relatively easy implementation of this would be to segregate vehicles into different lanes depending on their capabilities. This segregation will not be difficult since it is already assumed that the controller has accurate information on the braking capabilities of the vehicles on the road. Figure 9 below is a similar to Figure 2. It shows the capacity vs. speed when the vehicles are segregated (by braking performance) into 1 (no segregation), 2, and 3 groups. Figure 9 shows that you not only get more capacity by segregating vehicles, but you also are able to have higher speeds at capacity. As was said before, higher speeds can benefit other factors like trip time.

![Graph showing capacity vs. speed with different groupings](image-url)
Figure 9 - Capacity vs. speed plot for safegap spacing using 1, 2, and 3 segregation groups

7.7 Conclusion

This analysis has looked at the capacity effects of three different deployment strategies and the potential field safegap headway strategy. Analysis has shown that the hybrid and mixed mode strategies have better capacities at the initial deployment phases. Whether the system should stay mixed mode or evolve into a dedicated lane system using the hybrid approach depends on the regional situations. The reason why is that dedicated lanes (which the hybrid strategy uses) require much more civil infrastructure. If no segregation is used, then the maximum throughput is achieved near manual speeds and, therefore, dedicated lanes would not be needed. However, you can achieve still higher throughputs and shorter trip times if segregation and dedicated lanes are used. Thus, depending on what are the regional requirements of the AHS, either the mixed mode or the hybrid case would be a good solution. The only drawback of the mixed mode and hybrid strategies is that they are potentially more complex than the dedicated lane strategy. However, depending upon specific system characteristics like malfunction management, the difference in system complexity may or may not be significant. Also, since technologies like processor capability continue to improve, in time the complexity differences could become insignificant.
III. Responses to Measures of Effectiveness

It should be noted that the objectives and characteristics outlined may be possible when every vehicle in the country is automated. However, initially a few of these characteristics will stand out above the others as necessary and achievable for the early stages of AHS. Any attempt to try to claim all of these categories as given could make the AHS development effort lose credibility in the eyes of the public and achieve the opposite result of what we intended. With a subset of these virtues a strong case can be made for a product that is desirable and cost effective. It is only prudent for the AHS concept not to have any major areas of weakness that can be used to capsize the program, but, we must not feel we have to solve every problem with transportation in order to have a successful approach.

1.0 PERFORMANCE OBJECTIVES

1.1 Improve Safety

The AHS system design proposed here places heavy emphasis on driver safety. This is evident from the following factors:

1. The system design seeks to optimize the vehicle spacing and hence the safety while maintaining a desired throughput. (See the section on Controller and Spacing Strategy) This is opposed to optimizing throughput while maintaining a safety margin. This allows for greater safety during the majority of the operational time and only reaches safety margins during worse case scenarios. However, even this margin will be such that no collision should occur within the next few centuries. In effect, the system is able to maximize vehicle spacing within the available road surface, while maintaining the necessary throughput based on traffic density. The processors on the side of the road can contain algorithms that synchronize the activity of all the vehicles based upon individual vehicle response capability and traffic density. Also, the spacing can be made variable based upon individual vehicle response capabilities. For example, cars with flat tires and trucks would be given a greater proportionate headway than normal cars. When density is high this system will still be able to maintain the close headways found in a "platoon". This ability to adjust headway spacing at the planning level provides the system with greater flexibility to respond to potentially dangerous situations.

2. Placing some level of control on the infrastructure allows for a broader range of operating conditions including mixed mode traffic. Therefore, malfunction management schemes can be system wide or on an individual vehicle. For example, if the whole system fails the vehicles could initiate a predetermined
deceleration to minimize the potential of catastrophic failure. Also, if one vehicle is unresponsive then the surrounding vehicles can execute a synchronized response to the failure.

3. The proposed system involves communication between the vehicle and the roadside in a feedback loop. Thus, the system can be configured as a closed loop control system. A closed loop system can be designed in general, to be a stable system through feedback (11).

4. The system design attempts to improve safety through reducing the reaction time for the automated vehicles and taking into account the varying vehicle dynamics within the network. The system does not attempt to operate within the reaction time curve. Therefore, the system may sacrifice some throughput potential for insuring there is no collision.

As we discussed above, the system is designed to never have a multi vehicle accident by maintaining appropriate spacings and synchronizing the responses. As designed, a non-AHS vehicle trying to cause an accident with an AHS vehicle will not be able to cause an impact. Every effort will be made to make individual vehicle failures as graceful as possible. Levels of malfunction management will be part of the system design.

Number of crashes

In the early stages of deployment, there will be a reduced number of crashes as compared to the existing system. On the other hand, in the final AHS system, this number will be substantially reduced. This is so because there will be mixed mode in the early stages.

Number of annual fatalities due to crashes

In the early stages of deployment, there will be a reduced number of annual fatalities due to crashes as compared to the existing system. On the other hand, in the final AHS system, this number will be substantially reduced due to the highly robust and safe design.

Number of annual injuries due to crashes
In the early stages of deployment, there will be a reduced number of annual injuries due to crashes as compared to the existing system. On the other hand, in the final AHS system, this number will be substantially reduced.

**Injury rate**

In the early stages of deployment, there will be a reduced injury rate as compared to the existing system. On the other hand, in the final AHS system, this number will be substantially reduced.

**Severity of injuries on AHS vs. conventional highways**

In the early stages of deployment, the severity of the injuries will be lower as compared to the existing system. On the other hand, in the final AHS system, this will be substantially lower.

**Accident rate per kvt**

In the early stages of deployment, there will be a reduced injury rate per kvt as compared to the existing system. On the other hand, in the final AHS system, this number will be substantially reduced.

**Total annual cost of all crash related injuries**

In the early stages of deployment, there will be a reduced total annual cost of all crash related injuries as compared to the existing system. On the other hand, in the final AHS system, this number will be substantially reduced.
Hazmat crashes

In the early stages of deployment, there will be a reduced number of hazmat crashes as compared to the existing system. On the other hand, in the final AHS system, this number will be substantially reduced.

Annual property loss

In the early stages of deployment, there will be reduced annual property loss as compared to the existing system. On the other hand, in the final AHS system, this amount will be substantially reduced.

Property loss per kvt

In the early stages of deployment, there will be reduced annual property loss per kvt as compared to the existing system. On the other hand, in the final AHS system, this amount will be substantially reduced.

Travel security cost

In the early stages of deployment, there will be reduced travel security cost as compared to the existing system. On the other hand, in the final AHS system, this amount will be substantially reduced.

AHS vs Non-AHS ratio of occurrence of catastrophic crashes

In the early stages of deployment, this ratio will be lower as compared to the final AHS system.
**Accident response time**

In the early stages of deployment, there will be reduced accident response time as compared to the existing system. On the other hand, in the final AHS system, this amount will be substantially reduced.

**Incident clearance time**

In the early stages of deployment, there will be reduced incident clearance time as compared to the existing system. On the other hand, in the final AHS system, this amount will be substantially reduced.

**Infrastructure damage by vehicles**

In the early stages of deployment, there will be reduced amount of infrastructure damage by vehicles compared to the existing system. On the other hand, in the final AHS system, this amount will be substantially reduced.

**Time to respond to malfunction**

In the early stages of deployment, there will be reduced time to respond to malfunction loss as compared to the existing system. On the other hand, in the final AHS system, this amount will be substantially reduced.

**Down time due to vandals**

In the early stages of deployment as well as in the final stages, there will be low downtime time due to vandals, because the system will be
highly modular, and hence easily maintainable.

1.2 Increase Throughput

While the CIMS framework can be operated in a high throughput environment in a dedicated AHS highway, this is not its primary focus. Instead, CIMS can provide a platform in which automated and non-automated vehicles co-exist. While some marginal increase in throughput may be possible in this scenario, significant increases will not be obtained until there are sufficient numbers of automated vehicles to warrant dedicated facilities. Therefore, safety and convenience are the primary objectives of this concept.

Since the system can be designed for mixed mode traffic, AHS entry and exit can be as simple as turning on cruise control. By definition as the number of AHS vehicles increase the number of incidents should decrease improving throughput. Finally, when the numbers of automated vehicles is sufficient to warrant dedicated facilities the throughput possible can take significant leaps. The following figure shows a study we performed showing the impact on total throughput in regard to an evolving deployment of AHS. As can be seen the dedicated facility does out perform the mixed mode traffic in later stages of evolution, however, during early stages of deployment a dedicated facility would reduce the potential capacity of the roadway. Even if this was a new facility (or lanes) built for AHS vehicles, the capacity potential would be adversely effected due to underutilization until the percentage of AHS vehicles was sufficient to populate the roadway.

Vehicles per AHS lanes per hour

*Capacity of lane to move vehicles for light duty vehicles, transit vehicles, trucks*

In the initial phases, the CIMS will mainly be a mixed mode system. As can be seen in the throughput analysis, this means that there will only be slight improvements in throughput over conventional highways. Larger gains cannot be obtained because the large amount of manual traffic will dictate the flow characteristics.

In the final phases, the CIMS will likely be a dedicated facility. In any case, it will be able to achieve large throughput gains. As was shown, vehicle grouping will allow for large throughputs and higher speeds, although significant throughput gains can still be achieved without grouping. The throughput gains might be slightly smaller than
other systems due to the fact that the controller is optimizing for safety and will use the safegap headway strategy. These reductions should be slight, and the CIMS will still achieve large throughput gains over conventional highways. The CIMS will allow the same throughput gains for all vehicle types. The only factor affect vehicle type throughputs will be the feasibility of automating certain vehicles. For example, current automatic transmissions (which will be needed for automation) for heavy duty trucks are very costly and the cost could make some truck operators reluctant to buy automated trucks.

**Vehicle per right-of-way width per hour**

*Vehicles per right of way width (including shoulders, transition lanes, and automated lanes) per hour for light duty vehicles, transit vehicles, and trucks.*

When the system is mainly a mixed mode system, there will be no need for barriers or transition lanes. Also, the lane widths will need to be the same as they are for conventional highways to accommodate the manual traffic. Thus, there will only be a slight increase in vehicles per right-of-way width that is due to the slight improvement in throughput.

If the system becomes a dedicated lane system, there will probably be the need for some barriers, but the right-of-way that these use will probably be compensated by smaller widths for the dedicated lanes. Mixed mode systems will not have barriers, but the lanes will need to be wider. When a vehicle wishes to leave the automated lanes, it will be guided into the mixed mode lanes where it can leave automation at any time. This allows the system to work without transition lanes.

**Cargo per lane per hour**

*The capacity of lane to move cargo: Passengers and Freight*

There will be slight gains in both passengers and freight per lane per hour initially due to the slight throughput gains. However, these increases will not be large because the throughput gains are not large at the initial deployment.

When there are significant numbers of trucks automated, then there will be large gains in cargo throughput that are due to other factors besides throughput gains. One reason for large cargo throughput gains are that longer trailers would be safe enough to use on a automated highway. At the final deployment there will be significant throughput gains, but these will not necessarily lead to the same increases in
passengers per lane per hour. This is due to the possibility that the enhanced mobility of the system might create more demand and lessen the pressure to carpool. This would lead to a situation where there are more vehicles on the road but smaller numbers of passengers per vehicle. Without continuing policies which encourage carpooling (i.e., HOV lanes), the benefits of increased throughput might be lessened by this increased demand.

Check-in delay time

Amount of time added to trip time by AHS check-in process

Since the system will start out as a mixed mode system, the check-in delay time will be basically the same as for conventional roadways. Check-in will be initiated by the user as simply as one initiates cruise control today. Then, there will be a fraction of a second delay for the initiation of the wireless link between the vehicle and the roadway. This process will be quite fast since the vehicle was already being passively monitored when it was under manual control. At final deployment the check-in process might slow down slightly due increased load on the communications equipment, but this will be slight.

Entry rate

Number of vehicles allowed on to automated lanes relative to lane capacity

Since the check-in delay time will be small and since the AHS will have large capacities, there should be a rather large entry rate. When there are few automated vehicles, the manual drivers will dictate performance. When there are large numbers of automated vehicles, there will not be any significant bottlenecks which will limit entry rate.

Exit rate

Number of vehicles allowed off the automated lanes relative to lane capacity

Since the check-out procedure will be as simple as the check-in procedure, the only factor which should affect exit rate is the arterial loading. All AHS will have to deal with the fact that unless the arterials are improved, the AHS throughput will be limited by the exit rate. One advantage of the evolutionary deployment is that it will gradually
increase the impact on the arterials, thus allowing for a gradual increase in arterial capacity.

Check-out delay time

Amount of time added to trip time by check-out process

The check-out process will be as simple as the check-in process, and thus, the check-out delay time should be very small. There will be a number of activities which will need to be done in order to leave automation like making sure the driver is able to regain control of the vehicle. However, these processes can be scheduled to operate before the vehicle is ready to leave automation, so that no extra time is needed to check out.

Reduction of throughput resulting from incidents/crashes

The changes in hours of delay

The global management of the CIMS will allow for coordinated responses to situations, and this will reduce the likelihood of secondary accidents. Reductions in the number of secondary accidents will shorten the delays significantly because the incident will require less time to resolve. When there are large numbers of automated vehicles, then emergency vehicles will be able to get to incidents quicker because the system will be able to adjust traffic out of their way.

Equivalent conventional lanes to support traffic carried by one AHS lane

Number of square meters of right-of-way

There will be a large number of equivalent conventional lanes to support the traffic in one AHS lane because of the large throughput gains that will be realized.

Incidents

The number of incidents per VKT

The number of incidents in the system will reduced proportional to the number of automated vehicles on the highway. At the beginning, manual vehicles will be the
cause of most incidents. When all the vehicles are automated, then the likelihood of an incident will be very small. The malfunction management of the system will ensure that major incidents will hardly ever occur.

Local delays

The probability of local blockages that reduce throughput

When there are a small number of automated vehicles, there will not be a significant change in the probability of local delays. When there are significant numbers of automated vehicles, then the controller will be able to smooth out the traffic, and the number of local delays should decrease dramatically.

Maximum safe speed

The speed limit on an AHS: urban, rural, night, inclement weather

The maximum safe speed will definitely increase since automation will improve the vehicles’ responses. Visibility issues like night and inclement weather will not impact on the safe speed like they would for a human driver.

Vulnerability to single-point failure (SPF)

To what extent could a SPF shut down the entire system

The CIMS will have much redundancy built into the important parts of the system which will minimize the probability that a SPF will shut down the system. SPF on vehicle systems should not cause system shutdowns since the system will be able to handle individual vehicles without greatly affecting the other vehicles.

Average trip time

The average amount of time spent driving per origin/destination pair. The average amount of time spent on the AHS.

The average trip time for a given route should decrease. This is because the system will average out local delays and will prevent large delays due to incidents. With
dedicated lanes and mixed mode lanes not at capacity, higher speeds and thus shorter trip times are achieved.

**Standard deviation of trip time**

*The standard deviation of trip time for each trip per origin/destination pair. The standard deviation for each trip on the AHS.*

The standard deviation of trip times should decrease. This is because both local delays and incident delays will be reduced. Thus, the system will create a much more consistent flow of traffic.

### 1.3 Enhance Mobility and Access

**Trip time deviation**

*Ability to maintain predictable trip times. Standard deviation of AHS trip times compared to today’s trip times for same locations.*

The standard deviation of trip times should decrease. This is because both local delays and incident delays will be reduced. Thus, the system will create a much more consistent flow of traffic.

**Trip time**

*Trip time compared to today’s trip time under similar traffic conditions*

The average trip time for a given route should decrease. This is because the system will average out local delays and will prevent large delays due to incidents. With dedicated lanes and mixed mode lanes not at capacity, higher speeds and thus shorter trip times are achieved.

**Trip time distribution**

*The AHS trip time distribution compared to today’s highway trip time distribution taking into consideration traffic congestion, check-in and check-out waiting times, and vehicle/system failures.*
As mentioned before, both the average trip time and the trip time deviation should decrease due to smoother traffic flow and higher speeds.

**Trip length distribution**

*Average length, in km, of trips taken*

The average trip length should increase especially when there are large numbers of automated vehicles due to the decrease in trip times. This is because people will be more likely to take longer trips if the time it takes has been reduced.

**Wait time at ingress**

*The average amount of time, in minutes, spent at ingress point*

The wait time at ingress should not be that different from conventional highways. This is because the entry rate will be high and the check-in delay time will be small.

**Wait time at egress**

*The average amount of time, in minutes, spent at egress point*

The wait time at egress will mainly depend upon the arterial system into which the AHS is feeding. If the capacity of the AHS is large enough, then there could be significant delays at egress points if the arterials cannot support the increased capacity. As mentioned before, the evolutionary deployment will allow for a gradual increase in capacity which will allow the arterials to be gradually improved.

**Use by drivers with disabilities**

*Change in percentage of drivers with disabilities, or whose capabilities temporarily fall outside the norm, that can use the highways. Change in percentage of aged drivers who use the highway, Change in percentage of drivers with temporary limitations who use the highway.*

Since the CIMS will be very easy to use, people with certain disabilities should be able to use the highways with automated vehicles. The major factor in determining how many more disabled people will use the AHS is how difficult it will be for the disabled
driver to get to the highway without automation. There will probably only be a small portion of disabled drivers which will be able to do that.

Equity

Accessibility by all socio-economic groups

The requirements that the CIMS will put on vehicles will not be that great. Thus, the cost of automating a vehicle should not be prohibitively expensive. There should be a wide range of socio-economic groups which will be able to afford automated vehicles.

Transit Coordination

Time spent waiting for transit

This should not be affected to much by AHS since a good deal of transit operations do not use highways. Those that do will see the same trip time consistency that other vehicles would and this would improve coordination.

Transit coverage

Change in availability of transit to various population segments as a result of AHS

The transit coverage should not change to much as a result of any AHS. Most of the transit operations are in urban areas which will not be automated for some time (if at all).

User perceptions

The user perceptions of mobility enhancement

The user perceptions should be rather high. Hands off, feet off driving with increased speeds and reductions in delays will have positive influences on whether people feel their mobility is being enhanced.

Training/licensing
The number of hours of training per driver per year needed to qualify the driver to use the AHS. The number of years between update of training.

There should be very minimal training required for the CIMS. The CIMS will be designed to be as easy to operate as cruise control is today. For selecting destinations and other information, the user will be able to specify requests using a voice recognition system.

1.4 Provide More Convenient and Comfortable Highway Traveling

Introduction

Convenience is a primary benefit of this system. Eight hour trips will not be perceived to be nearly as long with highway automation. Since safety and convenience are our primary focus, the logical initial implementations of this concept lean more toward intercity travel than urban commuting. However, with long distance travel becoming safer and easier there are major areas of concern in increasing vehicle miles traveled and adversely effecting other modes of travel.

Access to CIMS should be no more difficult than current cruise control to initiate, use and exit. Once fully implemented, a totally disengaged driver is possible and desirable to free the driver of the driving task. Global knowledge of events and closed loop control makes the potential for a very smooth ride. Since more of the sophistication is on the infrastructure the vehicles should be relatively easy to service and maintain.

In order to fully understand the AHS from the driver’s perspective, we need to imagine the state of transportation several decades into the future. Intelligent Transportation Systems will hopefully be as well recognized as cruise control and anti-lock braking systems. We are assuming that technological advancements such as ATIS, adaptive cruise control, lateral guidance, and collision avoidance systems will be mundane accessories on all new cars. Drivers will be used to the visual and audio interfaces that an evolved ATIS will have, and more comfortable with the thought of smart processors having greater control of their car. Therefore, the psychological impacts caused by changing driving patterns of an AHS will not be as drastic as if it were implemented today.

In addition, the added complexity of tomorrow’s vehicles will not be so much of a shock to drivers. Even today, many new cars require certified technicians for basic
services throughout a detailed maintenance schedule. The fact that their AHS specific equipment cannot be fixed on the side of the road will not be hard to stomach.

The entire driving experience is an evolutionary one. Through small steps, our transportation system will evolve in a fully automated highway system. The CIMS architecture is designed to evolve with the AHS. It does not require a complete restructuring of the highway system to function. It can be deployed slowly, and as more and more automated cars reach the highways, it can change into a more mature AHS.

A fundamental paradigm of the CIMS architecture, is that until full automation is achieved and dedicated lanes exist of automated cars only, the driver will be in control of initiating all entry and exit from automated mode. Due to the random nature of mixed mode driving conditions, we feel it is important to allow the driver access to complete control of the car. When the time comes for dedicated lanes, then the uniformity of many automated cars will create more favorable conditions for the control of the vehicle to lie with the AHS system.

**Driver Involvement**  (low to none / none)

The amount and difficulty of driver actions required during the steady-state driving task

The CIMS architecture will require very little to no driver involvement throughout all stages of its implementation. In the initial deployment of the CIMS Automated Highway architecture, the driver involvement is designed as low to none. During the steady state driving task, the only normal interaction between the driver and the AHS will involve setting or changing the desired headway distance. The term coined for headway distance is aggression factor. The driver has the option of setting a higher aggression factor if they don’t mind following more closely to vehicles in front, or a lower aggression factor if they prefer to maintain a large gap between them and the vehicle in front. No other interchange is required between the driver and the AHS system during the normal steady-state driving task.

The early years of AHS will see a large mixture of automated and non-automated vehicles. The small headways that a fully automated system can handle would most likely cause a slight psychological problem for drivers new to automated vehicles. For this reason, the headway aggression factor will remain the responsibility of the driver during the early stages of deployment. At any time, the driver can take back complete control of the vehicle.

The CIMS architecture will evolve as more and more automated vehicles emerge on the highways. Larger populations of automated vehicles will allow for much smaller
headways than between non-automated and automated vehicles. When the number of vehicles capable of automated driving has reached the breakpoint to allow designated automated lanes, the responsibility for headway spacing will switch to the CIMS control. By this time, drivers will be comfortable with the higher speeds and smaller headways that automated highways are capable of. Once drivers engage the automated mode, no other interaction is necessary until the final destination exit is reached.

**Driver Access**  (minimal / minimal +)

The amount of time and effort required to enter and exit relative to conventional highway access

Entry and exit in the CIMS architecture is designed to tax the driver as little as possible. The amount of time and effort required to enter and exit relative to a conventional highway is minimal. Initiation of automated driving can occur as early on as the on ramp to the highway. Once initiated, the AHS will run vehicle diagnostics and originate the communications link with the infrastructure. The diagnostics are to ensure that the car is fully functional for automated use and the communications link prepares the vehicle and the infrastructure to accept automated travel. These two process require very little time and the progression from manual to automated mode will seem almost instantaneous. Transition to automated mode entails decreasing the weights given to driver input of steering and braking and increasing the weights given to CIMS input. The shift of control will be gradual and smooth.

Engaging automated mode merely requires pressing a set button, similar to the set function on standard cruise control. In fact, the controls for the CIMS architecture are designed to work with adaptive cruise control equipment that should be standard equipment on most new cars by the year 2005. Once employed, the CIMS takes over driving completely. In both early and final stages of deployment, this manner of entering the AHS will be employed.

In the early stages of deployment of CIMS architecture, no dedicated lanes for automated vehicles will exist; all driving will be mixed mode. In this situation, the responsibility for returning to manual mode from automated mode before exiting the highway will fall on the driver. Because the driver will deliberately initiate the shift from automated to manual mode, it is assumed the he or she is in possession of full faculties to resume control of the vehicle. Therefore, no special safety precautions are necessary to ensure the abilities of the driver. There will, of course, remain a monitoring protocol to filter out spurious actions, and ensure that the driver’s intent is deliberate.
During automated travel, the AHS system constantly scans inputs to braking and steering. It is designed to filter out spurious motions and only recognize constant and deliberate inputs from the driver. As the driver begins to brake or steer and the CIMS recognizes their actions as deliberate, it will gradually increase the weights given to driver input and decrease the weights of the AHS control. In this manner, transition to manual mode will appear very smooth and gradual to the driver. Once in full manual mode, the driver is free to exit the highway at will. The control system will initiate audio and visual feedback and verification of the automobile’s state; automated mode, transition mode, and or manual mode.

In subsequent stages leading to final deployment, the number of automated vehicles in the highways will justify dedicated automated lanes. In other AHS architectures, a transitional lane or period is necessary before full automation mode is capable. For the CIMS system, mixed mode traffic acts as the transition between total manual mode and full automated driving. In this manner, there is no need for a dedicated transition lane.

In a fully dedicated lane, a driver has the ability to enter a final destination exit to the system. Entering a designated exit will require a user interface between the driver and the vehicle. Possible interfaces include voice recognition systems or small numeric keypads. One advantage of the CIMS architecture over others, is that the driver has the option of engaging automated mode, and with their hands and brains free from the driving task, then proceed to enter final destination information. In this manner, at no time is the driver distracted from manual driving in order to enter destination information.

In order for the vehicle to exit safely from the dedicated lane and into mixed mode traffic before the designated exit, the system must ensure that the driver is awake and fully capable of regaining control of the vehicle. Special safety precautions and protocols will be designed to properly inform the driver of the upcoming exit and ensure the condition of the driver to manage manual mode driving. Once the system has ascertained the proper condition of the driver and their abilities are verified, the AHS will turn over control to the driver in the same manner as earlier deployments: gradual weight shifts towards full manual mode. As before, once in manual mode, the driver is free to exit the highway under their own control. Please note, that in the CIMS all command decisions are made by the driver under normal conditions. With this assumption, the driver readiness protocols will not be as detailed and complex as with other architectures.

As the numbers of automated vehicles continue to increase, the desire to create exit and lanes specifically for automated vehicles will increase. In the presence of an automated exit ramp, there will be no need to switch to manual mode before exiting. Arterial automation will be the next logical step and will allow fully automated exiting.
from the highway onto arterial systems. This, of course, will take a long time, fortunately the CIMS architecture is designed to evolve and grow with the highway system.

The highway infrastructure will require designated pull off facilities for vehicles that experience malfunctions or are low on gas. In addition, if facilities for automated modes are unavailable in certain sections, a pull off area should be made available in the event that a driver does not return to manual mode before the car reaches the end point of automated travel.

**Interface Complexity** (not applicable / low)

*The degree of difficulty and time required to enter destination information*

Designating final destinations will not be a main function of the CIMS architecture during early stages of deployment. If the demand is high, an alarm function can be implemented to inform drivers that their exit is approaching, but the AHS would not take any deliberate action upon approaching the exit.

The CIMS system will include a user friendly interface for entering destination information. Possible mediums include a voice recognition system or a numeric keypad for entering destination codes. It would only take a matter of seconds to enter the final destination exit. Additionally, any necessary equipment would be designed to add onto existing dashboard accessories and would not require a major installation procedure.

Once dedicated lanes for automated only traffic are available, entering final destinations and having the AHS “wake” the driver up will be a reality. The wake up protocol might include visual, audible and tactile alarm systems.

**Driver Interaction** (low / low to none)

*Ability to manage malfunctions and incidents using built-in controls and actions*

The CIMS architecture will have many levels of malfunction management, with the driver’s interaction at a minimal level. Please refer to the malfunction management section for a detailed description of the failure scenarios.

In the event of a malfunction or incident in mixed mode driving, the driver has the option to return to manual mode at any time. The vehicle will incrementally turn over control of the vehicle to the driver while maintaining any collision avoidance systems that were in place during automated mode. The vehicle will take the necessary
measures of action if the driver cannot or is unwilling to take over manual control. These measures would entail pulling the vehicle to the shoulder or nearest exit as safely and quickly as possible. The system might warn drivers that emergency action will be taking place and might give them a countdown until the protocol is engaged in order to allow the driver to decide if they want to take control or let the vehicle handle the situation.

In a dedicated automated lane, the vehicle will take over all management of malfunctions and incidents, with the driver interaction kept at a minimum. Once again, please refer to the malfunction management section for more detail.

**Serviceability** (low / low to moderate)

*Frequency and cost of maintaining and servicing AHS-specific equipment*

The AHS specific equipment on the vehicle includes a vehicle processor, actuators required to control the steering, acceleration and braking, the vehicle-based sensors, the communications transponder, the user interface and the self-diagnostic equipment. The user interface to determine driver readiness will not be standard equipment until the AHS has evolved to designated automated lanes. In the infrastructure part of the AHS equipment will consist of a series of transmitters and receivers controlled by a series of networked processors.

No driver adjustment of the equipment is necessary for complete operation in the CIMS architecture. The on-board computer processor will perform system diagnostics to ensure safe operation and reduce the incidence of vehicle failure on an AHS. A few operating cycles per second will be reserved for these operations. In addition to self-diagnostics, the processor will keep a log of the steering, acceleration and braking responsiveness at different velocities based upon the navigation command vs. the actual motion of the vehicle. When the vehicle responses become too sluggish or the time comes for routine maintenance, the driver will be instructed to have the vehicle serviced. Drivers failing to comply with service instructions will not be allowed to enter automated mode.

In addition, the self-diagnostics of the vehicle will assess features such as tire pressure, and fluid levels. If the state of any feature would prohibit proper AHS function, the vehicle will inform the driver of the problem and the fact that automated mode is not possible until the feature is rectified. The early warning systems will be designed as robust as possible to include diagnostics of communications and transmission characteristics based on system response.
Individual vehicle service would be on an as needed basis. If there are problems with the self diagnostics then service requirements will be instituted. There is no need to do that, unless it becomes apparent that a deliberate maintenance schedule seems necessary.

The bulk of sophistication of the AHS system is on the infrastructure. The costs of maintenance and service will be much higher than for the individual vehicles. In this manner the higher service costs can be dispersed among many users and the individual’s expenses are minimized.

**Control Usability** (easy / easy to moderate)

*The range of movement required to access AHS interfaces*

The AHS user interfaces include the engage / disengage apparatus, destination entry, and Safety protocol to ensure driver alertness. For the early years of AHS, the interfaces will not include driver alertness precautions. As mentioned earlier, the CIMS system will utilize standard cruise control mechanisms already on board the vehicle. These controls are strategically located on the steering wheel, or steering column to facilitate their ease of use. In addition, the driver does not need to interface with the AHS system before entering AHS mode. For example, they do not have to enter a final destination prior to engaging automated mode.

Data entry interfaces could consist of a numeric keypad input, voice recognition or a touch panel. This interface can either be permanently mounted in the dash board or steering wheel, or can be hand-held in nature. By the time of full AHS deployment, ATIS will have gone through several iterations. The interface of choice that has been selected

In the later stages of AHS evolution, the CIMS system will require the driver to satisfy a certain protocol in order to ensure their ability to regain manual control of the vehicle. This protocol has not yet been designed, but it must ensure a deliberate and conscious effort on the driver to guarantee that they can handle the vehicle after being in automated mode.

**Attention to Load** (minimal / low)

*Demand placed on the driver to perform simultaneous tasks*

A significant advantage of the CIMS architecture is that the driver need not perform any major functions before entering into automated mode. They don’t have to
enter a set destination, or merge into a transition lane before engaging automated mode. In addition, due to the relatively simple engagement mechanism the act of entering automated mode puts a small amount of load on the driver’s attention. The act of entering automated mode, should be a matter of seconds, and in that time, there would be no attention demands on the driver.

**Comprehension Delay** (minimal / low to moderate)

*The amount of time required to determine the function of a control or message*

During the initial stages of AHS deployment, all responsibility for emergency actions will lie on the vehicle. The driver can still take back control when they wish, provided that existing safety precautions such as collision avoidance are still maintained. In addition, the early scenarios will be more simplified than full automated mode, therefore any control messages will be very short and to the point.

Final stages of deployment will offer a greater range of interpretation of malfunctions than early stages. The scenarios are more complex and more equipment can fail. The malfunction management protocol might provide verbal suggestions for various component malfunctions.

**User Compatibility**

*The range of driving population capable of performing AHS-specific tasks*

For the most part, all of the current driving population is capable of performing the AHS-specific tasks. Any one capable of using standard cruise control has the ability to engage the CIMS automated mode. Naturally, there will remain those who are unwilling to trust new technologies. Computer-phobics might be reluctant to trust their vehicle to total automated mode, and might opt to not take advantage of automated mode. In addition, classic and antique vehicle owners might be unwilling to have their vehicles retrofitted for automated operation.

**Learnability**
The time required to learn a system and control operations. Degree of driver training, skill or certification needed to gain access to the AHS compared to that needed for access to conventional highways.

Training drivers for initial AHS operation will be as difficult as instructing someone on using cruise control. Keep in mind, that by the time an AHS is deployed adaptive cruise control and collision avoidance features would be standard on new vehicles, and the culture shock of automation shouldn’t be that great.

As the AHS evolves into dedicated lanes, the need for further instruction might become apparent. Training would include instructions on how to handle malfunction and emergency situations in a dedicated automated lane. Drivers need to be aware that in all but the most catastrophic failures, that the AHS will be responsible for a controlled pullover to the shoulder and for notification to emergency personnel.

Driver Population

Ratio of percentage of driving-age population who can use AHS relative to percentage who can use today’s highways.

An AHS that is simple to use might attract users such as the elderly or those that are afraid of modern highways due to congestion and high speeds. In a fully automated highway, they only need drive onto the entrance ramp and the AHS will take over from there.

One of the great things about a truly automated highway, is that those who cannot normally use the highway infrastructure, such as the visually impaired, would be able to use the AHS. Special entry and exit nodes would allow the visually impaired and others not normally using the highways a means of accessing the AHS. These predetermined entry and exit points would have an alternative means of transportation for traveling the non-automated arterials. For example, an AHS user could take the Metro to a designated AHS entry point, take an automated vehicle on the AHS and exit at another Metro station and continue on their way using the public transportation system. This AHS scenario would occur when the entire highway is dedicated to automated vehicles. The AHS would not require the drivers to perform any tasks that their handicap would preclude them from. In the case of a catastrophic malfunction, the standard emergency protocol would safely and quickly move the vehicle off the highway. The vehicles will be equipped with radios directly linked to the Transportation Management Centers to inform them of a down vehicle.
The increased emphasis on wireless communication on an AHS might cause complications for those drivers or passengers who have sensitive electronic equipment inside their bodies, i.e., pacemakers, defibrillators, hearing aids. Studies will need to be conducted to ensure that no interference occurs between AHS communications and personal medical devices.

**Accessibility Distribution**

*Probability distribution of length of time a high percentage of driver population can use AHS continuously compared to conventional highway driving.*

The driving times in conventional highways are usually limited by fatigue, hunger, gasoline, bathroom stops and general stiffness accompanying long bouts of driving. The CIMS architecture will help alleviate some of the constraints placed on the driver during highway driving. By controlling lateral and longitudinal headway, the AHS frees the driver from continuous attention to the roadway. With the freedom to look away from the roadway for minutes or even hours, the driver fatigue threshold would be much greater than for a conventional roadway. As the interior design of vehicles evolves with a fully automated highway, it will allow for greater movement and stretching helping to alleviate stiffness and sore muscles.

Additionally, the freedom to remove the hands from the wheel will allow drivers to eat without causing a safety hazard on the roadway. Unfortunately, the AHS can not do much to alleviate the need for bathroom stops for the majority of drivers. Larger campers equipped with AHS equipment would allow the driver to use the onboard lavatories.

The reduction in stress and fatigue combined with the increased mobility to move around and eat will allow most drivers the ability to travel for much longer between stops. In turn, this increased travel time will make those longer trips more bearable and proceed faster.

**Distance Accessibility**

*Probability distribution of distance a high percentage of driver population can travel on AHS continuously compared to conventional highway driving.*

Many of the factors contributing to longer driving times, in the previous section, would also have an increased effect on distance traveled. By driving longer stretches
one will travel longer distances as well. Furthermore, most intercity driving will occur at higher speeds, also leading to greater distances. An influx of AHS vehicles on the highway will allow for a much greater median speed without sacrificing any level of safety. Future cars would have their gearing redesigned to make these higher speeds more fuel efficient as well.

**Stress reduction**

*The degree of stress reduction compared to conventional highway driving.*

The high speeds of freeway driving coupled with chronic fatigue from long stretches at the wheel have the potential to create stressful situations. The CIMS architecture will serve to alleviate stress by decreasing the driver’s responsibility during automated driving. With the AHS in control of lateral and longitudinal control, the driver is free to divert his or her attention from the roadway. Not having to constantly remain attentive will certainly decrease the amount of stress that a driver will face throughout a long drive. In addition, the knowledge that the AHS has the capability for collision avoidance might decrease the fear and apprehension of an accident caused by another driver.

Due to the evolutionary nature of an AHS, drivers will gradually become more comfortable with the changes to their driving habits. Once the system has been tested and accepted by the driving public, they will feel more at ease with the AHS and its capabilities in keeping them safe.

**User Perception**

*User perception of AHS operations including mixed traffic operation, close spacing, speed, and operations during inclement weather conditions.*

During the initial years of CIMS implementation, the driver has the option of regaining control of the vehicle at any time. Knowing that they still maintain control of the vehicle will help to alleviate some fear of being helpless and at the mercy of other manual vehicles. It is in these early stages of implementation that drivers will grow more comfortable with the closer spacing and higher speeds that an AHS can offer.

Probably the biggest fear over a fully automated highway system is being vulnerable to a “manual maniac”: someone in a manual vehicle who maliciously tries to ram them or change their trajectory. The response time of the automated highway is predicted to be much faster than a human being. In the initial years of deployment, the
collision avoidance systems on an AHS will have an opportunity to prove this increased response time to the public. Once people realize that they wouldn’t be able to avoid a manual maniac any faster that the AHS could, they might feel more comfortable leaving the responsibility to the AHS.

One should keep in mind that when the AHS is finally implemented, collision avoidance systems will be in their second generation of development. The systems will have many years of field testing integrated in their development.

Ride Comfort

Variability of acceleration, deceleration and lateral maneuvers.

To achieve a high level of comfort for the driver and passenger on the AHS, the computer control will be designed to filter and smooth out drastic changes in velocity and trajectory. The overall control algorithm will minimize the number of accelerations and decelerations based on an optimal spacing chosen with safety in mind. This will of course be overridden in the event of emergency maneuvers.

The computer control can gauge how “aggressive” the driver is and how willing they are to shift lanes by the setting that they choose for the aggression factor for the headway spacing. Additionally, the decision for shifting lanes will be based on the differential speeds between the set speed of the automated vehicle and the vehicle in front of it. If a large differential in velocity is measured, then the vehicle will initiate a lane change. A driver who is comfortable with very small headways would most likely prefer to change lanes quickly when coming upon a slower vehicle. Those who chose a larger headway spacing might be content with following a slower vehicle for a longer amount of time before deciding to switch lanes. Once again, the driver can resume control at any time to initiate a lane change and then return back to automated mode.

The transition between manual and automated mode and visa versa will be accomplished by a gradually shift in weights between the vehicle control and the driver control. The change will be fluid and transparent to the driver and passengers.

Ride comfort is a key issue for the social acceptability of an AHS. Drivers must feel as or more comfortable as they are on conventional highways.

Vehicle Certification

Frequency, time needed, and cost to certify each vehicle.
Once the AHS specific equipment is installed on a vehicle, there will be no need to recertify it unless a malfunction occurs. The onboard diagnostics will keep track of necessary maintenance and will not allow the vehicle to engage automated mode until any problems are fixed.

Retrofitting existing vehicles will cost approximately $1000. Many features necessary for the AHS will already exist on most newer cars, therefore the newer the car the less expensive it will be to bring it up to AHS standards.

The CIMS architecture is optimized when all vehicles have a ultrawideband transmitter on board. The UWB technology is proposed as very affordable and could conceivably be used for many ITS applications such as electronic toll tags. Installing UWBs on all new cars prior to the implementation of an AHS will allow the CIMS architecture the ability to locate exactly almost every vehicle on the highway. The CIMS proposal can still fully function in a collision avoidance mode when surrounded by vehicles without a UWB transmitter, but the best performance will be seen when all vehicles have a UWB on board.

1.5 Reduced Environmental Impact

Some reduction in fuel use may be possible, but will not be significant until dedicated facilities are established. More than likely the initial impact will be to travel more miles with the adverse environmental consequences. However, these additional miles will be intercity and will not contribute to urban pollution.
2.0 USER SERVICES OBJECTIVES

2.1 Disengage The Driver From The Driving

**Driver engagement**

*The percentage of time on AHS driver is allowed to do non-driving tasks*

During the initial stages of deployment, the driver will retain the option of switching to manual mode when they please. Exiting off the highway or passing a slow moving vehicle will, for the most part, require the driver to perform the action. Other than situations like these, the driver is free to engage in any activity they want to.

Final deployment of the AHS will incorporate designated automated lanes that will free the driver’s time even more. These lanes will allow the driver to sleep while the AHS handles all driving tasks up until the appropriate exit nears.

**Driver tasks**

*The events that require driver interaction*

Driver interaction on the AHS whether during initial or final deployment is minimal. Engagement and disengagement of automated driving during normal operation are the driver’s responsibility. During initial deployment, the driver has the option of switching to manual mode by simply grabbing the steering wheel or touching the accelerator. Lane changes around slow moving vehicles and exiting automated mode for an upcoming exit fall under the driver’s responsibility.

For emergency situations, the AHS will maintain significant control until the situation has passed. In the event of failure of the AHS, the driver will work with the malfunction management protocol of the system to regain control.

In a dedicated AHS lane scenario, the only driver actions necessary are engagement and disengagement of automated mode.

**Ease of reengaging the driver**
How difficult will it be for the driver to regain control of the vehicle.

During initial deployment, our architecture is designed to make it very easy for the driver to regain control of the vehicle at almost any time. The AHS constantly scans for driver input at the steering wheel, brake and accelerator pedals. If these inputs are judged to be deliberate and not spurious, the AHS will smoothly turn over control of the vehicle to the driver. The weights given to computer control will slowly be decreased as the weights given to driver control increase. In this manner the transition to manual mode is performed seamlessly.

In a dedicated AHS scenario, the driver will signal their desire to return to manual mode by using the steering wheel, brake or accelerator. Once the AHS has determined that it is safe for the vehicle to leave the dedicated lane it will transfer control to the driver as described above. This protocol is necessary due to the potentially large speed differentials between dedicated lanes and mixed mode traffic.

2.2 Facilitate Intermodal And Multimodal Transportation

Mode connectivity

*Distribution of modes directly supported/connecting to AHS highway vs. conventional highways per lane kilometer*

Our architecture will have the same distribution of transportation supported by conventional highways during the early stages of deployment. Eventually, the AHS might provide greater connectivity and a more seamless connection between the highway and other modes of travel. For example, a vehicle might eventually have the ability to drive itself directly onto a freight train or cargo ship. Trucks could be automatically loaded or unloaded at a dock or rail yard and then automatically drive to a final destination.

Mode interfaces

*Incentives for efficient use of resources*

- By mode (vehicle type)
- Infrastructure

The incentives for other modes of transportation are essentially the same as those for passenger vehicles. Transit, and especially trucking will benefit from the increased traveling distances that the AHS will allow due to the opportunity to rest and sleep along with the increased gas mileage afforded by consistent automated control. In addition, the AHS will eventually help in reducing congestion, making it transit and shipping easier and more dependable.

Mode specific training

Training costs and requirements for transit and commercial vehicle operators (including taxis) beyond regular AHS training.

The training for various modes of transportation will be exactly the same as normal passenger vehicles. The AHS will be aware of the different vehicle dynamics of each unit in the system, and the driver need not perform any special duties besides the normal engaging of the AHS.

Indirect mode benefits

Improved passenger delivery/pickup at ports (air, sea, rail)

In time, automated travel will connect the highway with alternative ports such as airports, sea ports and railway stations. For example, one could designate their airline, and the vehicle will have the ability to drive to the particular entrance. Someday, the car might even be able to park itself after dropping the driver and passengers off for their trip.

2.3 Enhance Operations For Freight Carriers

Improved safety of freight carriers

Accident rates involving commercial vehicles on an AHS vs conventional highway
Commercial vehicles have a higher risk of accidents due to their unwieldy vehicle dynamics, poorer safety in inclement weather and a greater chance that the driver is tired. An AHS will help improve the safety of commercial vehicles in all of these areas.

The AHS will have better control of the vehicle and will ensure that proper headway is maintained to optimize to safety of the vehicle. In addition, the AHS will help to minimize fatigue in the driver by freeing them from the driving task.

The accident rate will be much lower on the AHS than on conventional highways. By keeping the commercial carriers within their safety limits and reducing driver fatigue, the highways should be much safer.

**Increased throughput of freight carriers**

*Capacity of lane to move goods and commercial vehicles*

During the initial stages of the AHS, safety will be the primary concern while throughput will be secondary until enough automated vehicles are on the roadway to justify dedicated lanes. Therefore, throughput will be about the same as a non-AHS highway during initial deployment. Throughput might be a little bit higher due to the reduced number of accidents and incidents due to the increased safety on an AHS.

Once the number of automated vehicles and trucks has reached a point to allow for the dedication of one or several lanes for automated only travel, the throughput will increase significantly. These dedicated lanes will allow for much greater speeds and reduced headways without increasing the chance of accidents.

**Length of time needed for CV inspection**

*Reduction of the amount of time needed for vehicle inspection, both per inspection, and per trip*

The diagnostic systems onboard automated vehicles will have an integral tie in with many of the vehicle’s vital functions. This tie in will make it extremely easy to inspect the vehicle for satisfactory performance by accessing the AHS diagnostic system. The requirements for automated travel are more strict than non-automated travel, therefore the diagnostics of the AHS will provide the same if not better information as conventional inspections. Checking the diagnostic system will be much faster and easier than manually checking each function on the commercial vehicle.
Predictable trip times

*Predicted trip time error rate on AHS vs conventional highway for commercial vehicles.*

During the initial stages of deployment, before any AHS lanes are dedicated, the trip time error rate of the AHS will be essentially the same as conventional highways. As dedicated lanes become available for automated vehicles, the predictability of trip times will improve significantly. These lanes will travel at a uniform velocity and density making predictions more reliable.

2.4 Support Automated Transit Operations

**Capital Costs**

*Facility costs for transit under AHS*

The facility costs for transit under AHS will be slightly higher than conventional transit systems. This increase in costs is directly related to the increase in complexity of the buses. The installation and maintenance of the AHS specific equipment will require an increase in manpower, equipment and time. As more and more public vehicles switch over to AHS, this cost will be shared among government agencies.

**Safety of transit carriers**

*Accident rate involving transit vehicles on an AHS vs conventional highway*

The safety of transit vehicles in an AHS environment will be greater than in a conventional highway. The greater control that the AHS has over headway spacing and lateral collision avoidance will decrease the accident rate involving transit vehicles.

In a dedicated lane environment, the increase in safety is even greater. By removing the random element of non-automated vehicles, the AHS has control over almost all aspects of the vehicles in the dedicated lane. This makes it much easier to deal with emergency situations and collision avoidance.

It should be noted that some of the equipment used for AHS travel will be beneficial on city streets as well. Obstacle detection and some communications capabilities are perfectly suited for city streets as well as AHS.
**Throughput of HOV Lanes**

*Capacity of lane to move transit and HOV passengers and vehicles*

For the early stages of deployment, safety will be emphasized over throughput. For this reason, the capacity of the lane to move transit and HOV passengers and vehicles will not be significantly higher than on conventional highways. As the number of automated vehicles and transit buses increases, the ability to take advantage of the automated control to increase throughput will be realized. Average speeds will increase and headways will decrease, creating a net increase in throughput.

**Unit operating costs**

*Unit operating costs for transit before and after AHS*

The operating costs for transit service under automated mode will be higher than under normal mode. Transit vehicles, just like automobiles, will require the necessary instrumentation for automated travel. Maintenance of the automated equipment will incur slight expense though might even create a reduction in safety inspection costs due to the increased ability of the new diagnostic system to check on many of the busses functions internally.

**Transit coverage**

*The amount of transit service added through use of AHS*

Since most transit services are on city streets, the increase in transit service from implementation of an AHS will be minimal. However, due to the reduction in fatigue from driving on the highway, a transit system could increase its coverage area by using the highway to connect different zones of service. In addition, the transit service could make use of the highway to offer more express services to major destinations.

**Transit vehicle speeds**

*Average transit vehicle speeds before and after use of AHS guideway*

In the early stages of development, where automated vehicles are mixed in with conventional traffic, the average speeds will be similar to today’s highways. However,
due to the greater consistency in an automated system, on the whole, the average speed might be slightly faster on an AHS.

When enough automated vehicles make a dedicated lane a reality, speeds will increase significantly

**Service reliability**

*On-time performance after AHS*

Those transit routes that make use of the AHS will most certainly have a better on time performance compared to using conventional highways. Automated mode will be much more consistent and predictable. The AHS might also provide a good lead in for intelligent transit systems. Arrival times could be updated based on information obtained from the AHS, making the transit schedule a dynamic one.

**Transit ridership**

*Use of transit after AHS*

When the transit system proves to the public that it is safer and more reliable under automated control, use of the transit will certainly increase. However, the added expense of the AHS equipment, and subsequent increase in fares must be compensated for by this positive impact on safety and reliability.

Additionally, the added benefits of features such as obstacle detection and increased communications will make the bus more appealing to people.

**Passengers per drive hour**

*The change in the number of transit passengers per driver hour after AHS implementation*

An AHS will not significantly affect the number of transit passengers per driver hour due to the fact that the majority of transit use is on city streets.

**Mode shift**
The number of people that begin using transit as a result in improvements in the transit system.

Because and AHS will have little impact on the transit system using mainly city streets, the number of people using the transit system after implementation of an AHS will be unchanged from today.

2.5 Apply To Rural Highway

Limitations

Limitation on operation of different vehicle types accommodated by AHS compared to conventional highways.

The CIMS design is such that it will not discriminate against any vehicle in terms of imposing restrictions on vehicle types. All vehicles could use the CIMS system in a rural setting just as in an urban setting. The rural CIMS program will essentially follow the same evolutionary structure as discussed before and will be such as to accommodate all vehicle classes at any stage of its evolution. As more and more automated vehicles become available in the rural environment, the rural CIMS will be progressively upgraded to cope without imposing restrictions on any vehicles. While restrictions are imposed on some vehicle types in using some road sections in rural environments with the conventional highway systems, this will not occur with the CIMS.

Vehicle class

Limitations on different classes of vehicle within a vehicle type accommodated by rural AHS compared to conventional rural highways

This follows the same discussions as in the previous section. As indicated there will be no limitations on different types of vehicles nor different classes of vehicles within a vehicle type. For example all types of trucks such as multi-unit truck will be accommodated on the AHS system just as any other kind. Unlike, the conventional highway system where there is sometimes limitations on vehicle weights that crosses certain boundaries and only at certain times, the CIMS design concept has no such biases.

Rural road access
Percentage of rural roads equipped to support full or partial AHS capabilities

The general CIMS design concept will apply to rural roads just as it will apply to urban roads. This means that the equipment of rural roads to support AHS capabilities will be evolutionary in nature. Very few miles of roads will be equipped at the initial stages. This will however increase with the number of automated vehicles. In this manner any upgrading of the rural roads to support AHS capabilities can be justified by the number of vehicles seeking to use it. This will also make it financially sound since the cost of upgrading can be imparted to the vehicles using the road through the use of tolls etc.

2.6 Support Travel Demand Management And Travel System Management Policies

Demand management

Ability to provide priority to multiple-occupancy-vehicles

The CIMS design concept will be such as to support local travel demand management policies. Provisions will be made under this new technology to accommodate HOV lanes, congestion and parking pricing and any other strategies developed to reduce congestion. The CIMS system shall be compatible with systems that allow financial incentives to promote transit use. There will also be improvement in transit access points and stops to encourage its use. In early stages of deployment, for example, when there is limited dedicated lanes and the number of automated vehicles seeking to use it are more than the dedicated lane can accommodate, but the automated vehicles are not high enough to warrant full automation of an additional lane, the travel demand management policies will serve an excellent purpose for the temporary management of the system. Other features of the system to promote transit usage will be trip time predictability and information systems at terminals to give indications of transit locations on the routes.

Induced travel

New travel resulting from AHS

There will be new travel resulting from the deployment of the CIMS. There is no doubt people will make more trips, especially non-work trips when the highway system is automated. Currently people forego certain leisure trips or use other modes such as air because of the level of congestion they will have to put up with, the inconvenience of
traveling, inability to predict the travel times with reasonable degree of accuracy. With the deployment of the CIMS all the above handicaps of travel on conventional highways will be significantly improved. The AHS shall also facilitate usage by the aged, impaired and inexperienced drivers, hence people who could not drive on the conventional highway systems will be driving on the automated system. In the early stages of deployment however the induced travel will be low, since vehicles will be operating in mixed mode and the system will not be as convenient as when it is fully automated.

**Dependence**

*Local degree of dependence on the automobile or public transit for mobility*

The automated system is expected to improve the usage of both the automobile and transit. Since people generally prefer to drive their automobiles, there is the likelihood of no shift of automobile users to use transit unless the demand management policies mentioned above are adopted. This will work particularly well during the initial deployment stages when there is only a partial automation of the highway system.

### 2.7 Support Sustainable Transportation Policies

**Introduction**

One of the issues of primary importance that needs to be addressed under the new AHS concept (CIMS) is that of support of sustainable transportation policies. These embraces two major areas namely land use and energy use. Each of these has been briefly described below.

**Land use**

*Does not require extra land or encourage unmanageable growth*

One of the great advantages of the proposed CIMS over the conventional highway system is that, the conventional highway system requires more land use to handle the same volume of traffic as compared to the automated CIMS system. This is because of the high capacities associated with the CIMS, especially in its final stages of deployment. This coupled with the fact that the CIMS system has significant safety
advantages makes it highly appealing. As such there will probably be very limited or no additional land use requirement besides the existing right of way for the automation of the highways.

In addition the CIMS, does not encourage unmanageable growth. The evolutionary concept of the CIMS makes it very handy to manage it in sequential stages as it evolves. A rapid and sudden growth would make it very difficult to manage.

**Energy use**

*Changes in fuel resources consumed per kilometer of passenger travel*

The implementation of the CIMS will be more energy efficient than the conventional system, especially in the long run when the system becomes fully automated. With the system automated, there will be steady flow of traffic which will improve fuel economy as compared to the stop and go traffic conditions that characterize the current conventional highway system. Also, this system will allow for the use of alternative and more efficient fuels. As a result the CIMS will reduce fuel consumption and tailpipe emissions per vehicle kilometer traveled as compared to conventional highway driving.
3.0 DESIGN CHARACTERISTICS

3.1 Easy To Use

**Driver in-vehicle interface**

*The time required to learn system and control operations. Degree of driver training, skill or certification needed to gain access to the AHS compared to that needed for access to conventional highways.*

The amount of training necessary for operation of the AHS is no more than the training required for operating cruise control. Automated mode is engaged by way of the same protocol for engaging cruise control. The only addition is setting an “aggression factor” for determining vehicle headway.

No special skill or certification is necessary, in fact people not comfortable or skilled enough to use conventional highways would be able to use the AHS.

**User acceptance of automated control**

*The degree of acceptance of the AHS*

We feel that the only way an AHS will be fully accepted is to approach its implementation in an evolutionary manner. Throwing drivers into a totally foreign environment of high speeds and small headways will only serve to increase frustration in the AHS. The initial deployment of our architecture is designed to work in concert with non-automated vehicles. The driver will set their desired speed and headway distance and will have the opportunity to switch to manual mode whenever desired. In no way are drivers “locked in” under the control of the AHS, a significant fear of many drivers.

In addition, the initial stages of deployment will require no significant infrastructure changes such as separated or raised highways strictly for automated vehicles. Such architectures are extremely expensive and might foster a “haves and have not” situation among automated and non-automated vehicles.

As drivers become more comfortable with driving in automated mode their acceptance of it will increase. When a breakpoint in the number of automated vehicles is reached, some lanes will be dedicated to automated mode only. These dedicated lanes will have the capabilities of higher speeds and smaller headways. By this time,
users will feel more comfortable with the faster speeds and smaller headways afforded by automated travel.

**Emergency Response**

*Difference in degree of driver participation required compared with the present system*

Emergency response protocol will attempt to minimize the driver’s participation as much as possible. In many situations, the computer will have the capability to respond far faster than a human driver could. The AHS will be responsible for the emergency response until such a time as it requires the driver to exit from automated mode and into manual mode.

Errors in automated mode will follow a designed malfunction management protocol geared towards minimizing the driver’s participation. Only in the event of catastrophic failure of the AHS will the driver be required to immediately take over control of the vehicle.

**3.2 Operate in Inclement Weather**

The system is designed to optimize safety. This is true in any weather scenario. If the dynamics of the vehicles are adversely effected by the inclement weather then the algorithms can adaptively adjust the spacings to compensate. In addition, the infrastructure has abundant knowledge of the road and weather conditions and can take those into account in the control process. The vehicle based sensors may experience some degradation in some conditions and must be accounted for in the sensor fusion process.

**3.3 Ensure Affordability And Economic Feasibility**

**System life-cycle cost**

*The total discounted cost of an AHS implementation over the operation life-time of the facility*

According to the Cost Evaluation performed by the AHS Consortium on September 20, 1995 for cost element No. 4 (Operations and Maintenance Costs), our architecture falls in a mid-priced range. Our architecture is infrastructure managed
(relative score of 7), incorporates full mixing of traffic modes (rel. score of 1) and uses auto sense/auto avoid for obstacle detection (rel. score of 5). In applying the designated weights given to each of these dimensions, the architecture has a scaled score of 50/100: right in the middle.

**Infrastructure capital costs**

*The cost of AHS implementation, including instrumentation of the roadway and installation of zone or regional equipment. Total capital costs compared to that of conventional infrastructure*

The Cost Evaluation of Element No. 1 (Infrastructure and Support Capital Cost - Civil/Structural) ranked our architecture as extremely low cost in this area. The architecture supports full mixing of AHS and non-AHS vehicles (relative score of 1) and complete mixing of classes of vehicles (rel. score of 0). After applying the designated weights to these scores, our total score in Infrastructure and Support Capital Costs is 8/100. This score is extremely low compared many other architectures for this design area.

**Infrastructure operation and maintenance costs**

*The cost of labor and equipment required to operate and maintain AHS specific instrumentation and equipment in the infrastructure*

In Element No. 2 (Infrastructure and Support Capital Costs - Systems and Instrumentation) we are infrastructure managed (rel. score of 7), a mixture of free agent and platooning (rel. score of 10), and use auto sense/auto avoid for obstacle detection (rel. score of 5). After multiplying by the noted weights, our total score is 69/100.

**Societal costs and non-user costs**

*For example, crashes, mobility, economic growth, air pollution, noise, and neighborhood disruption*

The societal costs will be minimal for this AHS concept. No AHS specific construction is necessary as with many other concepts. Our architecture is designed to use the existing roadways and work with mixed mode traffic.
The major emphasis is placed on safety in this concept. By reducing the human element in the system, it is hoped that the number of traffic accidents will drop significantly. This will have a positive economic impact by reducing insurance expenditures, and out of pocket expenses for injuries and accidents.

Economic growth is expected due to the ease of travel that the AHS affords. More people will be willing to make longer trips using and AHS and tourism related industries will gain from this growth. Air pollution due to the greater vehicle miles traveled might increase, but due to the AHS’s ability to drive more consistently and at more constant speeds, the vehicle’s engine will operate more efficiently and produce less harmful emissions.

**User Costs**

*Traveling time of drivers and passengers (including access time). Net change in capital and operating costs for transit and commercial vehicle operators.*

The increase in productivity due to the increased efficiency will have a major impact on the national economy when the AHS is fully deployed. Not only will trip times be reduced, but, the use of the time during the trip will become productive. The driver will be more ready to start producing upon arrival at the destination due to decreased stress and more preparation time.

For commercial operators the net operational savings will more than make up for initial and on going AHS costs.

**Bus or truck specific costs**

*Capital/maintenance/operational costs of AHS capable bus/truck to AHS ready and non-AHS bus/truck*

The heavy duty nature of the actuators and equipment required for trucks and buses will make the capital costs higher than light vehicles. However, the operational margin considerations are greater in the commercial vehicle industry and make payback much quicker.

**Benefits and/or willingness to pay**

*The ability and willingness of all segments of the population to pay the AHS costs*
A major stepping stone in implementing the AHS is getting the majority of the driving population to buy into the AHS. They must feel that it is worthy of their income and tax dollars. This concept tries to minimize the have vs. the have-nots syndrome by not needing physically separate lanes and attempting to balance costs between the infrastructure and the vehicle.

**Automobile vehicle purchase costs**

The price of AHS specific equipment on the vehicle.

The fate of an AHS lies in the hands of the public. If the cost of outfitting a car for AHS travel is beyond the means of the average driver, then an AHS is doomed. The cost of AHS specific equipment will not exceed $2000 per vehicle. We feel that this is the upper limit that the majority of drivers will be willing to pay for and AHS equipped vehicle.

**Automobile capital vehicle cost**

Capital cost of AHS capable automobile to AHS ready and non-AHS automobile.

Our architecture strives for a balance between the cost of the infrastructure and the cost of the vehicle. According to the Cost Evaluation Element No. 3 (Vehicle Base Capital Cost Instrumentation) we rank very well compared to many of the other proposed concepts. As an infrastructure managed concept we received a relative score of 3 and due to our auto sense/manual avoid for obstacle detection we received a relative score of 6. After implementing the weights, our total score is 51. Many concepts were judged more expensive in this category and only one was judged lower than this style of architecture.

**Automobile maintenance costs**

Maintenance costs (e.g. inspection and repair of AHS-capable automobile to AHS ready and non-AHS automobile.)

Much of the additions on the vehicles for AHS operation will be solid state electronics and sensors. These sub-systems tend to be very reliable and often outlive their host systems. If properly designed the system will have self diagnostics and be capable of quick replacement.
Automobile operational

Operational costs (e.g. fuel) of AHS-capable automobile to AHS ready and non-AHS automobile.

Operating costs of AHS vehicles are likely to be less than non-AHS automobiles. The computer control of these vehicles is much smoother and more consistent than human control and will lead to a more efficient driving style. Over long distances, this smoother driving will translate into better fuel economy.

Enforcement cost

Change in policing costs

During the early stages of deployment, there will be no need for any changes in policing on the AHS because of the ability of the architecture to operate in mixed mode traffic. However, when the time arrives where lanes are dedicated for automated use only, some policing will be required.

The AHS itself will be able to detect when a non-automated vehicle is using an automated lane. The AHS can then inform the suitable authorities of this violation. In this manner, the police unit can perform other duties without having to worry about abuse on in the automated lane.

Indirect societal and non-user costs

Changes in transit fares and goods costs as a result of AHS implementation

Everything we buy in the stores came to us through the highways. The savings generated in the shipping of goods via commercial AHS vehicles will ripple through to the consumer in lower prices at the marketplace.

Availability of funds

Are funds for infrastructure modifications available to use
Initial funding will be to improve safety and convenience over long trips and at dangerous spots. Public/private partnerships are likely to sell the service to the users. Later deployment will be a substitute to adding new lanes to expand capacity.

**System liability**

*Changes in legal costs associated with the implementation of the AHS*

Initially there will be little change over the current system. However, the increased safety as more vehicle are AHS capable will reduce the legal costs associated with liability claims. Any AHS system should be designed to never have an accident. Anything short of that will make the liability a problem that will be unbearable. If designed properly, then the AHS will so improve safety that the occasional failure will be countered with the weight of the statistics that prove its safety.

**Education**

*Additional cost to train users of the system*

- Drivers, operators, passengers

The operation of this AHS concept is designed to be as easy as possible. Engagement of the AHS will follow the same protocol as using cruise control, while disengaging the AHS will only require the driver to use the steering wheel, accelerator or brake showing a deliberate desire to return to manual mode.

Very little, if any formal training will be necessary for drivers, operators or passengers.

**Property loss**

*The total annual cost in dollars of all accident-related property losses. This includes vehicles (light transit and commercial), damage, transportation facility damage, and damage due to hazardous material crashes*

Property losses are expected to decrease after implementation of the AHS. The primary focus is on safety for this concept, and this increased emphasis will dictate a decrease in traffic accidents on the highway. All modes of travel including light transit, commercial, and hazardous materials transporters will benefit from the increased safety.
Out of pocket expense

Fee for automobile/bus/truck per VKT needed to defray the infrastructure capital and operating costs.

It is projected that by the time an AHS is implemented, much of the necessary instrumentation will already be on-board most vehicles. This will make the costs of the vehicle within reach of most drivers. The infrastructure costs will have to be defrayed by the local governments and driving public alike.

Some possibilities include implementing the AHS on designated toll roads or implementing a gas tax. These tolls and/or tax must be reasonable in order to not drive the public away from the AHS. It might be the case that local and state governments find that implementing and AHS will be more economical than building new roadways.

3.5 Provide Beneficial Impacts On Conventional Roadways

Introduction

A design approach of the Cooperative Infrastructure Managed System (CIMS) is capable of addressing the traffic safety problems and gradually increasing traffic throughput. The CIMS design concept has the fundamental objective of improving safety and driver convenience in its initial stages. The design is such that, the tasks that are best suited for the infrastructure will be performed at the roadside and those best suited for the vehicle will be performed in the vehicle.

The ability of the system to reduce the reaction time of the drivers by taking into account the vehicle dynamics within the network will tremendously help improve safety. Studies have indicated that 50 percent of all rear end and intersection-related collisions and 30 percent of collisions with oncoming traffic could have been avoided, had the driver recognized the danger half a second earlier and reacted correctly. Over 90 percent of these crashes could have been avoided had the driver taken appropriate measures one second earlier. The ability of the automated vehicles to operate in a synchronized manner in which case a failure of one of the vehicles will automatically transmit a signal to all others ensuring a synchronized response will be invaluable in accident prevention.
The system design assumes features on the vehicle that will improve its performance on non-automated highways. Some vehicle based design features of the system that will help improve safety include:

- Automatic obstacle detection
- Automated collision warning systems
- Back-up warning and side collision warning systems
- Driver vision enhancement and assistance systems

In this section, the beneficial impacts of the proposed AHS on trip time, arterial loading, interface congestion, and throughput reduction on conventional roadways have been described.

**Trip Time Reduction on alternate conventional highways**

*Average reduction in trip time due to increased capacity on AHS lanes reducing demand on conventional highway lanes*

The CIMS concept addresses safety issues at the early stages of deployment and then throughput at later stages as the system evolves. The safety features that will be incorporated in both the vehicles and the infrastructure will be upgraded over time to accommodate the increasing number of automated vehicles. Safety features on the vehicles and the infrastructure such as collision avoidance systems, automatic obstacle detectors etc. will help reduce incidents. The reduction in incidents which are the main causes of delay will lead to reasonably low travel times on the CIMS. Thus, although the CIMS system will not provide high throughput and speed increases at the initial stages, it will be more attractive as compared to the conventional highway system. The effect will be a redistribution of traffic as more vehicles will prefer to use the AHS systems. This will contribute to smoother traffic flows and reduction (although minimal) in travel times on the conventional roadways thereby resulting in a reduction in average trip time over the entire network.

With the gradual development and sequential technological improvements of the system, such as synchronization of the vehicles, it will be possible to finally operate the vehicles at close headways, thereby increasing throughput without compromising
safety. The fusing together of the multiple sources of sensory data from both the vehicles and infrastructure into layered control algorithm will help improve safety as the system develops. The increased throughput will enable more vehicles to shift from the conventional roadways to the AHS system. Also, the equipment on the AHS equipped vehicle will provide some level of safety benefits on non-AHS roadways. The systems will provide obstacle detection and warning and rear end collision warning allowing for some reduction in incidents. Since, incidents cause a majority of the delays the trip time on conventional roadways should be reduced. Reduction in volume on the conventional highways and secondary use of AHS equipment implies reduced average trip times on the entire network.

Arterial Loading

The number of vehicles traveling AHS access and egress routes in excess of existing traffic patterns

As outlined in the previous section, the CIMS design concept will have several devices that will guarantee the safety of the system. This will likely make the AHS system more attractive than the conventional roadways, hence motorists will prefer to use the AHS system compared to other roadways. The result might be a minimal shift in traffic from other non-automated roadways/arterials to the AHS. This shift will be less in the initial stages of deployment since there will not be significant relative increase in AHS throughput. Hence, there will be virtually no change at the access and egress routes of the system at initial stages of deployment.

Though the CIMS design concept will not significantly increase throughput at the beginning there will be quantum improvements in throughput at the final deployment stages when more vehicles become automated. This will increase the number of vehicles shifting from the use of the conventional roadways to the AHS. Nonetheless, traffic will discharge from the AHS onto the arterials and vice versa, which means the egress and access routes will have to handle more traffic. Since the CIMS concept is an evolutionary approach, there will be a gradual upgrading of the access and egress routes to accommodate the changing traffic volumes at every stage. For example, redesign of the access and egress routes to directly connect to primary and secondary arterials, could help maintain normal flow or near normal flow conditions.
It must, however, be noted that in absence of the AHS, improvements will have to made to the access and egress routes as well. If the conventional highway network will have to be improved to accommodate the increasing volumes of traffic then four lane highways will be made into six and eight lane highways. These widened highways will hold more traffic and require modifications to surrounding arterials to handle the increased load requirements. Therefore, a side by side comparison of conventional solutions to congestion and an AHS solution show the same requirements for surrounding arterials except the fact that AHS equipment on vehicles can add some safety benefits on arterials as well as AHS roads. Also, connection to future dynamic traffic assignment systems is facilitated with the AHS instrumentation. In this case, if one arterial is blocked the vehicles can be routed around the incident. In general, this concept will be slightly superior to conventional roadways in dealing with arterial loading.

**Interface Congestion**

*Level of congestion/delay at or near the interfaces (e.g. AHS transition lanes and highway-to-arterial interchanges) and resulting environmental impacts*

As indicated in the previous sections, the CIMS has the initial objective of addressing safety concerns, hence there will not be a significant shift in traffic volumes from the conventional system to the AHS system at the initial stages of deployment. As such there will be no interface congestion issues to be addressed initially.

Unlike the initial deployment, the final deployment of the AHS will attract a significant amount of traffic onto it from the arterials and other conventional/non-automated highways because of its potentially high degree of safety and increased capacity. As a result, there could be a high level of congestion on the highway-to-arterial interchanges if there are no changes in the design of these facilities. Nevertheless, with the proposed CIMS system, the congestion problems could be significantly reduced if not eliminated. As the CIMS is expected to evolve over time from its initial deployment to the final deployment, the system design will be gradually updated to deal with any such problems. There could be longer arms or flyovers which could discharge traffic directly to secondary and tertiary arterials other than dumping traffic directly onto the primary arterials and vice versa.
Another aspect of the evolution process will be the defacto presence of collector roads to aid in the transition between high capacity automation and manual travel. When there are many high volume exits in a close proximity it is a normal practice to introduce collector roads parallel to the highway to allow for the acceleration and deceleration of vehicle without disrupting the normal flow of traffic. Since this concept starts with mixed mode capability and gradually adds high capacity dedicated lanes as the number of AHS vehicles increase, vehicles transitioning to the manual lanes from the dedicated lanes will do so under automation. The driver will take back control any time after he has been resumed to the mixed mode lanes. Also, the driver enters automation in the mixed mode lanes and is transitioned to the dedicated lanes automatically. Therefore, the remaining mixed mode lanes serve as a collector road for the dedicated lanes. Entry and exit from interchanges occurs under manual control as they do currently.

As in the previous section, it must be noted that in absence of the AHS, improvements will have to made to the access and egress points as well. If the conventional highway network will have to be improved to accommodate the increasing volumes of traffic then four lane highways will be made into six and eight lane highways. These widened highways will hold more traffic and require modifications to the interchanges to handle the increased load requirements. Therefore, a side by side comparison of conventional solutions to congestion and an AHS solution show the same requirements for interface modifications except the fact that AHS equipment on vehicles can add some safety benefits and lessen the congestion at interchanges. Also, connection to future dynamic traffic assignment systems is facilitated with the AHS instrumentation. In this case, if one entrance or exit is blocked the vehicles can be routed around the incident. In general, the presence of the mixed mode collector lanes and evolutionary approach reduce the interface congestion over current systems and have a superior approach at handling transition between manual and automated modes.

**Throughput Reduction**

**Effect of throughput reduction on AHS (e.g. inclement weather conditions and incidents/accidents on AHS) on non-AHS roadways**

There is a possibility of throughput reduction on the AHS due to inclement weather conditions or incidents which could greatly impact the non-automated roadways. The CIMS infrastructure is such that it has abundant knowledge of the road and weather conditions, hence the headway algorithms can adaptively adjust the headways to compensate without outrageous reductions in capacity. Since the system
is infrastructure managed, it synchronizes the response of the vehicles to the real-time dynamic conditions of the environment and roadway. If a vehicle detects a slippery spot on the road then all the vehicles are aware of that location and adjust their spacing and trajectory to compensate. Therefore, most situations that occur will be adaptively addressed by the system. While inclement weather and partial failures may cause slight capacity reductions they will be nowhere near current levels of reduction due to weather and accidents.

Although the CIMS system being proposed is designed for extremely high reliability and implements a detailed malfunction management system for fail-soft response, there is some small probability of a situation that could shut down the entire system. In this rare case it might result in significant reductions in capacity on the AHS highway which would cause significant increase load on the conventional highway system. The solution to this is to construct a system that is so reliable that this level of degraded performance is not encountered in a normal life time. This has significant implications on the equipment reliability and maintenance requirements. See the malfunction management section for more details.

3.6 Provide Infrastructure Compatibility

**Extent of modifications required**

There are no modifications required in the infrastructure to support the AHS system. However, the final deployment will be able to carry higher capacities without having to add new lanes. Therefore, AHS is superior to conventional roadways in that modifications are not required for a longer period of time.

3.7 Operate in a Mixed Traffic with Non-AHS Vehicles

**Cost of mixed traffic operation**

The cost of a mixed mode deployment are much less than a dedicated lane system. However, since existing roadways are mixed mode there is no savings over conventional roadways, at least for the initial deployment. Later deployments that specifically optimize the mixed mode interaction can experience gains over conventional roadways with no such optimizations.
3.8 Support a Wide Range of Vehicle Types

The CIMS concept does not limit the type or class of vehicle that can exist on the AHS roadway. Operational advantages may hasten the deployment of one class over another, but, there is no inherent part of the system that would restrict its use. However, since current roadways are fully mixed it is hard to conceive how we could score better than a 5.

3.9 Ensure AHS is Progressively Deployable

Introduction

Deployment of the AHS technology is one of the most important if not the most important part of the entire AHS program. The success of the deployment program which embodies among other things, economic feasibility, market penetration, etc. depends on research, planning, cooperation among the agencies involved and effective organization. This section discusses the feasibility issues associated with the deployment of some aspects of the AHS technology which have been deemed to be of primary importance. These aspects include (i) Infrastructure modification (ii) Usage of existing facilities (iii) Usage of existing instrumentation (iv) Traffic interruption (v) Planned upgrades (vi) Intermediate benefits (vii) Public acceptability (viii) Agency acceptability and (ix) Market penetration. Each of the these aspects have been briefly described in subsequent sections.

Public acceptability

Meets market needs of users

Convenience and safety are the primary benefits of the automated highway system, with other subsequent benefits such as reduced congestion and reduced travel times. For a concept to have public acceptance it must be acceptable and desirable at every point of its deployment. Therefore, it should be evaluated at each stage of its evolution. Vehicle based technology such as obstacle detection and collision warning systems will offer safety to the users and be the building blocks of the CIMS concept. With the additional safety of automatic lane keeping and curve warning systems the infrastructure will begin to be deployed. Cruise control including lane keeping will also make the driving task more convenient. As these lane keeping systems become infrastructure managed systems the user will gain additional safety and convenience benefits as well as some gradual throughput benefits. Finally, as dedicated lanes are deployed in urban areas there will be significant reductions in congestion.
The convenience and comfort of travel together with the high degree of safety and reduced travel times afforded by the CIMS is enough to make it acceptable to the general public. The frustration of long delays that motorists suffer today in traffic queues will be eliminated. In addition, the new system will be reasonably affordable since the cost will be distributed among the infrastructure and the vehicle. The improvements in the vehicle include processing, sensors, communications and user interface and will be within the willingness to pay of the users. Other systems such as toll collections, etc. will be introduced to pay for the infrastructure cost which will be distributed over a long period. Many other great advantages that make the system more acceptable such as the reduced environmental impact due to the use of more efficient and more steady flow of traffic will add to the public acceptance. See the social acceptance section for more details.

**Agency acceptability**

*Meets local needs and mandates of the transportation agencies*

Transportation agencies such as Departments of Transportation will be well disposed towards the deployment of the CIMS as it will meet their local needs and mandates. Reducing the death rates on the interstates will be the primary concern for the DOTs. The system will be more desirable to the agencies than the conventional highway systems. Significant advantages such as reduced congestion, environmental quality and safety improvements are just a few of the benefits that will warrant its acceptability by local agencies. Unlike the conventional highway system, the organized fashion in which the CIMS will operate will help provide local agencies with more accurate traffic databases which will be useful for other transportation system management purposes.

**Infrastructure modification**

*Cost of infrastructure modification*

The CIMS technology will necessitate the modification of part of the existing infrastructure so as to be able to achieve the desired results. Considering the nature of the CIMS technology being proposed, there will not be any major problems involved
with modifying the existing infrastructure. The fact that the proposed CIMS technology will be an evolutionary process relatively simplifies the infrastructure modification task.

Since there will be no dedicated lanes at the early stages of the CIMS deployment and vehicles will be operating in mixed modes, there will be no need for civil infrastructure modifications such as lane additions etc., hence there will be no costs. However, as more and more vehicles become automated and there are dedicated lanes in place, there will be the need for additional civil infrastructure such as barriers with gaps for lane separations. The cost from this will however be modest and will be justifiable because of the immense benefits as compared to conventional roadways.

The electronic infrastructure modification task will be in stages just as the entire AHS technology. The implication is that, the modifications will be made progressively as they are needed. While, the cost of modification will be initially low, it could be relatively high as the system gets more advanced and more and more vehicles are getting to use the system. However, the nature of the proposed AHS will make the overall modification relatively cheap and more effective than a system which embarks directly on the advanced stages of AHS. The reason being that, the performance of a previous stage will make it possible for changes to be made in a predesigned program before its implementation. Also, by the time of the CIMS deployment, other components of the ITS such as ATMS and ATIS would have sufficiently developed, hence most of the electronic infrastructure needs would have already been in place, thus reducing the cost of the needed infrastructure for the CIMS.

**Usage of existing facilities**

*Percentage of existing infrastructure not requiring modification for AHS*

In the initial stages of deployment, virtually no modifications will be required to use the existing civil infrastructure facilities. Also, given that the ATIS and ATMS technologies would have been in place by the time of the CIMS deployment, a great deal of modification will not be required for the use of existing electronic infrastructure facilities at the early stages of deployment.
The facilities requiring modification will however increase as the system evolves towards the final stages of deployment, since more and more vehicles will get automated. However, this will gradually build upon previously existing facilities, thus will not make the system too complicated to understand.

**Usage of existing instrumentation**

*Percentage of automated control functions achieved using previously available services*

The deployment of the CIMS do not require a major technological breakthrough. In most part, the technologies already exist and all that is needed is the integration of these technologies to achieve the desired results. By the time of deployment of the CIMS, most communication facilities (fiber optics) and sensors from ATMS and ATIS would have already been in operation. Most of the in-vehicle devices such as communication systems, user interfaces and processors might have been already in use. Thus this makes the deployment of the entire technology relatively cheap. However the possibility exist that, there might be the need to develop some new devices for integration with existing ones in the advanced stages of the AHS.

**Traffic Interruption**

*Interruption to existing level of service for AHS deployment*

There will be very little interruption of existing traffic, if any at all during the deployment of the CIMS technology. Most of the required infrastructure for the CIMS will be deployed by the road side and therefore cannot interfere with traffic. At the final stages of deployment where there might be the need for placement of barriers and other modifications to the civil infrastructure there is the likelihood of interference with existing levels of service. However, this will be very minimal, given the nature of such operations. Also, since the deployment of the CIMS is an evolutionary process, it implies that changes to the highway system will also be gradual, thus minimizing any traffic interruption effects, if any at all.

**Planned upgrades**

*Applicability of planned infrastructure modification independent of future deployment of AHS*
It could be feasible to carry out modifications on the planned infrastructure independent of future deployment of AHS, depending on the organization of the system.

By taking advantage of the structure of the system being proposed, it will be possible to embark on any upgrading of the infrastructure without affecting future deployment programs. This design is envisaged as organized in a form such that various components could be designed independently and then integrated for operation, thereby facilitating independent work on any component. In the case of any repair work on any part of the system, rerouting can be done by reprogramming the dedicated lanes.

**Intermediate benefits**

*Safety and capacity benefits at intermediate deployment stages*

The planning of the AHS system is such that it will begin to yield benefits right from its inception. The benefits will primarily be in the form of improved safety at first hence reduced accidents to achieving higher capacities and reduced travel times while still maintaining or increasing the degree of safety. Thus safety, improved speeds, and capacity benefits are feasible at every stage of the deployment process. This contributes to the overall feasibility of the program. The intermediate benefits will attract more and more users who were not originally using the system. Also, depending on the mechanism adopted the monetary benefits that accrue at early and intermediate stages from tolls etc. could be used to pay for the advanced stages.

**Market penetration**

*Percentage of vehicles in place to use the AHS*

As stated earlier, not many vehicles are expected to use the proposed AHS at the initial stages. This will be partly due to the fact that only limited highways will have the necessary automated facilities and also not many people will own the vehicles with the relevant devices initially. Nonetheless, as the system develops and more and more facilities get automated, market penetration will go up. Motorists not previously using the system will begin to see the benefits of the system. The gradual increase in market penetration will generate more and more revenues which could be used to finance the advanced stages of the AHS program. In general market penetration will start from 0 percent and will ultimately reach 100 percent.
3.10 Provide High Availability

Introduction

High availability of the proposed AHS system, in general terms includes such factors as system utilization (i.e. system on line percentage or system off line percentage), reliability, downtime and downtime distribution, mean time for repair and maintenance frequency. These issues pertaining to high availability of the AHS have been discussed in the subsequent sections.

System utilization

The fraction of time that the AHS operates at full service

System utilization refers to the percentage of time that the AHS system will be in use or in service. The high safety nature of the proposed AHS system will attract a lot of users to it right from inception. The fact that it will be a lot safer system than the existing conventional highway system, will induce motorists to shift from the conventional highway system. Since traffic conditions vary throughout the day with high volumes during the peak periods, it is expected just as on any highway that utilization of the AHS system will be relatively low during non-peak periods. However, it will be of full utilization during peak periods. Over time when throughput on the AHS system increases more and more vehicles will be attracted to it.

The full utilization of the system can be increased by a proper linkage of the system with some traditional traffic demand management measures such as staggered work hours. Since some vehicles might not be able to use the AHS system during the peak hours when it is already at full utilization, implementation of staggered work hours which enable workers to spread their departure times over the day could increase the full utilization of the system. Motorists that might use other highways (conventional highways) during morning peak because of the high volume on the AHS could then use the AHS later in the day because of the shift in their departure times.

Reliability

The mean time between failures of automated subsystems integral to AHS operation

The reliability of the AHS system here refers to the mean time between failures of automated subsystems which are integral to the AHS operation. The design concept of
the system is to ensure the performance reliability of the system, hence the subsystem
integral to the AHS operation will be of high design standards. This design criteria will
reduce the relative rate of failure of the system and hence mean time between failures.
It must however be recognized that every component of the AHS system will be
sufficiently equipped with back-ups such that the failure of any of the system
components will not affect the functionality of the system.

**Downtime and down time distribution**

*Downtime duration and affected area per unit time per lane-length for AHS compared to
conventional highways*

As stated earlier, every component of the proposed AHS system will have a
sufficient back-up such that its failure will not affect or interrupt the operation of the
system. There might however be situations (although rare) such as major power
failures etc. when the whole system will be inoperative. The probability of such
occurrences in the CIMS design is however very minimal. Nonetheless, if any of such
major failures should occur, the affected area per unit time per lane length will be
significantly higher with the CIMS system than on the conventional highway system.
This is because of the coordination that will exist with the automated system so that
such failures will not be localized as will be the case with the conventional highway
system. Such failures will however be almost immediately corrected if they should
occur at all, because of the high efficiency of the system and the available back-ups to
take care of such emergencies.

**Mean time to repair**

*The time required to restore service*

The mean time to repair is the average time that it will take to restore service on
the AHS system after it has failed. Because of the anticipated high dependency on the
system, by its users, there will be a very efficient and all time team readily available to
correct any defects in the system. Thus the mean time to repair is expected to be
reasonably low which will enable the restoration of the system to service as soon as
possible after it has failed. Because of the high technological nature of the AHS
system, it will be easier to detect and to respond to incidents on the system early as
compared to the conventional highway system. It is however expected that, with the
CIMS, any failure will not disrupt service since control will automatically be transferred
to actuate the back-up equipment to replace any failed part.
Maintenance frequency

*Frequency of AHS roadway infrastructure inspection/maintenance compared to conventional highway infrastructure*

Frequency of maintenance of the AHS infrastructure will almost be a continuous process. Since the system is heavily dependent on high level technology, it will be constantly under check to ensure a proper functioning of all the components and their back-ups. This is because any major failure that could cause an entire breakdown of the system could have a lot more serious adverse effects as compared to similar failures on the conventional highway system. As such, maintenance is expected to be correspondingly higher than on the conventional highway systems.

3.11 Provide System Flexibility

**Applications**

The section on the evolution and the section on the ultra-wideband device both show a wide range of synergetic applications that will make transition to AHS more graceful.

**Vehicle accumulations**

There is no reason to believe that vehicles will be accumulated in high traffic areas by the introduction of AHS. The initial deployment is high volume intercity routes and later capacity increases will only substitute for widening roads. There are many other forces that determine vehicle accumulations that are much stronger influences than AHS would be.

**Number of user choices**

Initially the AHS function will be very similar to cruise control with only slight modifications. Later systems will utilize the spare time the driver has to give them more detailed choices on their route and destinations with access to a wide range of traveler information resources.
**Open architecture**

Any AHS will have some technologies that are proprietary which would make a valid response be less than 5. However, there is no reason to believe that with such a long lead time before deployment that arrangements can be made for multiple sourcing of enabling technologies. Also, there may be more than one technology that can accomplish the required tasks to an acceptable level of performance. It is too early to tell whether this concept will experience any problems. The ultra-wideband technology is being developed by a number of different sources. Other applications of the technology make it more likely to be easily attainable for AHS use.

### 3.12 Provide System Modularity

Without detailed specifications and design it is impossible to determine the degree of modularity of a system. On average we would expect it to be similar to current technologies or possibly slightly better.
### Performance Objectives

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**Enhance Mobility and Access**

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**Provide More Convenient and Comfortable Highway**

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