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Collision Avoidance: Smart Trucks on Rural Roads

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With interest in collision avoidance technology for highway vehicles on the rise, this report presents an overview of current collision avoidance technology, the technical work required to bring these systems to a commercially viable product, and the societal issues that need addressing before wide-scale deployment can occur. Many questions remain about the benefits of deploying such systems, the costs, the effect of these systems on drivers, and the steps necessary to effectively regulate vehicles equipped with such systems.

In addition to technical aspects, the report also discusses the issues that society will face during development and deployment of these systems, which may prove bigger impediments to deployment than technical issues. The report also recommends a research plan to perform fair, unbiased evaluations of emerging collision avoidance technology.

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Collision Avoidance: Smart Trucks on Rural Roads

Final Report

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Executive Summary

Collision avoidance technology for highway vehicles has received considerable attention in recent years. The big three U.S. automakers have invested significant time and money in this area, as has the National Highway Traffic and Safety Administration (NHTSA) Office of Crash Avoidance Research. This report presents an overview of the current state of collision avoidance technology, the technical work required to bring these systems to a commercially viable product, and the societal issues which need to be addressed before wide scale deployment will occur. Because of the current state of development of collision avoidance technology, many questions remain regarding the benefits which will arise from the deployment of such systems, the cost of deploying these systems, their effects on the general motoring public, and the steps necessary to effectively regulate vehicles equipped with such systems.

After a brief report on the current state of the art and what the future holds, an overview of the technical work currently underway in the area of collision avoidance is provided. Besides describing the technical side of collision avoidance technology, we also discuss the issues (i.e., regulation, liability, cost, etc.) that society will face during the development and deployment of these systems. In fact, societal issues may become a bigger impediment to the deployment of these systems than technical issues. Finally, to address the technical and societal issues involved with collision avoidance technology, we recommend a research plan which will provide Mn/DOT a means with which to perform fair, unbiased evaluations of emerging collision avoidance technology.

I. Introduction

Collision avoidance technology for highway vehicles has received considerable attention in recent years. The big three U.S. automakers have invested significant time and money in this area, as has the National Highway Traffic and Safety Administration (NHTSA) Office of Crash Avoidance Research. This report presents an overview of the current state of collision avoidance technology, the technical work required to bring these systems to a commercially viable product, and the societal issues which need to be addressed before wide scale deployment will occur. Because of the current state of development of collision avoidance technology, many questions remain regarding the benefits which will arise from the deployment of such systems, the cost of deploying these systems, their effects on the general motoring public, and the steps necessary to effectively regulate vehicles equipped with such systems.

After a brief report on the current state of the art and what the future holds, an overview of the technical work currently underway in the area of collision avoidance is provided. Besides describing the technical side of collision avoidance technology, we also discuss the issues (i.e., regulation, liability, cost, etc.) that society will face during the development and deployment of these systems. In fact, societal issues may become a bigger impediment to the deployment of these systems than technical issues. Finally, to address the technical and societal issues involved with collision avoidance technology, we recommend a research plan which will provide Mn/DOT a means with which to perform fair, unbiased evaluations of emerging collision avoidance technology.

Every successful driving maneuver incorporates collision avoidance. Although the words "collision avoidance" conjure up images of emergency action, the tasks of maintaining proper headway, turning corners successfully, and moving to the left lane to allow another vehicle to merge from the right exemplify examples of successful collision avoidance behaviors. Under most circumstances, collision avoidance remains a subconscious task; only occasionally does collision avoidance become a conscious effort. Collision avoidance systems are designed to emulate the human collision avoidance behaviors, allowing the driver to focus on other tasks.

One of the promises of the national Intelligent Vehicles and Highway Systems (IVHS) program is to help the driver avoid collisions (or reduce their severity) through the effective application of advanced emerging computer control and sensor technology. Collision avoidance systems can take two forms. The first form notifies the driver of the potential for collision, and possibly

"recommends" a countermeasure. Examples of such systems include forward looking radar used to detect objects in the path of the vehicle during heavy fog or rain and radar located around the periphery of the vehicle to warn the driver of potential collisions while backing, changing lanes, and merging. Possible interfaces range from an audible warning to a Head Up Display (HUD) which provides heading, range, and closing rate data. The second form is an automated system which senses and constructs maps of the local environment (including obstacles and road boundaries) and then computes and executes collision avoiding trajectories. In an autonomously[1] controlled vehicle, obstacle sensing and collision avoidance algorithms would run in parallel to other vehicle control tasks. This second form, termed Automated Collision Avoidance, becomes necessary when the "time to collision" is too short for a human to reason about the situation, make decisions, and take action. Both forms of collision avoidance systems require reliable sensing of the vehicle's location with respect to the road and the location of all vehicles or other obstacles surrounding the vehicle.

Autonomous collision avoidance behaviors will follow a hierarchical structure based on the complexity of the behaviors. Options will vary depending on the situation. For example in a rural interstate highway application, the first collision avoidance behavior would be for the vehicle to stay in its present lane and maintain desired speed. If the lane is obstructed by a slower vehicle, the controlled vehicle should reduce speed so that proper headway is still maintained. Speed reduction should be such that vehicles behind are not endangered. If deceleration fails, a move to an adjacent lane constitutes the next option. The move to an adjacent lane occurs only if sensory information indicates that room is available. If the vehicle is positioned next to the shoulder, the next option would be to guide the vehicle onto the shoulder and slow down. Once on the shoulder, the vehicle would attempt to move back into the traffic lane as soon as sensory information indicates that such a maneuver is safe. The above scenario may seem straightforward but nevertheless can involve considerable complexity.

The first collision avoidance system to see production will be an Intelligent Cruise Control (ICC) (or longitudinal control or headway control) system. Such systems will be capable of more than just the speed regulation provided by today's cruise control. ICC will use either forward looking radar or infrared (IR) sensors to determine the distance and the closing rate to the vehicle directly ahead. Based on this sensory information, appropriate changes in throttle position, transmission gear, and (eventually) brake application will be commanded by the vehicle controller. Such systems promise to increase traffic flow rates on rural and urban highways by decreasing the

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[1] Our use of the term autonomous does not imply that there is no driver in the cab. It is used here to describe vehicle control maneuvers that are undertaken independently of the driver.

intervehicle distance needed for safe following. Radar and IR systems have information bandwidths on the order of 1000 Hz whereas humans have a bandwidth of approximately 5 Hz. This higher bandwidth allows these systems to detect changes in relative velocity and range to target at much higher rates than humans. This higher rate of information transfer combined with the elimination of delays due to human reaction time will result in a closer safe following distance. By occupying the dead space normally reserved for safe following, throughput on existing roads can be safely increased, decreasing the need for new roads. If such systems can also be applied to slower high density traffics areas (e.g. bumper to bumper situations) then collisions due to driver inattention can be significantly reduced. However, reducing the spacing between vehicles will require more aggressive control strategies as well as increased confidence in the technology. If a driver doesn't feel confident in the technology, then the driver will not use it. Such driver acceptance is a prerequisite to the dissemination of this technology.

Leica of Germany has installed an ICC system on a fleet of Saab 9000's and has demonstrated this system both in Europe and the U.S. The University of Michigan Transportation Research Institute (UMTRI) has one of these Saabs, and demonstrated the vehicle at the "Workshop on Collision Avoidance Systems," which was sponsored by the IVHS America Safety and Human Factors Committee and the National Highway Traffic Safety Administration (NHTSA), held in Reston, VA, March 21-22, 1994. One of the authors drove this vehicle, and found it to be rather impressive in straight-line highway situations. Other unbiased drivers have also indicated that the vehicle performs well during heavy rain and at night. Such systems only operate above a minimum speed and headway threshold, usually associated with highway speeds.

The trajectories of highway vehicles are straightforward to measure and estimate. The occurrence of completely unexpected vehicle trajectories is rare, due in part to the limited dynamic capability of most highway going vehicles. However, estimating the trajectories of other obstacles becomes more problematic. For instance, a deer may run out onto the roadway; a human has trouble accurately predicting what the position and velocity of that deer will be a short time later. With the accuracy, resolution, and high information bandwidth of a radar system, real time state estimates and predictions of the deer may be developed. The ability to predict the future state of the deer can lead to the computation and execution of an optimal trajectory which avoids the deer with the least deviation from the desired path while at the same time avoiding the other vehicles on the roadway. Target state estimation and the tracking of multiple targets is performed successfully in numerous military applications, and such technology is already finding its way into consumer products, e.g., the autotracking autofocus camera.

A great deal of attention has been paid to the collision avoidance problem, especially in the recent (3-5 year) past. The majority of the work, however, consists of paper studies, analyses, reports, and the evaluation of the *components* required to construct collision avoidance systems. However, the integration of the technologies required for a comprehensive collision avoidance *system* has not yet occurred. For example, the Leica system relies on vehicle engine braking via closing the throttle and downshifting the automatic transmission. Such behavior is adequate for vehicles of relatively low inertias for which stopping distances are short. However, for a semi-tractor trailer loaded to the legal limit, the application of engine and service brakes may fail to slow the vehicle at a rate great enough to avoid a collision. In the event of such a situation, the semi-tractor trailer *safely steer around* the obstacle (possibly while braking) in order to avoid an imminent collision. Heavy trucks carry much greater yaw and roll intertias than do automobiles; this increased inertia lengthens the time it takes a truck to execute lateral position changes. To operate in the same environment as automobiles, trucks require sensors with ranges greater than those to be used on automobiles *and* the capability to avoid obstacles using steering maneuvers. The plan of the Smart Truck consortium is to integrate a number of the elements required for collision avoidance into a comprehensive collision avoidance system which can be evaluated in a number of different environments on a semi-tractor trailer. Before the plan is described in section IV, the work of other researchers in this area is described in section II, and the issues regarding the development and commercial deployment of such systems are described in section III.

II. Related work

The Office of Public Safety for the State of Minnesota annually prepares a comprehensive compilation of information and statistics regarding motor vehicle accidents in "Minnesota Motor Vehicle Crash Facts," [MnCrash, 1993]. For Minnesota in 1993, 538 people died and 4139 were severely injured in motor vehicle crashes. Losses amounted to $1.38 billion. Factors influencing these crashes include "driver impairment," which was responsible for 108 fatalities, and "following too closely," which was responsible for 7 fatalities. Semi tractor-trailers were involved in 42 fatal crashes and 624 crashes involving injury; driver inattention represented 20% of all factors which contributed to these truck crashes. One third of these truck crashes took place in rural areas with a population of less than 1000; 62% of these rural crashes took place on major highways, including interstate, state and federal trunk highways.

Crash statistics such as those listed above have prompted a significant activity in the area of collision avoidance systems. A vast supply of paper studies and analyses of collision avoidance countermeasures and systems exists in the literature. Given all of the literature concerning collision avoidance, it is interesting to note that no comprehensive research has been done with full scale hardware implementations. In this section, we provide an overview of work that has been recently undertaken.

NHTSA has sponsored a number of collision avoidance programs and currently has a five thrust R&D program to apply driver information and control technology to reduce the number and severity of crashes involving highway vehicles. NHTSA has identified areas which show the greatest potential for reductions in highway collisions. The NHTSA collision avoidance program is described in [Knipling, 1994]; a brief overview is provided below.

NHTSA is targeting driver error as a means to decrease the number and severity of highway vehicle crashes. Driver error can be broken down into three categories: recognition errors, decision errors, and performance errors. Recognition errors encompass situations that the driver "did not see" or did not perceive as potentially dangerous. Decision errors include the driver taking inappropriate collision avoidance actions; e.g., braking instead of steering. Performance errors include braking at an insufficient rate, under-steering, etc. From the three categories, the vast majority of collisions arise from recognition and decision errors. The NHTSA program is aimed at using driver information and sensor systems to provide the driver with additional time for assessing the situation and determining and executing the correct control commands. By

increasing the amount of time the driver has to assess the situation, a crash may either be avoided or made less severe.

It is our contention that heavy combination trucks ought to represent the first target for collision avoidance technology applications. First, trucks have much higher per vehicle risks and consequences for crashes due to collision; second, the incremental cost for adding a collision avoidance system to a semi tractor-trailer is considerably less (as a percentage of the vehicle cost) than the incremental cost for a standard automobile. With a successful deployment on heavy trucks, interest in automobile applications will follow.

NHTSA has sponsored research on rear and side object detection systems for collision avoidance, the results of which are reported in [DOT, 1994]. The technologies examined for rear collision avoidance were sonar based; for side object detection, both sonar and radar sensors were examined. However, the results of this research were limited in the sense that sonar sensors fail to offer the range and reliability necessary for highway vehicles. As an extension to this work, NHTSA currently is implementing a five thrust IVHS/collision avoidance R&D program as part of their Office of Crash Avoidance Research aimed at reducing both the number and severity of highway vehicle crashes.

- Thrust one targets the development of research tools and knowledge bases for identifying causes of crashes and developing countermeasures aimed at preventing or reducing the severity of crashes. Specific projects include National Advanced Driving Simulator (NADS) studies, Portable Driver Performance Data Acquisition System for Crash Avoidance Research (DASCAR) development, Quantitative Characterization of Vehicle Motion Environment (VME), Driver Workload Assessment, Crash Avoidance and the Older Driver, and In-vehicle Crash Avoidance Warnings: Human Factors Considerations. DASCAR allows a portable "flight recorder" type system to monitor driver performance in everyday driving environments. VME involves a tower mounted camera looking down onto a roadway to quantify the specific motions of vehicles in relation to traffic and roadway boundaries. Knowledge of driver behavior should allow the development of automated collision avoidance systems which do not adversely affect human drivers.

- Thrust two focuses on the identification of promising crash avoidance opportunities in order to focus resources on crash scenarios where technology applications will have the greatest benefit. Tasks undertaken in phase two include descriptions of crash scenarios

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and characteristics, assessment of countermeasure concepts in terms of technology and human factors issues, and the modeling and evaluation of countermeasure actions. Reports documenting countermeasure assessments include [Knipling, 1993], [Tijerina, 1993], and [Chovan, 1993].

- Thrust three will develop performance specifications for advanced collision avoidance technologies. These specifications will provide technology developers goals and a means with which to evaluate the performance of their systems/algorithms. These specifications may also lead to standards for collision avoidance systems. NHTSA presently has seven performance specification projects underway: countermeasures against lane changing, merging, and backing collisions, countermeasures against rear end collisions, countermeasures against roadway departure, countermeasures against intersection/crossing path, vision enhancement systems for nighttime and inclement weather, driver status and performance monitoring/drowsy driver detection, and enhanced emergency medical service response.

- Thrust four is to promote commercial development and early deployment of safety effective products. NHTSA is working with industry to promote the development of commercially viable products. Performance, reliability, cost, market-readiness, and driver acceptance are to be tested and evaluated under "real-world" conditions. Five cost-sharing cooperative projects are currently underway: Human Factors of Autonomous Intelligent Cruise Control with Ford, Forward Crash Avoidance Systems with (UMTRI) and Leica, Forward-looking Automotive Radar Sensors with the Environmental Research Institute of Michigan (ERIM) and TRW, Lane Detection with Rockwell International, and Automatic Braking for Heavy Vehicles with Eaton.

- Thrust five is to assess the safety implications of other IVHS products such as driver information systems and route guidance/navigation systems. Projects to be evaluated include TravTek in Orlando, ADVANCE in Chicago, FAST-TRAC in Oakland County, MI, and TravelAid along I-90 in Washington State.

The collision avoidance program outlined in section IV is aligned with the NHTSA program, primarily with respect to thrusts two and three.

In addition to NHTSA, other contributions to the literature are legion. A thorough review of collision avoidance technologies which includes the topics of rear-end collision avoidance

countermeasures, ICC, blind spot elimination, lane position monitors (both vision based and laser based retro-reflective), vision enhancement (millimeter wave radar, IR, CCD cameras with illumination, and ultraviolet (UV) high beams) and intervehicle communication can be found in [Fancher, 1994] and [Najm, 1994]. Human factors and driver warning system issues have received attention in [Faciane, 1993], and driver performance and collision avoidance systems have been discussed in [Clarke, 1993]. A road departure warning and intervention system is discussed in [Ervin, 1994]. This system fuses road geometry information, machine vision based lane detection, driver state models, and a man-machine interface to monitor the driver's behavior, warn the driver of potential road departures, and take control of the vehicle if the driver fails to respond and road departure is imminent. A prototype system has been used for simulation, but the system has not yet been integrated and installed in a roadworthy vehicle.

To ensure that vehicle control commands will not cause other serious problems (i.e., spins, skids, jackknifing, etc.), an adequate vehicle dynamic model is required. The vehicle dynamics of both front wheel drive and rear wheel drive cars can be found in [Allen, 1986]. Here, the effects of tire quality, drivetrain layout, vehicle mass were extensively studied on a Honda Accord (front wheel drive) and a Nissan Sentra (rear wheel drive).[2] In a more recent work [Allen, 1993], the lateral stability of lane changing maneuvers were studied. It was reported that single lane changes rarely excite instabilities, but lane changes of 2 lanes or greater have an increased propensity to incite instability.

What has not been done to date (at least with results generated for the public domain) is the integration of radar, vehicle dynamic models, and feedback control to develop a collision avoidance package beyond ICC. Paper studies and simulation are valuable tools for research and development, but to fairly evaluate the potential of these systems, they must be incorporated into an operational vehicle. Moreover, until the public sees such a vehicle operate, technologies such as ICC and autonomous collision avoidance will remain, in their view, "pie in the sky." Unless the public has a reasonable idea of what to expect in terms of advanced vehicle control systems, many societal issues regarding such systems cannot and will not be addressed. In section III, a number of technical and societal issues which can and will affect both our development program and the commercial deployment of advanced vehicle control systems will be discussed. The role Mn/DOT and the University will play in implementing emerging technologies in an actual test and evaluation program will be described in section IV.

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[2] It is interesting to note that the experiments were performed on rental cars!

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III. Technical and Societal Issues

In this section, technological (sensors, computer hardware and software, man-machine interfaces) and societal (legal, regulatory, and public acceptance) issues involved with the design, development, and widespread deployment of automated collision avoidance systems for highway vehicles are examined. Successful deployment of advanced vehicle control systems will require much more than a technical effort; in fact, the technical issues may prove to be the least difficult. In point of fact, even the phrase "collision avoidance" is not without controversy. To some, "collision" paints a picture of destruction and carnage, and is something about which most would rather not think. "Obstacle detection and avoidance" has been suggested as a more palatable description. Another problem with perception is that the phrase "Collision Avoidance" can imply that if a collision is not completely avoided the system didn't work as portrayed, even though the crash *severity* may be greatly decreased. Seemingly minor issues like these pose significant problems for people developing and trying to market such systems to the general public.

Technical Issues. The collision avoidance system is designed to enhance the safety of the vehicle in which it is installed, adjacent vehicles, pedestrians, and the environment in which these operate. As with any safety system, reliability of the system becomes the highest priority[3]. Four components comprise the collision avoidance system: sensors, computer hardware, computer software, and control strategies (which include the human interface). Radar sensors which have been developed for military applications have been suggested as appropriate for vehicle use. The military specifications for radar are quite stringent [RADAR, 1994]; the conditions under which military radar must operate are considerably more severe than those encountered by most semi-tractors. Although testing will be necessary to ensure reliable operation, adaptation of military radar sensors should be a routine process. One major concern at the present is cost but given the potential sales volume in the commercial marketplace, costs will drop significantly.

Beyond the determination of what sensors to use lies the questions of sensor orientation, maximum range, minimum range, angular and linear resolution, number of sensors required, operating frequency, etc. Mathematical analysis and simulation can provide information regarding a starting point from which to begin testing, but they cannot replace the knowledge gained by implementing systems on an actual vehicle. Moreover, radar signatures from a variety

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[3]Although it can be argued that if by chance such a system failed to operate properly, the effects of the crash would be no worse than if the system hadn't been installed.

of obstacles likely to be encountered by radar need to be documented, and such signatures can be obtained only through experimentation on actual vehicles.

Computation and execution of vehicle control commands must be made in real time under a wide range of conditions. Ensuring acceptable performance will require extensive analysis of the system architecture; points of analysis include the number and model of processors needed to reduce the radar data and compute vehicle trajectories based on that data, the amount of hardware redundancy needed to ensure reliable operation, and the highway environment in which the collision avoidance system is to operate. Specific hardware requirements may call for standard "off the shelf" processor, ADC, DAC, DIO, and communication boards to keep costs down and parts availability up.

For the first few years of operation, collision avoidance systems may be restricted to highly structured environments such as rural interstate highways. Rural intestate highways provide an excellent first application of this technology; 73% of traffic fatalities in Minnesota occurred on rural and interstate highways [MnCrash, 1993]. As experience with these systems increases, so too will the sophistication of the computational and control algorithms. Software upgrades which allow operation in less structured environments need to be available (and compatible with existing hardware) to improve the overall performance of these systems. Finally, a failure mode analysis program must be undertaken to determine the effects of the loss of a radar sensor, a CPU, a communication link, etc. A self-diagnosis report before each trip would simplify system troubleshooting and improve consumer confidence in the product.

Only "user friendly" systems will be accepted by the general public. Many technically superior products have failed in the marketplace because of a poor man-machine interface, while products with less technical sophistication but better interfaces have won wider acceptance among non-technical consumers (i.e., the Apple Macintosh computer). A sample of the pertinent man-machine interface issues facing the designers of systems providing driver information is provided below:

- The driver must have confidence that the system is up, working, and providing accurate information regarding the local environment. One reasonable scenario is that a HUD will present radar system data to the driver, and conditions permitting, the driver will correlate radar data with a visual inspection of the mirrors and the windshield.

- The system must present the data in an manner which increases the efficiency with

which a driver monitors the local environment. Local "maps" should be provided continuously in a clear, concise manner so that driver workload is decreased. A HUD could provide such information.

The man-machine interface issues pertaining to collision avoidance systems add to the list above; a partial list of these issues is found below:

- The role of the human operator under automatic collision avoidance mode needs to be determined. A human driver monitoring the operation of the collision avoidance system may detect a behavior contrary to what experience has taught the driver to be correct. The driver may attempt to override the automatic system; should the system allow this? Should the driver be allowed to overpower the controls (steering wheel, brakes, throttle) or should a deliberate deactivation of the system be required before assuming control? More questions arise regarding the behavior of the control algorithm during human override. During override, human control inputs could generate large error signals in the automatic systems; with adequate actuator force, the control system could take control from the intervening human.

- Collision avoidance systems are designed to operate properly under specific environments; for instance, initially only on rural interstate highways. In a situation where the environmental operational constraints are violated, the system may fail to function. How the driver is to be warned, and how the driver is to assume control in a short period of time requires analysis. In such a scenario, dynamic instabilities could arise during the transition from computer to human control; experimentation is required to determine its existence and magnitude. How the automatic control system will come back on-line requires attention, as does the effect such a transition has on the driver's confidence of the automatic system.

The interaction between vehicles driven by humans and vehicles equipped with automatic collision avoidance systems poses a number of potential problems. With an experienced driver, much of the driving task involves anticipating the maneuvers of other drivers. For instance, a vehicle will often merge after passing without the use of the turn signal. To most drivers, this comes as no surprise because humans "know" how humans drive. Whether a human driver will "know" how a vehicle operating under automatic collision avoidance will react to certain situations remains to be seen. For instance, the human reaction may be to brake when an obstacle is detected in the vehicle path whereas a vehicle operating under automated collision avoidance

may steer around the obstacle (provided that there is room to do so safely). The human may not be anticipating such a maneuver, which may instigate problems.

The possibility exists that the interaction between two different collision avoidance systems could excite dynamic instabilities. One system may be designed to maintain a relatively close proximity to an adjacent vehicle whereas the other system may place higher priority to maintaining a more distant spacing. This may in fact be a parameter that drivers might adjust as a function of their comfort level. Putting these two systems into close proximity may lead to a limit cycle type of behavior. A level of adaptability may have to be incorporated into these systems to avoid stability problems.

Societal Issues. Societal issues may pose a greater impediment to the deployment of automated collision avoidance systems than do technological issues. The technology required for the automated vehicle control systems has been tested and demonstrated; technology developers appreciate what work needs to be done to bring the products to a commercially viable state. The general public, however, have only read or seen brief demonstrations of these products, and may continue to discount their need for such devices. Although society is becoming less reluctant to embrace new technologies, an automated collision avoidance system represents a much greater technological deviation from everyday driving than does a cellular phone from a standard stationary phone.

The issues of liability, regulation, and public acceptance are intimately related. For instance, the degree of public acceptance cannot be quantified until exposure to these systems becomes widespread. However, widespread deployment will occur only when regulations governing the operations of these vehicles exist. The public won't want to or be able to operate these vehicles unless adequate liability protection is available. Liability, regulation, and public acceptance are all discussed below.

Questions regarding the liability of automated collision avoidance systems are legion. As with any product sold today, parts suppliers, manufacturers, integrators, retailers, and the operators of the vehicles all require liability protection. The cost of liability claims and liability insurance affect whether manufacturers are willing to produce these systems, whether dealers are willing to sell such systems, and whether consumers are willing to pay for these systems. Although such systems have the potential to improve traffic safety and therefore *reduce* the cost of insurance, until such systems are proven, insurance costs are likely to rise. It is also conceivable that for a

period of time, insurance companies will consider such systems to be high risk, and may refuse to insure them.

The operation of the first generation of commercially available automatic collision avoidance systems will most likely be limited to highly structured environments such as rural interstate highways. Users, cautious at first, will respect the operational limitations in place. However, as the drivers' confidence in the system increases, so too does the potential for system use in less structured environments. If an accident were to occur in an environment of less structure than for which the system was designed, who is to blame? If the collision avoidance system senses an environment for which it cannot compute and execute the proper vehicle commands, warns the driver of the situation, and the driver does not take over vehicle control and an accident occurs, on whom does liability rest? An extensive failure mode analysis may lead to a knowledge base of what to expect in the case of system failures. Knowledge of the failure modes may promote the development of effective countermeasures which may protect the vehicle and those adjacent to it.

Regulatory decisions must be made before these systems will be allowed to operate on the nation's highways. First, will performance and/or reliability specifications be mandated by the U.S. Federal Government, or will states be required to develop their own? Although automotive standards are typically written and enforced from the national level, at least one collision avoidance technology has been regulated by the states. For example, the radar based FOREWARN system for warning bus drivers of school children in the path of their bus has been approved for use in more than 35 states [FORE, 1994]. In the case of Minnesota, FOREWARN is not "approved;" it is simply "not prohibited" [RADAR, 1994]. As technology becomes more sophisticated, so too must departments of transportation in order to effectively evaluate systems as they become available. Who determines whether a collision avoidance system will perform as promised or mandated? Will state departments of transportation be required to staff a technology evaluation center responsible for approving automated vehicle control systems, or would a centrally located Federal office evaluate these systems?

A decision has to be made regarding whether system performance needs to be monitored and regulated. On one hand, the system protects the vehicle and the occupants in which it is installed, which should motivate proper maintenance. On the other hand, the condition of the collision avoidance system directly affects the safety of the vehicles and passengers in adjacent vehicles. The occupants in the adjacent vehicles desire some assurance that automated systems operate correctly. Citing another automotive example, the U.S. EPA has determined a performance level for automotive exhaust emission control systems. However, there exists no comprehensive U.S.

plan to monitor vehicle exhaust emissions for compliance with the law. The seven counties in the Minneapolis-St. Paul Metro area have established a procedure in which vehicle exhaust emissions are checked once per year. If a vehicle fails its test, no new license tabs are issued until the problem has been remedied. This program met considerable opposition even though the average test takes fewer than 5 minutes and a high percentage of vehicles pass the test. Monitoring the performance of a collision avoidance system is considerably more difficult than monitoring an emission control system because the emission control system offers hard physical evidence, whereas the collision avoidance system does not. Requiring annual inspections of collision avoidance systems may result in considerable opposition.

At the present time, only a small percentage of the population appreciates that systems such as automatic collision avoidance are feasible; a program such as that being put into place by the Smart Truck consortium [Mn/DOT, 1994] will help disseminate knowledge regarding the potential of automated systems. Further steps towards public acceptance will occur when people drive or ride in vehicles equipped with these technologies. Simply driving or riding in such a vehicle becomes a "catch 22" dilemma in that to release vehicles to the public, some of the issues regarding liability and regulation must be resolved. However, legislators are not apt to spend the time making decisions regarding these systems until an adequate amount of data and feedback from the general public is available, and until driver demand for these systems warrants their attention.

The final word on public acceptance will come from the individual vehicle buyer. When any new product or technology is released, a small percentage of the public will purchase it simply because the product is new, but the product may not generate enough interest to warrant continued manufacture. Recent examples of such products include the Digital Compact Cassette (DCC) from Phillips and the Mini Disk player/recorder from Sony. However, products which perform well and provide a good cost/performance ratio will find favor with consumers for the long term. An example of a product which has found long term favor with consumers is the Compact Digital Disk (CD). People purchased CDs initially for their durability and sound quality, even when playback hardware was expensive and unrefined. As greater numbers of consumers realized the potential of the CD, many abandoned analog recordings and proceeded to purchase large numbers of both CDs and CD players. As the demand rose, so too did the production rates, ultimately yielding lower consumer prices. Lessons taught from the CD revolution indicate that people will embrace automatic collision avoidance only if the system works, is convenient, and is cost effective (i.e., offers good performance to price ratio, low regulatory and liability costs, etc.). Compact disc sales surpassed analog cassette sales for the

first time in 1993 - eleven years after CD's were commercially introduced to the marketplace. Given the complexity of the driving task, at least a decade beyond initial commercial introduction will be needed to directly gage public acceptance and accurately assess the value of such systems.

IV. Research at the University of Minnesota

The Mechanical Engineering Department, the CAMDAC Robotics Laboratory and the IVHS Institute at the University of Minnesota and Mn/DOT have a three prong program underway in the area of collision avoidance. The three thrusts consist of the development of a simulation environment, the development of the University's Autonomous Land Experimental Robotic Testbed (ALX), and the development of the semi tractor-trailer experimental testbed. The development of ALX and its initial guidance and collision avoidance algorithms was partially funded under this grant. A description of each of these three thrusts is provided below.

Simulation and Model Development. Work has begun at the University to develop a vehicle dynamics and behavior simulation environment which will allow an initial evaluation of vehicle sensors, control algorithms, and computational requirements in a completely safe manner. In this environment, models of vehicles (automobiles, trucks, tractor-trailers, motorcycles, etc.) equipped with various degrees of collision avoidance systems will dynamically interact on a simulated roadway. A human interface will be incorporated so that the interaction between humans and the automated systems can be investigated. This simulation environment will allow safe, fast evaluation of a number of high performance (and potentially high risk) algorithms for collision avoidance; these algorithms include lateral control, longitudinal control, automatic braking, intelligent lane changing, merging, etc.

The development of such an environment requires the generation of a number of models which represent vehicles, roadways, and sensors. The models to be developed include:

- Vehicle models. At the present time, tractor and tractor-trailer dynamic models representative of the tractor and trailer to be operated on Mn/ROAD have been coded and are presently undergoing evaluation and refinement. Only the tractor-trailer planar dynamics are modeled at present; this is due to the (nearly) constant operational speed of the truck currently providing loads to the generally "flat" test track pavement. With some additional effort, the model will accommodate the inclusion of other dynamic effects including roll, longitudinal dynamics, etc. To work beyond simulating the Mn/ROAD environment, dynamic models representing a variety of automobiles, trucks, and motorcycles need to be developed and included.

- Roadway models. For a vehicle simulation of reasonable fidelity, accurate

representations of the roadway must be incorporated. Because of the structure of the Mn/ROAD facility, its roadway model will be relatively simple. However, to check the behavior of vehicles merging, lane changing, and braking, a library of highway elements needs to be developed. Experimental highways could be constructed from elements of the roadway library, which could lead to the design of highways optimized for vehicles with automatic collision avoidance systems.

- Sensor models. For valid simulations, modeling uncertainties require analysis. One of the more difficult problems in the area of autonomous collision avoidance systems is that of acquiring and processing accurate sensory data. Radar systems, for instance, are susceptible to errors due to specular reflections, multipath, weather; IR based systems are unable to detect objects through fog and heavy snow. Sensor characteristics, which include range and angular resolution, the information bandwidth, maximum and minimum range, and specular artifact will be incorporated into the sensor models used for simulation. In order to construct accurate sensor models, hardware will be tested to determine the sensor characteristics mentioned above. Preliminary models may be constructed from manufacturer specifications, but accurate simulations require accurate, verified models. It should be noted that an accurate model of a sensor differs from an accurate sensor. An accurate model of a poor sensor is of greater value than a poor model of an accurate sensor; an accurate model yields a simulation of high fidelity, and provides relevant information regarding the potential performance of the system. Results of the simulation may show that a sensor is inadequate or that it exceeds what is required. Given these results, a change in sensors may arise, resulting in a better match of sensor performance with system requirements. The radar sensors to be tested, modeled, and implemented are described in the next subsection.

Vehicle, roadway, and sensor models will allow a broad spectrum of traffic scenarios to be simulated. For instance, the interaction between vehicles equipped with different automatic collision avoidance algorithms may be examined for potential dynamic instabilities. The effects of stationary and moving obstacles in the line of traffic and the effectiveness of state estimation used to determine trajectories of moving obstacles and adjacent vehicles may also be considered. To investigate the interaction between automated collision avoidance systems and human drivers, an interactive mode will be incorporated into the simulation environment. This will allow a human driver (or drivers) to execute maneuvers as the simulation executes in order to determine the compatibility of human drivers with automated collision avoidance systems. Preliminary human-autonomous collision avoidance studies will be performed in the CAMDAC Engineering

Visualization Laboratory; when adequately refined, the simulation should be ported to the driving simulator associated with the University's Human Factors Lab.

Vehicle Implementation. Two vehicles comprise the fleet available to the University. The first vehicle, ALX, is based on a Yamaha electric golf cart equipped with control computers, actuators and feedback sensors, an array of up to sixteen sonar sensors for collision avoidance, and a vision system for lateral control (lane following). Power for the control computer is provided by an array of deep cycle batteries; power for the vision system and vehicle propulsion is provided by an array of six 6 Volt industrial batteries.

ALX is primarily used by graduate students to evaluate advanced collision avoidance techniques which may be too dangerous or which may lack the refinement necessary for application on the semi tractor-trailer testbed. A self contained system to support ALX has been developed at the University. This system currently consists of ALX, a mobile (cart mounted) Silicon Graphics Indigo Extreme for monitoring and for rapid prototyping ALX during field trials, and a Radio Frequency (RF) ethernet connecting the vehicle control computer to the mobile workstation. A portable Honda 1500W generator provides AC power to the mobile workstation. For safety reasons, ALX currently has governed a top speed of 3.6 km/hr. The vehicle can operate at speeds up to 15 km/hr, and will do so as required.

In its present state, ALX uses a fusion of vision and sonar sensor data to perform navigation, guidance, and collision avoidance tasks. The integration approach differs from other approaches such as that found in [Dickmanns, 1991] where visual information alone is used for collision avoidance, navigation, and guidance. One problem with the approach of [Dickmanns, 1991] is that the number of obstacles tracked is limited by the vision processors on board the vehicle; in the reference cited, only 3 obstacles can be tracked at any one time. The use of vision for guidance and sonar or radar for collision avoidance allows a greater number of potential obstacles to be tracked. Moreover, in a multi-processor system, one processor can be devoted to vision processing, and another can be devoted to obstacle detection, yielding higher computation rates and throughput.

On ALX, the collision avoidance trajectories are designed to keep the vehicle between lane markings (as sensed by the vision system) when kinematically possible. Sonar sensor data is processed to determine whether regions in a preconfigured conical grid are occupied with obstacles. Based on grid occupancy, vehicle trajectories which avoid the occupied areas are computed. If obstacles are positioned such that the vehicle is unable to avoid violating lane

constraints, a trajectory is computed and executed that drives the vehicle outside the lane for either the shortest time period or distance. An M.S. thesis [Du, 1995] documenting the design and development of the present navigation, guidance and collision avoidance strategy will be completed in early 1995; a copy will be sent to Mn/DOT upon its completion.

Future hardware plans for ALX include the development and implementation of a more accurate dead reckoning package. A fiber optic gyro to determine vehicle orientation will be implemented in the updated dead reckoning package. Currently, a fluxgate magnetometer (electronic compass) is used to determine vehicle heading. However, fluctuations in the local magnetic field adversely affect the heading information provided by the magnetometer. The fiber optic gyro is unaffected by the variations in the local magnetic field, and should provide significantly more accurate heading data.

Future modifications to the navigation and collision avoidance scheme on ALX involve the implementation of both Potential Field (PF) and Artificial Neural Network (ANN) approaches to collision avoidance. With the grid approach, occupied "sectors" are simply to be avoided and either a minimum time or minimum distance path constitutes an optimal obstacle avoiding trajectory. This minimum time or minimum distance trajectory is determined via a numeric search.

The PF approach uses points of attraction and points of repulsion to determine collision avoiding trajectories. Examples of areas of attraction include the empty space in the lane directly in front of the subject vehicle or the empty space to the immediate left of the vehicle when traveling in the right lane of a multi-lane interstate highway. Examples of areas of repulsion would include the space occupied by another vehicle directly ahead of the subject vehicle, the space associated with the left lane in the case of a two lane country road in which the left lane carries opposing traffic and the region to the right of the road boundary. In an attraction potential field for a two lane country road, the vehicle would travel forward, in its own lane, in order to reach a destination. As such, the space directly ahead of the vehicle would represent a region of greater attraction than the space on either side. Given that the damage incurred in a head on crash usually exceeds that for a rear end collision, the left lane can be represented as a region of greater repulsion than would the area directly ahead of the vehicle. A shoulder can be assigned some degree of repulsion but not enough to prevent its use for collision avoidance. The PF approach allows different attractive or repulsive weights to be assigned to different sources; the attractive or repulsive "force" is proportional to the distance to the point of attraction or repulsion, respectively. With the attractive or repulsive fields defined by the relative weightings and

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distance to the source, an optimal collision avoidance trajectory may be computed "on the fly". If the attractive or repulsive forces are proportional to the square of the distance to the source, then least squares methods may be used to compute instantaneous collision avoiding trajectories.

With the current grid filling implementation, the grid must be reconstructed as the vehicle moves. Grid filling works adequately for slow moving vehicles, but presents computational problems at higher vehicle speeds. The ANN method to be implemented [Morellas, 1994] takes a geometric approach, and "arranges" neurons in order to create a geometric representation of the local environment. The ANN is recursive, and weights new data against previous data to adapt the map to the changing environment. This recursive process augments old data with new, easing the computational burden associated with building completely new maps at specified vehicle displacements. From this geometrical representation of the local environment, PF methods can be used to compute optimal trajectories.

A literature research performed under this contract led to the realization that no results have been published which document full scale vehicle tests which integrate lane following and collision avoidance. Given the potential benefits associated with such tests, the safety concerns at the Mn/ROAD pavement research facility and its availability to the University through Mn/DOT, the decision to build a second experimental vehicle, the semi tractor-trailer experimental testbed, was made. The tractor is a Navistar 9400 series equipped with an electronically controlled Caterpillar 3406E engine and an Allison HD 4060 transmission. Traction control and anti-lock brake systems (TCS/ABS) are tentatively to be supplied by the Bendix. Electronic control eliminates the need to mechanically actuate throttle, brake, and gear selection, and allows the engine, transmission, and brakes to be an integral part of the vehicle control system. Real time engine, transmission, and brake control are to become components in our obstacle avoidance strategies. Steering will be either electrically or pneumatically actuated via computer control. The tractor is equipped with a sleeper cab which will house computers, power supplies, servo amplifiers, and air conditioning equipment. If required, an on-board alternator will provide conditioned power to electronic components and the computer hardware. The trailer purchased to provide dynamic loads at the Mn/ROAD facility will be used for the experimental testbed.

A significant amount of time and effort is to be spent on systems integration. To ensure long term success and to avoid premature obsolescence, state of the art communication, sensor, and computer hardware will be employed. An open architecture is critical in order to ensure that any additional and/or changing technologies may be readily implemented on the testbed. Finally, the integration must be done in such a manner as to ensure safety for those in the cab as well as for

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those working near the truck. Control logic will be designed so that a "run away" or "out of control" vehicle is prevented.

The experimental testbed will be designed so that a minimal number of external actuators need to be installed on the vehicle. Control commands may be issued electronically to both the engine and transmission enabling these components to play a role in vehicle control. This arrangement simplifies engine and transmission actuation, and avoids potentially damaging control scenarios (i.e., full throttle shifts from forward to reverse gears) via the application of the proper control logic in the Mobility Systems Controller (MSC, see below).

By exploiting "fly by wire" technology, only the steering (and possibly the brakes) need external actuation. Both the steering and the brakes will be actuated in a method transparent to the driver. This allows the vehicle to be driven off of the test track without any additional effort put forth by the driver. Sensors to provide control actuation feedback will be provided both on steering and braking systems.

Three sensor groups will be installed on the experimental testbed during the precursor phase system integration: a vehicle mobility group, a vehicle status group, and a dead reckoning group.

The vehicle mobility group of sensors provides actuator feedback to the MSC. The sensors in this package provide signals including engine RPM, steering angle, and amount of 'brake apply'. These signals are critical for providing system mobility, and sufficient redundancy will be built into the system.

The vehicle status group of sensors provide the operator and MSC information regarding the operational status of the vehicle. This suite of sensors provides signals including fuel level, engine temperature, oil pressure, and alternator output. The mobility systems controller will monitor these signals, and if any signals drop or climb out of spec, the MSC will take appropriate action (e.g., either issue a warning or shut the vehicle down).

The dead reckoning sensor group is the third sensor group to be installed on the experimental testbed. This sensor group includes a highly accurate odometer (either Doppler based true ground speed or a driveshaft mounted encoder), a fiber optic gyro to determine vehicle heading, differential GPS, pitch and roll axis clinometers, and a vehicle turn rate sensor. This sensor group will provide the measurements necessary for a retro-traverse control mode.

With the open architecture of the experimental testbed, a modular approach to vehicle control will be undertaken. To ensure modularity, the computer which processes vision data is separate from the Main Vehicle Processor (MVP) used to compute lateral and longitudinal control trajectories. Although the vision data is required to compute these trajectories, this modularity allows different image processing algorithms and/or computers to be readily integrated into the control system. All reference signals (including lateral and longitudinal control commands) are passed to the MSC for interpretation, servo amplification, and transmission to the appropriate actuator. In the same vein, actuator sensor feedback is passed to the MSC and subsequently routed to the appropriate control computer module. The MVP will be based on the VME backplane; a MVME 167 will serve as the main processor. The retro-traverse control will run from the MVME 167 installed in the MVP.

The communication protocol between the image processing system and the MVP will be via ethernet. Using this standard communication protocol will reduce communication development time and support the open architecture concept. Control systems to be added at a later date will be required to support ethernet communication.

Discussions have been held with Alliant Techsystems, Millitech, and VORAD to determine the applicability of Millimeter Monolithic Integrated Circuit (MIMIC) radar technology to collision avoidance systems. MIMIC technology appears promising for vehicular applications for a number of reasons; details may be found in [Radar, 1994]. To summarize, MIMIC technology will allow an electronically steered phase arrayed radar on the front of the vehicle and an array of radar sensors to be positioned around the periphery of the vehicle to create a "smart skin."

Electronically steered radar is important for two reasons: cost and accuracy. First, an electronically steered radar will allow the forward looking radar beam to "follow" the front wheels of the tractor as the vehicle lane changes and negotiates turns. One arrayed antenna can cover the front of the vehicle, eliminating the need for multiple fixed antennas otherwise required to ensure the required coverage. Steering electronically rather than mechanically eliminates the need for a dedicated mechanism to track the front wheels, increasing reliability and decreasing cost.

Although the potential for low cost electronically steered radar exists, the development costs for vehicle based prototype systems promises to be high. For the initial radar based collision avoidance system development, multiple fixed sensors will be used in place of a steered array. With the successful conclusion to the initial work with multiple fixed sensors, a subsequent

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phase consisting of the development and implementation of a vehicle specific steered array system would commence.

An array of radar antennae around the vehicle periphery will eliminate the blind spots associated with cars and large trucks. Radar on the periphery will allow real time maps of the local environment to be computed; these maps will allow the computation and execution of collision avoiding vehicle trajectories.

The Mn/ROAD closed course pavement test facility provides a highly structured, low speed environment in which to initially test the collision avoidance system. Initially, front looking radar used to locate impediments to the desired vehicle trajectory will be installed, tested, and evaluated. The first battery of tests performed at Mn/Road will be from the systems point of view; the radar systems and collision avoidance algorithms have to be optimized simultaneously. For instance, the range, range resolution, angular resolution, and information bandwidth of the radar system directly affect the design and execution of collision avoidance algorithms including both the PF and ANN approaches. If the radar system exhibits high maximum range, and good range and angular resolution (i.e., provides accurate *early* warnings), then the collision avoidance algorithms can be more comprehensive than those found on a system which offers less radar sensor performance. Although a more comprehensive algorithm will require more time to compute control commands, the added range and accuracy offered by a higher performance radar system will accommodate the added computational time.

Forward looking only radar will prove adequate for the initial Mn/ROAD work because the experimental testbed will be the only vehicle operating on the test track. The system will be used to sense if people inadvertently cross the path of the truck. Radar sensors on the vehicle periphery are required if collision avoidance technology is to make the transition from the test track to actual highways. If a collision avoidance trajectory requires a lane change, the radar on the vehicle periphery will check to ensure that such a maneuver may be executed.

The second group of tests at Mn/ROAD will involve both forward looking and periphery radar, with much the same intent as the experiments described above. The semi tractor will operate on the Mn/ROAD facility while obstacles impede its desired trajectory and other vehicles follow in a manner to potentially interrupt a desired lane changing maneuver. Algorithms which use both forward looking and periphery radar information will be analyzed and modified as required to bring the system to a level capable of advanced collision avoidance in a rural interstate highway environment.

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The next logical progression is to further the system development and evaluation by operating and evaluating in an environment offering less structure and higher speeds than the Mn/ROAD facility. The limited access High Occupancy Vehicle (HOV) lanes found on I-394 west of Minneapolis, when closed to the public, represent an ideal location in which to extend the work from Mn/ROAD; entrance and exit ramps provide a means with which to test automated merging and exiting, and the Interstate highway layout of the road allows high speed operation.

The testing to be undertaken on the HOV lanes will follow a program similar to that undertaken at Mn/ROAD. The higher speeds attained on the HOV lanes will place greater demands on the control algorithms than does the operation on Mn/ROAD. At high speeds, trajectory computation and execution become more difficult, as does the processing of radar data needed to construct dynamic local maps. PF methods will be employed to eliminate limitations associated with search techniques. To increase the speed with which local maps are constructed, Kohonen transformation neural networks are being developed for providing on-line dynamic local maps [Morellas, 1994]. Vehicle dynamics change considerably with vehicle speed, and control inputs must be properly regulated so as to not excite any instabilities, rollovers, or jackknifes. Because of the dependence of vehicle dynamics on speed, the vehicle controller used on Mn/ROAD may require modification to accommodate higher speeds; the modification may include the use of sliding mode or other adaptive control.

In addition to the change in physics associated with the higher speeds achieved on the HOV lanes comes a change in the operating environment. The HOV lanes offer an operating environment quite similar to that of a standard rural interstate highway with merging, passing, headway regulation occurring in both environments. Moreover, situations likely encountered in rural interstate driving such as the merging of two lanes into one because of construction can be created on the HOV lanes. Controlled merging, exiting, and lane changing experiments can be performed by using other vehicles with the semi tractor-trailer experimental testbed.

The final portion of the collision avoidance development cycle will be to use the lessons learned from the Mn/ROAD and HOV lane experiments to operate the vehicle on public rural interstate highways. Operation on rural intestates will follow a two step process; step one will keep a human driver "in the loop," and step two will allow the vehicle to operate autonomously under computer control but with driver supervision.

In step one, control commands will be issued to the driver rather than the vehicle; the driver will only follow commands put forth by the controller which the driver regards as safe. This operation poses only a slightly greater threat to the public safety than does pure human operation because the human makes the final decision regarding what action to take. Such a method introduces time delays due to human reaction time. The introduction of the human delay time should not degrade the tests because of the relatively small speed differentials found between the test vehicle and others on the highway. In the case of an emergency, the sensory information provided by the collision avoidance system will complement the information acquired by the driver, and should provide a warning to the driver in less time than if no additional sensors were on-board. All commands to the driver will be recorded; those determined inappropriate will be analyzed to determine the effects of performing such a maneuver. If such maneuvers prove to be dangerous, collision avoidance algorithms will be modified so that such behaviors will be avoided. The dynamics between the computer controlled vehicle and the human drivers in other vehicles will also be evaluated. Ultimately, such systems will have to be accepted by all - both those who use them on their own vehicles and those who do not. Problems observed due to interaction effects will result in modifications in order to minimally "upset" the human driving population. To prevent biasing the response of human drivers, the computer controlled truck will not be equipped with special markings or warnings.

Step two is to implement a fully operational collision avoidance system on rural interstate highways. In this system, the collision avoidance system will fully execute vehicle control commands; however, the human driving supervisor will be able to assume full control of the vehicle when appropriate. As in the case with the human driver in the loop, other vehicles operating on the roadway will not be made aware of the truck operating under computer control; otherwise human drivers of other vehicles may alter their driving habits if provided with this a priori knowledge. As a final test, operation in this manner will determine the potential for safety and performance improvements of such systems.

IV. Conclusions and Recommendations

Conclusions. Automated highway vehicle systems are here to stay; in fact, VORAD, San Diego, CA [VORAD, 1994] has begun a marketing campaign to equip fleets of semi tractor-trailers with their Collision Warning System. Although this system provides only information to the driver concerning the vehicle directly ahead, work has been done to integrate collision warning systems with "brake by wire" technology. This marriage of technology will result in an automatic braking system if the gap becomes too small or the closing rates between vehicles becomes too great. General Motors has indicated that they intend to offer vehicular radar by model year 1997 or 1998 [Costlow, 1994].

State Departments of Transportation are responsible for regulating traffic and vehicles to ensure the safety and productivity of transportation users. Mn/DOT has realized the impact that emerging technology will have on transportation, and has underway an extensive program to evaluate and develop technology designed to improve traffic safety and efficiency. As a recognized leader in Intelligent Traffic Systems, Minnesota is in a position to establish a national guideline for the implementation and regulation of these intelligent traffic systems. By having other states follow the standard set by Minnesota, Minnesota can minimize infrastructure costs required to accommodate precedents set by other states.

Although the development of automated vehicles systems is not a primary function of Mn/DOT, knowledge of the benefits and potential problems associated with these systems remains crucial for efficient legislation and regulation. Realizing the necessity of this information, Mn/DOT and the IVHS Institute have sponsored research in the automated vehicle area [Du, 1995], have contributed to the purchase and system integration of a semi tractor-trailer experimental testbed, and have made facilities available for the test and evaluation of such systems. With the development of the experimental semi tractor-trailer testbed, the legislature and the general public can be kept informed of the imminent reality of IVHS, and be made aware of the societal issues which they will face. With an adequate amount of relevant information, enlightened policies which accommodate new technologies can be made.

Recommendations. Minnesota has put forth considerable effort to become a leader in IVHS technology. Because of the accelerating interest in technology based solutions to transportation problems, maintaining this leadership role will require an ongoing effort. To support Mn/DOT's IVHS effort, the following three phase program is proposed.

Phase one consists of further development of the vehicle simulation environment. The greatest effort in this arena is the development of sensor and collision avoidance algorithm models to be used in this simulation environment. The simulation environment may be used both as a research tool and an educational tool. This simulation environment can be used to both support the development of the semi tractor-trailer experimental testbed and to give students the opportunity to examine the behavior of a variety of collision avoidance schemes.

Phase two involves further work and development of ALX. With the proper support, ALX can serve as a tool for continued graduate student research on collision avoidance and prevention of road departure. Potential research projects include the implementation of a vision based collision avoidance system along the lines of Dickmanns in Germany and the continued development of a collision avoidance system based on a fusion of vision and sonar sensor data. ALX provides and excellent platform with which to safely demonstrate the potential of automated collision avoidance systems. ALX is readily transported, and can be demonstrated nearly anywhere in the state. Taking the vehicle to national competitions also increases publicity for the program; attendance at the 1994 AUVS Unmanned Vehicle Competition may have increased our credibility with TACOM, which partially sponsored the AUVS competition.

Phase three would implement the work described in section IV regarding the semi tractor-trailer experimental testbed. Minnesota offers unique facilities with which to perform full scale vehicle based collision avoidance research and analysis. Using these facilities to their full advantage will allow Minnesota to remain a leader in this area. As a leader, Minnesota can work to set standards, which will serve legislators, regulators, the general public, and the nation. This effort should not be considered altruistic; Minnesota will benefit by having other states conform to its standards rather than vice versa. If decisions have to be made on the federal level, experience in this area will also prove beneficial.

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