Key Human Factors Research Needs in Intelligent Vehicle-Highway System Crash Avoidance

LOUIS TIJERINA

The Intelligent Vehicle-Highway System (IVHS) program attempts to enhance surface transportation safety, efficiency, and comfort by applying advanced technologies, including information processing, communications, control, and electronics. One goal of IVHS is to reduce the number of crashes as well as the severities of crashes that do occur. Crash avoidance systems (CASs) are therefore a focus of research in the IVHS program and related programs abroad (e.g., DRIVE and PROMETHEUS). An important step in CAS research and development is to understand the sizes of various crash problems and their etiologies. This provides the necessary background for the development of CAS concepts. It is equally important to understand the time and distance budgets required and available for crash avoidance to assess the role that the driver might play. An IVHS program sponsored by the Volpe National Transportation Systems Center (VNTSC) and the Office of Crash Avoidance Research of NHTSA pursues this important step. A brief synopsis of key findings from the VNTSC crash problem studies is provided, and key research needs in the area of human factors are addressed. The issues are organized in terms of driver–CAS interface issues, driver response to CAS activation, the secondary effects of CASs on safety, and comprehensive crash avoidance. The topics discussed include the need to understand driver behavior, the impact of novel displays on driver acceptance, the use of graded alarms, driver reliability and reaction time, the effects (both positive and negative) of CAS false alarms on drivers, the feasibility of drivers taking evasive maneuvers, decreased driver attention to the driving task, increased hazard exposure on the roadway, change in driver behavior with the presence of CASs, expectancy violations, and the design of an integrated CAS.

The Intelligent Vehicle-Highway System (IVHS) program attempts to enhance surface safety, efficiency, and comfort by applying advanced technologies, including information processing, communications, control, and electronics (*1*). One goal of IVHS is to reduce the number of crashes as well as the severities of crashes that do occur. Crash avoidance systems (CASs) are therefore a focus of research in the IVHS program and related programs abroad (e.g., DRIVE and PROMETHEUS).

An important step in CAS research and development is to understand the sizes of various crash problems and their etiologies. This provides the necessary background for the development of CAS concepts. It is equally important to understand the time and distance budgets required and available for crash avoidance to assess the role that the driver might play. An IVHS program sponsored by the Volpe National Transportation Systems Center (VNTSC) and the Office of Crash Avoidance Research of NHTSA pursues this important step. The present paper provides a brief synopsis of key findings from the VNTSC crash problem studies and addresses key research needs in the area of human factors.

Battelle, 505 King Avenue, Columbus, Ohio 43201.

SYNOPSIS OF CRASH ANALYSES AND CAS CONCEPTS

Figure 1 delineates the crash types analyzed for crash problem studies and the percentages of U.S. police-reported crashes in 1 year accounted for by each crash type. These percentages are derived from a series of reports prepared as part of IVHS program crash problem studies (*2,3–10*) and other studies (*11–14*). Since the sample sizes of detailed crash cases examined in the various crash problem studies were limited, the samples do not necessarily represent the nationwide population of crashes. However, the figure provides some indication of the relative incidences of different crash types.

As a point of reference, approximately 6,110,000 police-reported crashes occurred in 1991 according to the statistics of the General Estimates System. The eight crash types analyzed account for roughly 68 percent of all crashes. As indicated in Figure 1, rear-end crashes account for almost one of every four police-reported crashes that occur in the United States each year. Single-vehicle roadway departures account for approximately 20 percent of all such crashes, and intersection-related crashes (signalized and unsignalized straight-crossing-path crashes and crashes involving a left turn across the path at an intersection) account for roughly 17 percent of all such crashes. The category labeled "other" in Figure 1 includes all other crash types such as animal strikes, untripped rollovers, and at-grade railroad crossing crashes.

Table 1 lists each crash type and its problem size estimate along with crash subtypes and causal factors (associated factors thought to be key contributors to crash occurrence). The data in Table 1 were also derived from the series of reports generated for IVHS program crash problem studies (*2–10*). These were determined by a clinical analysis of crash cases carried out by expert crash investigators at Calspan Corporation. The materials to support such analyses were detailed crash reports from the Crashworthiness Data System of the National Accident Sampling System. These reports included driver and witness statements, police comments, coded variables on reporting sheets, scaled schematics, measurements taken at the crash scene, and photographs of the involved vehicles.

Rear-end crashes are the most common type of crash. The analysis indicated that for about three of every four such crashes, the lead vehicle was stationary for some period of time before the impact. In the remaining crashes the lead vehicle was moving. Driver inattention and use of an inappropriate following distance or headway accounted for almost 93 percent of such crashes according to the cases analyzed. This suggests that there is potential for forward obstacle detection (for the case of a stationary lead vehicle), headway detection (for the case of a moving lead vehicle), or intelligent cruise control to alleviate at least some of these crashes.

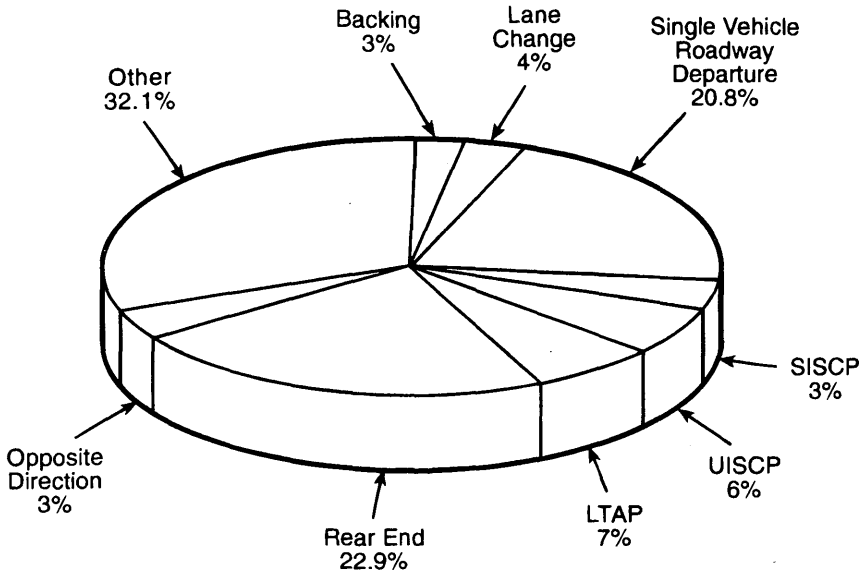

FIGURE 1 Distribution of crashes analyzed in VNTSC crash problem studies.

Single-vehicle roadway departures (SVRDs) are almost as prevalent as rear-end crashes. Roughly 6 of 10 roadway departures occur at curves; this suggests that a driver speed warning system cued to the presence and design speed of the curve (adjusted for slippery road conditions) would be promising. The remaining 4 of 10 roadway departures occur on straight road segments and may benefit from a lane-keeping aid. Unlike rear-end crashes, the etiology of SVRD crashes is much less uniform. According to the analysis, driver incapacitation is associated with roughly one of four such crashes, with slippery roads (20 percent), excessive speed (14 percent), and inattention and/or evasive maneuvering (29 percent) accounting for smaller percentages. Pavement monitoring (combined with speed warning) and driver impairment detection and warning may prove to be useful for countermanding some of these causal factors.

Backing crashes are of two main subtypes. One subtype involves the subject vehicle (SV) backing into a stationary or slowly moving object such as parked vehicles and pedestrians or pedal-cyclists. The SV is usually traveling at a slow speed. For this problem rear-zone detection and warning systems should be of benefit. The second subtype involves the SV backing out and moving into the path of a principal other vehicle (POV) that is traveling in a crossing path, usually at a substantially higher speed. Avoidance of such crashes will likely require a system that takes into account the POV time to arrival or gap to warn the SV driver (or perhaps the reverse, to warn the POV driver).

Lane change crashes occur predominantly because the SV driver was not aware that there was another vehicle in the adjacent travel lane. In the proximity subtype the POV was found to be not only in the blind spot but also occasionally beside or even slightly forward of the SV (although still overlapping laterally). This finding suggests that side-zone detection and warning may be beneficial but that detection only in the blind spot is not likely to be sufficient. The fast approach subtype, in which the one vehicle changes lanes unaware that another vehicle is fast approaching, was infrequent among the cases analyzed. The reasons for this were not found, but it may be due to increased alertness on the part of all drivers in situations in which fast-approach crash hazards are most likely (e.g., in merging traffic).

The intersection crashes analyzed involved both signalized (traffic light present) and unsignalized (stop or yield sign present) intersections and included both straight-crossing-path and left-turn-across-path crashes. Although the associated casual factors vary by intersection crash type, driver inattention and misperception of the POV are dominant. CAS concepts that are cued to signal state, sign presence, and gap or time to collision are likely to be of greatest benefit. In particular, a comparison of the time gap for a POV to arrive in a collision zone with the estimated time needed to complete an intersection maneuver may be especially useful for crash avoidance.

Based on the sample data, opposite-direction crashes are most often associated with an intoxicated driver; this is followed by evasive maneuvers (perhaps caused by a sudden intrusion into the SV's travel lane), slippery roads, and driver inattention (*10*). Interestingly, improper passing is seldom the cause of the opposite-direction crash, perhaps because drivers are usually alert when engaging in such a maneuver. Lane drift and vehicle control loss, along with the causal factor of driver intoxication, might be alleviated by driver impairment detection, lane detection and warning, and pavement monitoring and speed warning systems. Given the multiplicity of different crash circumstances, a single CAS concept will likely not be sufficient.

With this synopsis as background, the following sections will introduce key human factors issues in IVHS crash avoidance. These issues suggest research needs and challenges to bring IVHS crash avoidance to fruition.

DRIVER–CAS INTERFACE ISSUES

The user interface is the driver's gateway to CAS functions. Internal logic and features are only apparent through the interface, and the usability of that interface determines the extent to which the person gains access to the capabilities that the product or system has to

TABLE 1 Crashes, Crash Subtypes, Causal Factors, and CAS Concepts Analyzed

Crash Type	Problem Size	Crash Subtypes	Key Causal Factors	Key CAS Concepts
Rear-end Crashes	23%	• Lead Vehicle Stationary (75%) • Lead Vehicle Moving (25%)	• Driver Inattention and/or Following Too Closely (93%)	• Forward Obstacle/Headway Detection
Single Vehicle Roadway Departure (SVRD)	20%	• Straight Road Departure (39%) • Curve Road Departure (61%)	• Driver Incapacitation (DUI, Drowsy, Seizure) (25%) • Slippery Roads (20%) • Excessive Speed (14%) • Inattention and/or Evasive Maneuver (29%)	• Driver Impairment Detection • Pavement Monitor and Speed Warning • Curve Detection/Speed Warning • Lane Detection and Warning • Forward Obstacle/Headway Detection
Backing Crashes	1%	• Encroachment (43%) • Crossing Paths (57%)	• Did not see (61%) • Improper backing (Did not look?) (27%)	• Rear-zone Monitoring • Gap Monitor (Cross Traffic) and Warning
Lane Change Crashes	4%	• Proximity (93%) • Fast Approach (7%)	• Driver unaware of POV	• Side-zone Detection
Signalized Intersection Straight Crossing Paths Crashes (SISCP)	3%	• Straight Crossing Paths (100%)	• Deliberately Ran Signal - Ran Red Light (23%) - Tried to Beat Signal Change (16%) • Inattention (36%) • Intoxicated Driver (13%) • Vision Obstructed (4%)	• Signal-cued Warning/Control • Driver Impairment Detection
Unsignalized Intersection Straight Crossing Paths Crashes (UISCP)	6%	• Did Not Stop (42%) • Stopped, Proceeded Against Traffic (58%)	• Misperception of POV (49%) • Inattention (23%) • Vision Obstructed/Impaired (15%) • Intoxicated Driver (3%) • Deliberate Sign Violation (3%)	• Sign-cued Warning/Control • Gap Monitor (Cross Traffic) and Warning • Driver Impairment Detection
Intersection Left Turn Across Path Crashes (LTAP)	7%	• Did Not Stop Before Turn (72%) • Stopped, Then Turned (28%)	• Misperception of POV (28%) • Looked Did Not See (24%) • Vision Obstructed (24%) • Deliberate Traffic Control Device Violation (16%)	• Gap Monitor (Opposite Traffic) and Warning
Opposite Direction Crashes (ODC)	3%	• Lane Drift (47%) • Vehicle Control Loss (48%) • Improper Passing (5%)	• Intoxicated Driver (37%) • Evasive Maneuver (18%) • Slippery Roads (15%) • Inattention (7%)	• Driver Impairment Detection • Forward Obstacle/Headway Detection • Lane Detection and Warning • Pavement Monitoring/Speed Warning

offer. Although many reports discuss the ergonomics of displays and controls (*15*), a selected set of issues emerged from the analyses conducted in the crash problem studies.

Need To Understand Driver Behavior

A basic research need is to better understand typical driver behavior, the modifiability of that behavior, and the implications of these to CAS design, implementation, and assessment. Farber and Paley (*16*) presented data collected at New Mexico's I-40 near Albuquerque that showed that almost 30 percent of drivers were driving with time headways of 1.0 sec or less, which greatly increases the risk of a rear-end crash. How modifiable is such behavior if one were to introduce a headway monitoring system that alerts the driver that he or she is following too closely? In the backing case what are the typical eye, head, and body movements used in backing? This bears on the success of a driver warning system that is visual in nature. Although an auditory warning may alleviate the problem, what happens if multiple CASs are present in the vehicle and the driver must decide to what the warning refers? In the lane change crash what are useful indicators of the driver's intent to change lanes? This would be very helpful to tailor the CAS to present warnings only when they are appropriate. Even if some drivers use turn signal indicators, what is the sequence of turn signal use to lane change (before, during, or after)? How modifiable might turn signal use be if a CAS were provided with instructions that benefits will only accrue when the turn signals are used? In the case of left turns across path at intersections, what will a driver do when a CAS warns against turning yet the driver cannot visually verify a crash hazard (as may occur in cases of obstructed vision or driver misperception)? Answers to these questions are likely to require collection of data over a relatively long period of time to see both the time course and the steady-state behaviors of drivers.

A need to gain more information about driver behavior in crash circumstances also exists. For example, in the lane change crash analysis no information was available on the distributions of lane change times and the lateral accelerations associated with common lane changes (not evasive steering). In the case of straight crossing path crashes at intersections there is a need for information on the distributions of the velocities and accelerations that drivers exhibit while approaching and crossing intersections. Data on normal lane keeping would be helpful for the design of a lane detection and warning system. Finally, human factors engineering has learned the "fallacy of the average man," that is, trying to design a system to fit the 50th percentile person. Although distributional information may be useful for modeling and simulation in support of system development, a CAS may have to be tailored to the individual driver.

Novel Displays and Driver Acceptance

The nature of the displays for CASs will require careful research to arrive at acceptable solutions. Two examples will clarify this point.

Ward and colleagues (*17*) reported on a field study of a contact analogue head-up display (HUD) that provided infrared camera output directly on the windshield superimposed on the actual objects in the road scene. Compared with drivers who had no HUD, drivers using the prototype HUD drove more slowly and reported a higher subjective workload. Tijerina et al. (*18*) point out that speed reduction is a common technique that drivers use to manage high workloads, so these results are consistent with other human factors data. In an oral presentation of the paper and a videotape of the contact analogue HUD of Ward et al. (*17*), it was indicated that it was quite difficult to drive with the display because of the time delay in superimposing the infrared image with the real object and in the ghostly appearance of the infrared images. What is clear is that drivers will have difficulty in getting accustomed to the HUD imagery that is likely to be feasible (at least with infrared sensors) in the near term. Systems that cause greater workloads and travel times will likely find a lack of acceptance.

Consider next the use of kinesthetic-tactile displays in CASs. This approach uses torque shifts in the steering wheel and counterforce on the accelerator pedal to signal to the driver both a warning and indications of what to do. Theory and laboratory investigation suggest that such displays provide a stimulus and feedback that afford fast and accurate responses with little driver attention. However, drivers have sometimes described such displays as distracting and disturbing (*19*), and drivers might be unwilling to have such systems in their vehicles (*20*). Furthermore, when coupled with automatic vehicle control, kinesthetic-tactile displays were the least preferred from among several alternative CAS interfaces (*21*). Thus, the use of a novel display system with demonstrated performance-enhancing benefits may nonetheless fail to be accepted by drivers.

Another dimension to the acceptance of CAS interfaces may be social in nature. COMSIS (*22*) alluded to a social factor in interface design in which a warning presentation to a driver while one or more passengers are in the vehicle could be a cause of embarrassment. Research is needed to assess (a) how important such a factor might be, (b) what driver behaviors change in light of negative social consequences, and (c) how interface design might ameliorate or aggravate such social effects. For example, the kinesthetic-tactile display may come to be preferred to a buzzer or other more obvious warning delivery system by virtue of its subtlety.

Use of Graded Alarms and Transitions Between Levels of Intervention

Human factors literature suggests that graded alarms (e.g., crash possible, probable, or imminent) enhance performance over an all-or-nothing alarm system (*23*). It is therefore reasonable to consider the use of graded alarms for CAS implementation.

Several components are needed to make graded alarms feasible. First, the hazard or potential hazard must be detected by the CAS early enough to provide for alarm gradation. The time budgets may be inadequate to support the graded alarm concept in such circumstances as sudden intrusion by a POV, pedestrian, or pedal-cyclist into the SV travel lane. Second, there must not be an adverse consequence to the traffic system in general. For instance, graded alarms for rear-end crash avoidance would have to be carefully selected so that traffic flow is not degraded. Third, there must be sufficient structure in the driving environment to support graded alerts without introducing a multiplicity of false alarms. For example, one analysis conducted to provide a warning to the POV driver of an oncoming SV driver in the scenario of a straight crossing path crash at a signalized intersection determined that, at least for the conditions assessed, it was not feasible to provide graded warnings if the warning is cued to the SV's location from the intersection and anticipated decelerations given an assumed travel speed (*6*). On the other hand, graded warning or intervention for the SV driver at a signalized intersection (*6*) or stop sign (*7*) seemed more feasible, assuming that signal status and stop sign location could be known in advance. Finally, Horowitz (oral presentation, IVHS Human Factors Workshop, 73rd Annual Meeting, TRB, Washington, D.C., 1994) has raised concern about the psychological refractory period. This is a phenomenon found in the human performance laboratory in which presentation of a signal delays the response to a subsequent signal. Although such effects diminish with the interstimulus interval and disappear after an interval of 0.5 sec, this has not yet been assessed in the crash avoidance arena.

DRIVER RESPONSE TO CAS ACTIVATION

Driver Reliability and Reaction Time

Modeling CAS effectiveness involves some assessment of (a) the probability that the driver will respond appropriately and (b) the latency of that response. In general, models of CAS effectiveness assume full and accurate compliance with the CAS's warning. Farber (*24*) presented an example of human reliability that assumed that drivers were operating in parallel with the CAS. Given the nature of reliability of parallel systems, Farber (*24*) demonstrated that such a system will be highly reliable. On the other hand, Tijerina et al. (*6*) note that a series system may be the more appropriate reliability model for a CAS that is warning an inattentive or unaware driver. In a series system the system fails if any component fails. Tijerina et al. (*6*) demonstrated that if the CAS really works in series with the driver who is unaware of the crash hazard, then the total system is less reliable than either component alone. Research into the nature of how drivers respond to CAS activation from a reliability standpoint would be informative and might suggest a means for improving overall reliability.

The issue of latency of response is the next issue worthy of research. Taoka (*25*) favors modeling surprisal brake reaction time with a log-normal distribution. In particular, the data of Sivak et al. (*26*) were used in several analyses to assess, given a maximum time budget available for delay compatible with crash avoidance, what proportion of the driver population could respond as fast or faster than the maximum time available. An interesting point is to consider the validity of this approach for determining driver latency to respond to a CAS warning.

Figure 2, taken from Forbes (*27*), presents the cumulative distribution functions for brake reaction time collected in a variety of field settings by different methods and with different subjects. The distributions varied. What is of concern is that in most of the studies the drivers knew that they were involved in an experiment. Although they may not have anticipated the surprise stimulus that they experienced during the trial(s) represented in the data, they were nonetheless likely to be highly alert. What is needed are data, either obtained through field observations or extrapolated from theory, that will provide reaction time distributions associated with CAS warnings. In particular, it is interesting to speculate that the reaction time distribution will shift given (a) uncertainty about the threat (its location or existence) and (b) the time to select the appropriate response. Since systems in general and CASs in particular will not be 100 percent reliable or accurate, the impact of this may be manifested in a search-and-verification step on the part of the driver, a step that will take time and that should be factored into driver reaction time estimates to support both CAS effectiveness modeling and CAS design. Finally, given that older drivers exhibit slower responses, inclusion of data on older drivers in IVHS CAS effectiveness prediction and CAS design efforts is warranted.

CAS False Alarms and Their Effects on Drivers

Signal detection theory states that for a fixed level of sensitivity moving the decision threshold to afford a greater probability of correct detections will of necessity involve a greater incidence of false alarms (*28*). The problem of false alarms is difficult to assess in a limited experimental framework. Even though it may be possible to assess false alarms in a laboratory over the course of an hour, there may be little validity of such results to real-world conditions in which false alarms may occur over days or weeks rather than minutes. The costs and benefits of correct detections and false alarms and the probability of a hazard will also affect driver tolerance of false alarms.

Farber (*29*) recently presented quasi-Monte Carlo simulation results assessing the effectiveness of a rear-end collision warning for the lead vehicle moving. He compared the stopping distance

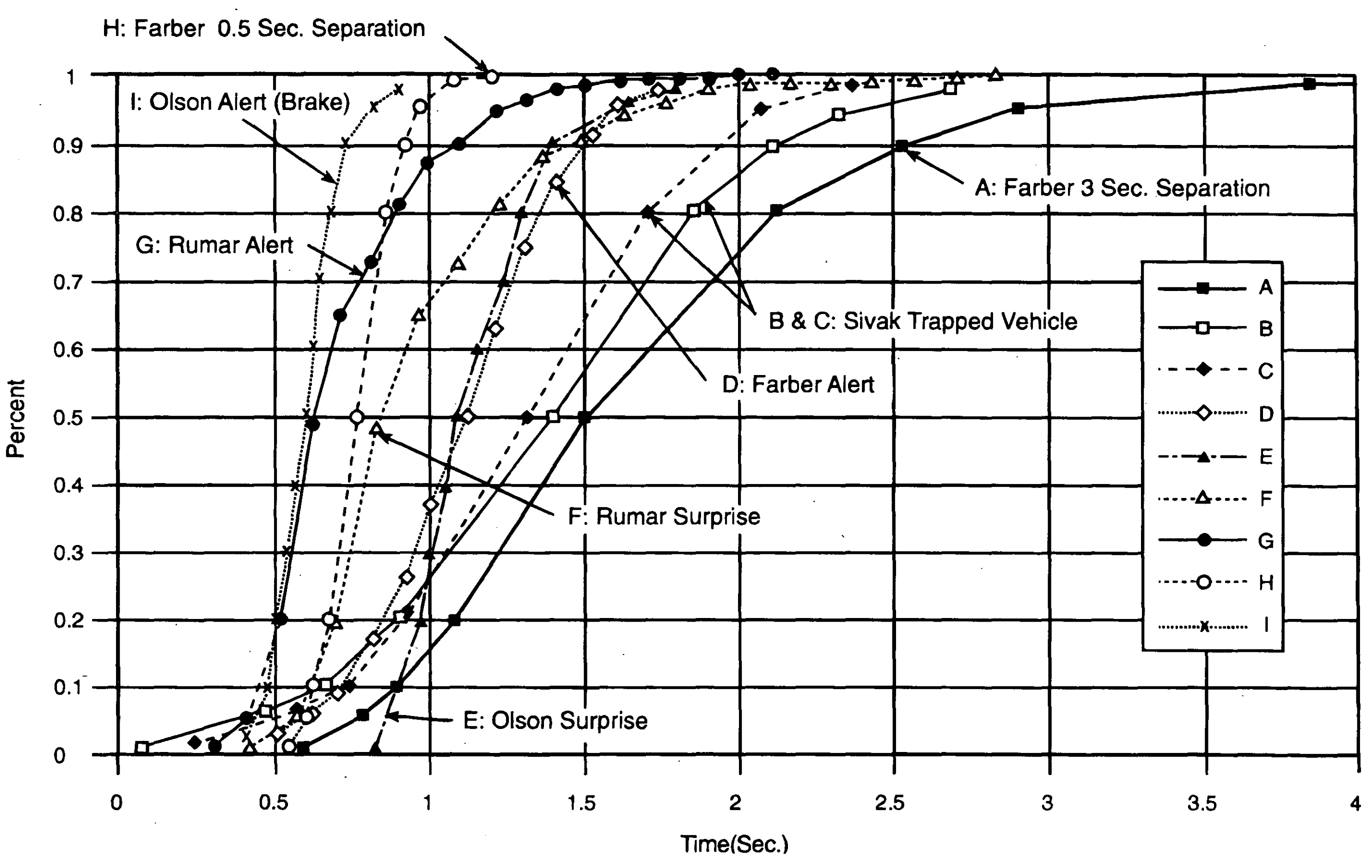

FIGURE 2 Brake reaction time distributions from various studies (*27*).

algorithm reported by Knipling et al. (*3*) with a closing rate algorithm using time headway data collected from more than 31,000 vehicle pairs on I-40 in New Mexico. Farber found that although the stopping distance algorithm had effectiveness rates approaching 100 percent, it gave approximately 1,100 false alarms for every crash, whereas the closing rate algorithm gave 6 to 11 false alarms per crash. Farber correctly points out that drivers may not be willing to respond to such frequent warnings, the great majority of which will be false alarms.

Close consideration of Farber's analysis suggests research issues associated with false alarms. First, the high incidence of false alarms results primarily from the fact that the New Mexico data included data for substantial proportions of drivers traveling with headways of less than 1.0 sec, which would lead to a preponderance of stopping distance algorithm alarms. It is plausible that, and perhaps worthy of a longitudinal study to determine if, drivers would modify their car-following behavior in the presence of a rear-end CAS. A study by Janssen and Nilsson (*20*) suggests that this will happen. In their simulator research they found that in most instances the distribution of headways with a CAS was shifted to reduce the proportion of close headways. Second, Farber (*24*) reports that drivers in the United States average about one reportable rear-end crash every 50 years. Amortizing 1,100 false alarms (recall that this is the number of warnings per crash) over 50 years, this amounts to less than 2 false alarms a month, on average. If the CAS provides a warning under alarming circumstances and such near-miss situations arise more frequently than actual crashes, perhaps the false alarm problem is really a blessing in disguise. One might hypothesize that such warnings provide familiarization to the driver and intermittent reinforcement to honor the CAS. Intermittent reinforcement has proven to be an excellent means of building resistance to extinction of a conditioned response (*30*) and may serve a similar function in IVHS crash avoidance. Thus, the issue of false alarms is indeed fundamental to CAS development, but it may involve both good and bad properties that should be assessed in a variety of ways, including longitudinal assessments of CASs perhaps in IVHS demonstrations.

Feasibility of Driver Response

In most kinematic analyses of crash avoidance, drivers are assumed to make braking responses alone or steering responses alone. Seldom are combined steering and braking responses considered. Allen (*31*) explicitly addressed this point. Figure 3 depicts stability limits on combined steering and braking maneuver accelerations on the basis of data for rear-wheel-drive and front-wheel-drive vehicles. Figure 3 shows that single responses may be more aggressive, but if both steering and braking inputs are applied, the vehicle may become directionally unstable, thus leading to secondary crash consequences. The abilities of drivers to provide the expected response is suspect and may require automatic control intervention to assist the driver and maintain safe control of the vehicle at all times during the emergency response. Alternatively, if the driver is provided with an early alert or warning, it is less likely that the driver will perform extreme and potentially unstable maneuvers.

SECONDARY EFFECTS OF CAS

A CAS could inadvertently undermine safety in a variety of ways. Some key concerns that have arisen over the course of the various crash analyses are presented.

Decreased Driver Attention to Driving Task

A major concern is that CASs will result in decreased driver attention to driving conditions. This might be manifested in decreased time spent looking at the road scene and less frequent mirror sam-

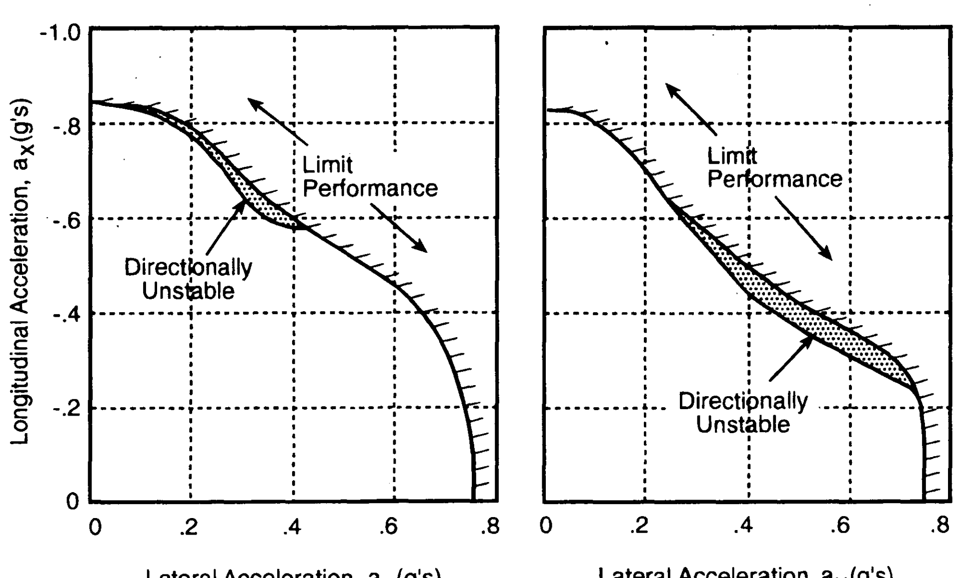

FIGURE 3 Limits on combined steering and braking maneuvering accelerations: *left*, rear-wheel drive; *right*, front-wheel drive (*31*).

pling. Drivers might develop a false sense of security that the CAS will protect them even when this is not true because of miscalibration or changes in settings, environmental degradation, or situations beyond the performance envelope of the CAS. Assessment of this concern should be a high-priority human factors research need. If it is found to be true further research will be needed to find ways to countermand this adverse consequence.

Increased Exposure on Roadway

Another secondary effect that CASs may have is increased hazard exposure. If, for example, CASs allow for greater traffic volume or invite more drivers onto the roadway under conditions that those drivers might previously have avoided (e.g., vision enhancement at night or during bad weather), then this puts more vehicles on the road and may increase crash probabilities given that CASs, vehicles, and infrastructures are less than perfectly reliable. Assessment of such effects will likely require longitudinal studies or large-scale demonstration projects.

Changes in Driver Behavior

Modifications in driver behavior have been mentioned previously. That some behavioral changes might adversely affect safety can be illustrated by a sample of studies. Nilsson (*32*) described work by Nilsson and Alm (*33*) who investigated vision enhancement in a driving simulator by simulating driving under clear conditions, foggy conditions, and foggy conditions with a simulated vision enhancement system that consisted of a monitor positioned on the hood near the windshield (i.e., simulating a HUD). On the monitor a clear picture of the road and its environment was presented to the driver. Drivers in the simulator with the HUD chose higher travel speeds than those chosen by drivers without the vision aid. Enhanced visibility benefits could be negated by higher speeds, especially if reduced visibility due to weather is accompanied by poorer traction or if higher speeds are not expected by other drivers sharing the roadway.

HUDs are supposed to provide the driver with an image on the windshield so that the driver does not have to take his or her eyes off the road. However, because of packaging constraints, only a portion of the road scene ahead will be subject to enhancement; this is called the HUD "eye box." The scene outside the HUD eye box will remain without enhancement. It is possible that the benefits of HUD vision enhancement will be offset by a reduced rate of detection of events in the periphery. Bossi et al. (*34*) conducted a simulator study of this and found significant impairment of peripheral target detection and identification performance under conditions intended to simulate night. These results need to be replicated by other methods since it was a simulator study rather than real-world driving, the targets were symbols presented in various locations rather than actual objects, and the driver's response time was to activate the high-beam stalk. However, it appears that the HUD for vision enhancement may capture a driver's visual attention and decrease a driver's attention to objects outside the eye box.

Consider a rear-end crash avoidance example to introduce the notion of modified safety margins. Janssen (*35*) presented a hypothetical effect of the presence of a CAS on the distribution of time to collision under normal car-following conditions (Figure 4). If there is a fixed criterion it is possible that drivers, over time, will compress the distribution of time headways or time to collision from the right-hand side because they are confident that the CAS will warn them. Although the warning thresholds presumably will be judiciously chosen, it is possible that there will be an increased crash potential if the CAS fails, if there is environmental degradation, or if there is a change in the warning threshold setting that the driver does not fully comprehend.

Expectancy Violations

Drivers depend a great deal on expectancies while they are on the roadway (*36*). Expectancies refer to a driver's readiness to respond to conditions, situations, events, and information in predictable and successful ways. Expectancies are of two different types: a priori and ad hoc. A priori expectancies are those that drivers bring to the

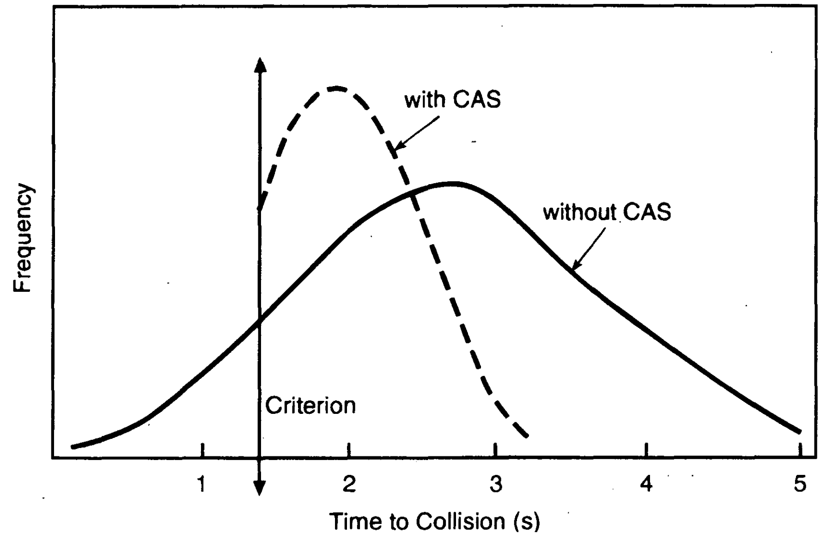

FIGURE 4 Hypothetical effect of CAS on distribution time to collision (*35*).

driving task on the basis of long experience, learning, culture, or upbringing. Ad hoc expectancies are those that develop from situation-specific factors encountered while driving. Violation of driver expectancies can have adverse consequences for safety.

As mentioned earlier adverse safety consequences might arise as a result of violated expectancies. Ervin (oral presentation, IVHS America Safety and Human Factors Committee and NHTSA Workshop on Collision Avoidance Systems, Reston, Va., 1994) has presented an interesting example in which the presence of a CAS in one vehicle leads to a crash because of violated expectations on the part of another driver. On a foggy night one driver of a vehicle without vision enhancement is waiting at a stop sign on a side street to make a left-hand turn onto a major road. The driver notices in the distance the dim headlights of an oncoming car. Expecting that no sane driver would be driving at high speeds with such poor visibility, the driver on the side street begins to pull out. Too late, the driver realizes the approaching vehicle is indeed traveling fast and a crash ensues. The hapless driver on the side street made use of expectancies developed through past experience that did not, and that perhaps could not, take the new vision enhancement technology into account. Assessments of such problems will be an important, although difficult, part of CAS evaluations.

Another potential complication in need of research is the extent to which performing maneuvers to avoid one crash leads to another crash as a by-product. Examples might include emergency braking to avoid rear-ending a lead vehicle. This could nonetheless precipitate a rear-end crash, albeit with the emergency braking vehicle now being the struck rather than the striking vehicle. Work analyzing crash avoidance opportunities to date has focused on single vehicles or pairs of vehicles for preliminary assessment of crash avoidance potential. Examination of the impacts of CASs on the traffic system in a more global perspective is warranted. It is likely that there will indeed be some instances in which there is no simple means of crash avoidance. Therefore, the design of a CAS that can gather evidence and quickly suggest an optimum solution or response is unlikely. This will probably be true if for no other reason than that which is optimum depends on the variables and the weights assigned to those variables in a cost function; these may vary by driver and circumstance.

COMPREHENSIVE CRASH AVOIDANCE AND HUMAN FACTORS IMPLICATIONS

The presence of more than one CAS in the vehicle (or an integrated CAS that provides warnings of more than one type of hazard) poses the potential for driver overload and confusion. The COMSIS Corporation (*22*) discusses means of prioritizing warnings and the need to convey different crash hazards to the driver in an effective manner. In a recent review of that document several human factors researchers in transportation were doubtful that multiple crash hazards are all that likely. Thus, the problem of multiple hazards and multiple warnings may be moot. On the other hand, a recent analysis of Crashworthiness Data System crash cases in support of the development of intersection crash avoidance specifications suggests that the issue bears further investigation. In particular, it was noted that a large proportion of crashes that occur at intersections are actually rear-end crashes. Presumably, a CAS that sensed a rear-end crash threat as the foremost crash threat would warn the driver of that first. Additional in-depth analyses of crash circumstances might uncover such scenarios of potential hazards so that further study can be undertaken to assess the likelihood that two crash hazards would arise simultaneously or in close succession.

CONCLUSIONS

CASs are a unique part of the IVHS mission because they are intended to have a direct link to safety. As such it is perhaps appropriate to verify that above all such systems do no harm. Thus, research needs should address both the positive effects and the negative effects that such systems might have. This work will benefit by taking a variety of approaches to answer specific questions. Laboratory work and studies in part-task simulators with rapid prototypes of CAS–driver interfaces may be useful for understanding and enhancing their human factors properties. Vehicular control studies to assess stability are well suited to the test track. High-fidelity simulation on a system such as the National Advanced Driving Simulator will be useful for testing driver performance under simulated crash circumstances in realistic scenarios that cannot be replicated on the roadway. Systems such as the portable Data Acquisition System for Crash Avoidance Research may provide a means of capturing real-world driving behavior and vehicle performance to augment simulator research. Many secondary effects on the driver and the traffic system as a whole will likely be understood only in the context of large-scale demonstration programs that take place over a long period of time.

CAS design, implementation, and evaluation involve many other issues besides human factors issues. These other factors include fail-safe operation, hardware reliability, and interoperability for cooperative systems, maintainability, and cost-effectiveness. It is hoped that a comprehensive, systems-oriented approach to CAS development will lead to systems that truly enhance traffic safety for many years to come.

REFERENCES

1. Najm, W. G. A Review of IVHS Crash Avoidance Technologies. Paper presented at IVHS America Safety and Human Factors Committee and NHTSA Workshop on Collision Avoidance Systems, Reston, Va., March 1994.
2. Hendricks, D., J. Allen, L. Tijerina, J. Everson, R. Knipling, and C. Wilson. *VNTSC IVHS Program Topical Report 1: Rear End crashes*, Vol. I and II. Battelle, Columbus, Ohio, 1992.
3. Knipling, R. R., M. Mironer, D. L. Hendricks, L. Tijerina, J. Everson, J. C. Allen, and C. Wilson. *Assessment of IVHS Countermeasures for Collision Avoidance: Rear-End Crashes.* Report DOT HS 807 995. NHTSA, U.S. Department of Transportation, 1993.
4. Hendricks, D., J. Allen, L. Tijerina, J. Everson, R. Knipling, and C. Wilson. *VNTSC IVHS Program Topical Report 2: Single Vehicle Roadway Departures*, Vol. I and II. Battelle, Columbus, Ohio, 1992.
5. Tijerina, L., D. Hendricks, J. Pierowicz, J. Everson, and S. Kiger. *Examination of Backing Crashes and Potential IVHS Countermeasures.* Reports DOT HS 808 016 and DOT-VNTSC-NHTSA-93-1. John A. Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1993.
6. Tijerina, L., J. D. Chovan, J. A. Pierowicz, and D. L. Hendricks. *Examination of Signalized Intersection, Straight Crossing Path Crashes and Potential IVHS Countermeasures.* Reports DT HS 808 143 and DOT-VNTSC-NHTSA-94-1. John A. Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1994.
7. Chovan, J. D., L. Tijerina, J. A. Pierowicz, and D. L. Hendricks. *Examination of Unsignalized Intersection, Straight Crossing Path Crashes and Potential IVHS Countermeasures.* Reports DOT HS 808 152 and DOT-VNTSC-NHTSA-94-2. John A. Volpe National Transportation

Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1994.
8. Chovan, J. D., L. Tijerina, G. Alexander, and D. L. Hendricks. *Examination of Lane Change Crashes and Potential IVHS Countermeasures.* Reports DOT HS 808 071 and DOT-VNTSC-NHTSA-93-2. John A. Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1994.
9. Chovan, J. D., L. Tijerina, J. H. Everson, J. A. Pierowicz, and D. L. Hendricks. *Examination of Intersection, Left Turn Across Path Crashes and Potential IVHS Countermeasures.* Reports DOT HS 808 154 and DOT-VNTSC-NHTSA-94-4. John A. Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1994.
10. Chovan, J. D., J. J. Everson, D. L. Hendricks, and J. Pierowicz. *Analysis of Opposite-Direction Crashes.* Battelle, Columbus, Ohio, 1994.
11. Knipling, R. R., D. L. Hendricks, J. S. Koziol, Jr., J. C. Allen, L. Tijerina, and C. Wilson. A Front-End Analysis of Rear-End Crashes. *Proc., IVHS America 1992 Annual Meeting*, 1992, pp. 17–20.
12. Knipling, R. R. IVHS Technologies Applied to Collision Avoidance: Perspectives on Six Target Crash Types and Countermeasures. *Proc., IVHS America 1993 Annual Meeting*, 1993, pp. 249–259.
13. Najm, W. G., J. S. Koziol, Jr., L. Tijerina, J. A. Pierowicz, and D. L. Hendricks. Comparative Assessment of Crash Causal Factors and IVHS Countermeasures. *Proc., IVHS America 1994 Annual Meeting*, 1994, pp. 412–421.
14. Mironer, M., and D. L. Hendricks. *Examination of Single Vehicle Roadway Departure Crashes and Potential IVHS Countermeasures.* Reports DOT HS 808 144 and DOT-VNTSC-NHTSA-94-3. John A. Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1994.
15. Peacock, B., and W. Karwowski. *Automotive Ergonomics.* Taylor and Francis, London, 1993.
16. Farber, E. I., and M. Paley. Using Freeway Traffic Data to Estimate the Effectiveness of Rear-End Collision Countermeasures. *Proc. IVHS America 1993 Meeting*, 1993, pp. 260–268.
17. Ward, N. J., L. Stapleton, and A. M. Parkes. Behavioral and Cognitive Impact of Night Time Driving with HUD Contact Analogue Infra-Red Imaging. Paper presented at XIVth International Technical Conference on the Enhanced Safety of Vehicles, May 1994.
18. Tijerina, L., B. H. Kantowitz, S. Kiger, and T. H. Rockwell. Driver Workload Assessment of In-Cab High Technology Devices. Paper presented at XIVth International Technical Conference on Enhanced Safety of Vehicles, Munich, Germany, May 1994.
19. Farber, B., K. Naab, and J. Schumann. *Evaluation of Prototype Implementation in Terms of Handling Aspects of Driving Tasks.* DRIVE Project V1041. Traffic Research Center, University of Groningen, Groningen, The Netherlands, 1991.
20. Janssen, W., and L. Nilsson. *An Experimental Evaluation of In-Vehicle Collision Avoidance Systems.* DRIVE Project V1041. TNO Institute for Perception, Soesterberg, The Netherlands, 1990.
21. Nilsson, L., H. Alm, and W. Janssen. *Collision Avoidance Systems—Effects of Different Levels of Task Allocation on Driver Behavior.* DRIVE Project V1041. TNO Institute for Perception, Soesterberg, The Netherlands, 1991.
22. *Preliminary Human Factors Guidelines for Crash Avoidance Warning Devices.* COMSIS Corporation, Silver Spring, Md., 1993.
23. Sorkin, R. D., B. H. Kantowitz, and S. C. Kantowitz. Likelihood Alarm Displays. *Human Factors,* Vol. 30, 1988, pp. 445–459.
24. Farber, E. I. Intelligent Vehicle Highway System Benefits and Public Policy. Paper presented at 13th International Technical Conference on Experimental Safety Vehicles, Paris, 1991.
25. Taoka, G. T. Brake Reaction Times of Unalerted Drivers. *ITE Journal,* March, 1989, pp. 19–21.
26. Sivak, M., P. L. Olson, and K. M. Farmer. Radar Measured Reaction Times of Unalerted Drivers to Brake Signals. *Perceptual and Motor Skills,* Vol. 55, 1982, p. 494.
27. Forbes, L. M. Lyman M. Forbes discussion of Wade Allen's Paper: The Driver's Role in Collision Avoidance Systems. Paper presented at IVHS America Safety and Human Factors Committee and NHTSA Workshop on Collision Avoidance Systems, Reston, Va., March 1994.
28. Kantowitz, B. H., and R. D. Sorkin. *Human Factors: Understanding People–System Relationships.* John Wiley and Sons, New York, 1983.
29. Farber, E. I. Using the Reamacs Model to Compare the Effectiveness of Alternative Rear End Collision Warning Algorithms. Paper presented at XIXth International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, 1994.
30. Houston, J. P. *Fundamentals of Learning and Memory*, 2nd ed. Academic Press, New York, 1981.
31. Allen, R. W. The Driver's Role in Collision Avoidance Systems. Paper presented at IVHS America Safety and Human Factors Committee and NHTSA Workshop on Collision Avoidance Systems, Reston, Va., March 1994.
32. Nilsson, L. Simulator Studies and Driver Behavior Research. In *Driving Future Vehicles* (A. Parkes and S. Franze, eds.), Taylor and Francis, London, 1993, pp. 401–407.
33. Nilsson, L., and H. Alm. *Effects of a Simulated Vision Enhancement System on Driver Behavior and Driver Attitudes.* PROMETHEUS Report VT1. Swedish Road and Traffic Research Institute, Linkoping, Sweden, 1991.
34. Bossi, L. L. M., N. J. Ward, and A. M. Parkes. The Effect of Simulated Vision Enhancement Systems on Driver Peripheral Target Detection and Identification. Paper presented at 12th Triennial Congress of International Ergonomics Association, Toronto, Canada, Aug. 15–19, 1994.
35. Janssen, W. H. *The Impact of Collision Avoidance Systems on Driver Behavior and Traffic Safety: Preliminaries to Studies Within the GIDS Project.* DRIVE Project V1041. TNO Institute for Perception, Soesterberg, The Netherlands, 1989.
36. Alexander, G., and H. Lunenfeld. Positive Guidance and Driver Expectancy. In *Automotive Engineering and Litigation*, Vol. 3 (G. A. Peters and B. A. Peters, eds.), Garland Law Publishing, New York, 1990, pp. 617–679.

Publication of this paper sponsored by Committee on Vehicle User Characteristics.