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Attention-Based Model of Driver Performance in Rear-End Collisions

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Several driver-performance factors contribute to rear-end collisions—driver inattention, perception-reaction time, and limitations of the human visual system. Although many evaluations have examined driver response to various rear-end collision avoidance systems (RECAS) display and algorithm alternatives, little research has been directed at creating a quantitative model of driver performance to evaluate these alternatives. Current considerations of driver behavior in developing warning algorithms tend to ignore the fundamental problem of driver inattention and assume a fixed driver reaction time with no further adjustment after the initial response. A more refined model of driver response to rear-end crash scenarios can identify more appropriate and timely information to be displayed to the driver. An attention-based rear-end collision avoidance model (ARCAM) is introduced that describes the driver's attention distribution, information extraction and judgment process, and the reaction process. ARCAM predicts the closed-loop nature of collision response performance and explains how the driver might use RECAS warnings.

Rear-end collision avoidance systems (RECAS) may help alleviate an important traffic safety problem. Front-to-rear-end crashes involving two or more vehicles currently represent approximately one-fourth of all collisions. Specifically, the National Safety Council reported that there were approximately 11.3 million motor vehicle crashes in 1995, of which 2.7 million were rear-end crashes (about 23.8 percent of the total) (*1*). According to the General Estimates System and Fatal Accident Reporting System, in 1992 there were approximately 1.4 million police-reported rear-end crashes. These rear-end crashes constituted approximately 23 percent of all police-reported crashes, but only about 4.7 percent of all fatalities. Beside the injuries and fatalities caused by rear-end crashes, rear-end crashes also cause approximately 157 million vehicle hours of delay annually, or approximately one-third of all crash-caused delays.

Several driver-performance factors contribute to rear-end collisions—driver inattention, perception-reaction time, and limitations in the human visual system. Driving an automobile is a complex task, one that requires the operator to scan the environment constantly and respond properly in order to maintain control, avoid obstacles, and interact safely with other vehicles. Knipling et al. estimated that driver inattention accounted for 64 percent of all police-reported rear-end crashes (2). All drivers experience some level of inattention while driving (e.g., talking to passengers, daydreaming, adjusting in-vehicle controls, or noticing extravehicle distractions). Inattention can be manifested in the various elements of driver behavior such as failing to attend to the roadway or not processing the information from the environment. As inattention is the primary cause of rear-end collisions, a model that examines the attentional aspects of the rear-end collision would be a valuable tool.

Over the past 10 years, the focus on technological solutions to the rear-end crash problem has intensified. Many prototype systems have been developed and tested to determine the best possible method for warning drivers of potential rear-end collisions. These systems have been developed and tested to identify algorithms and displays that will help drivers avoid rear-end collisions (*3*, *4*). A few have been marketed—primarily for commercial vehicle operations (Vorad, Nissan). These prototype and operational systems have employed a number of algorithms and displays.

Although many evaluations have examined driver response to various display and algorithm alternatives, little research has considered creating a quantitative model of driver performance to aid in these evaluations. Most systems have been designed using many simplifying assumptions regarding human performance. A fixed driver reaction time to the warning, constant braking at a given level, and a continuously inattentive driver are examples of these assumptions. Although these assumptions simplify the problem and allow for some analyses of the algorithms, they do not provide a comprehensive explanation of how the algorithm and driver interact (*5*). A more sophisticated attention-based quantitative model can provide more precise and accurate design guidance. This paper describes such a model: the attention-based rear-end collision avoidance model (ARCAM). ARCAM provides a flexible tool to examine the simplifying assumptions currently being made in RECAS algorithm development. Additionally, ARCAM will integrate the empirical data concerning driver attention and perception into the rear-end collision context.

THESIS

A quantitative model of the rear-end crash scenario will allow for the examination of a wide range of factors that affect the driver's ability to avoid collisions, including warning systems, without the time and expense required for field and simulator studies. The elements that define a rear-end collision situation include the driver as an information processor, the driver's vehicle and its related braking performance, and the lead vehicle's braking behavior. Figure 1 shows that this representation assumes that the effects of other vehicles are negligible. The inputs to the model are a desired index of cautiousness and lead vehicle behavior. The outputs of the model are the speeds and relative positions of the two vehicles.

A computational model of the driver can examine potential rear-end collision circumstances with and without RECAS to determine the safety benefit of RECAS. Current considerations of driver behavior in developing warning algorithms tend to assume a fixed driver reaction time with no further adjustment after the initial response (*3*).

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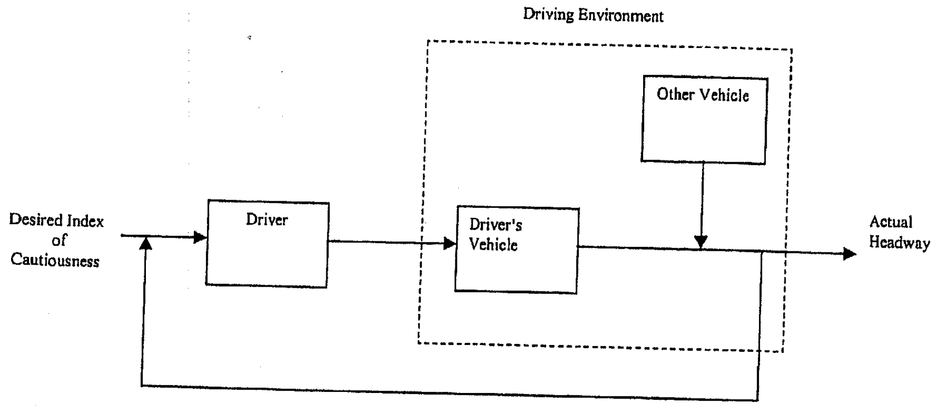

FIGURE 1 Dynamic representation of a rear-end collision situation.

A more refined model of driver response to rear-end crash scenarios can identify how these assumptions affect the joint driver–RECAS system and whether more appropriate and timely information can be displayed to the driver. This paper presents a conceptual model that outlines the structural requirements of predicting driver response to rear-end collision situations.

BASIS OF DRIVER MODEL

The driver portion of the model is of particular interest. Figure 2 shows an expanded view of the driver module, ARCAM. ARCAM is much more complex than a simple reaction time and step function response. Initially ARCAM will be constrained to longitudinal

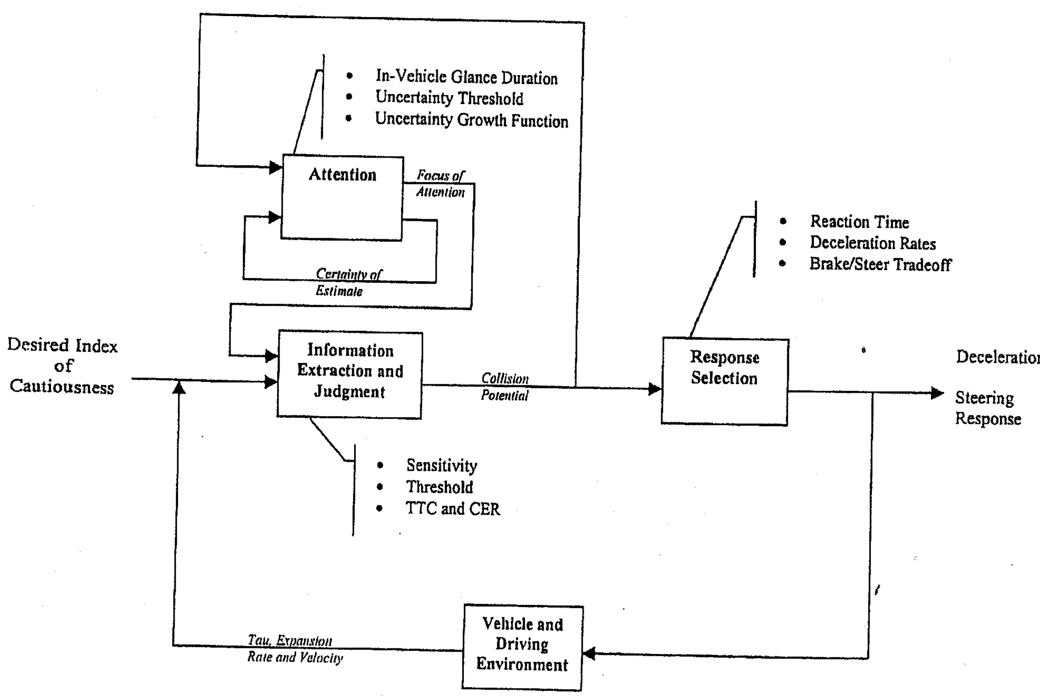

FIGURE 2 Attention-based rear-end collision avoidance model.

control; however, some aspects of lateral control will be briefly addressed. As ARCAM will not initially attempt to explain driver performance other than longitudinal control, the implementation of this theoretical model into a quantitative model is simplified compared to more general models of the driver that have been attempted in the past (*6*). By starting with a more manageable model, it can be implemented and incrementally expanded to include more situations. The driver's attention distribution, the information extraction and judgment process, and the reaction process are all incorporated in this model. The inputs to this model are desired index of cautiousness, tau, expansion rate, and velocity. The index of cautiousness, tau, and expansion rate will be discussed in the following sections. The outputs of the model are deceleration and steering response.

Attention

For the driver to react to a rear-end collision, his or her attention must, to some degree, focus on the lead vehicle. Typical driving does not require constant attention to the forward roadway; a surplus of visual scanning capacity exists that approaches 50 percent at times for driving (*7*). Because the driver's attention might not be focused on the forward view, he or she may not notice the visual cues that indicate a possible rear-end collision (*4*). Senders et al. predict that an observer will sample the environment at the rate information changes and that the glance length will be dependent upon the information in the sample (*8*). In general, they found that the duration of any given glance was between 0.3 and 0.5 s and that the sampling rate reflected uncertainty regarding the system state. A driver's attention to the roadway also depends on an uncertainty about the information contained in the last forward view. This uncertainty increases until it reaches an unacceptable level, at which time the driver will return attention to the forward view to decrease the uncertainty about the situation (*9, 10*). The uncertainty grows as a function of the information density of the road, the velocity of the driver's vehicle, the rate of forgetting, and the time interval over which the road is not being attended (*9, 11*). The driver's uncertainty about the environment also can be explained by the following simplified equation, where t is the time since the last sample and the constants define the situation (*10*):

$$\text{Standard deviation of memory position} = \alpha + \lambda \times t^{1.5} \qquad (1)$$

For the rear-end collision situation, uncertainty grows concerning the potential of a collision with the vehicle ahead. Collision potential is defined as the relationship between how much distance is required to stop and how much distance is available to stop. When the driver is unsure that the collision potential is safe, attention is shifted back to the roadway. The concept of collision potential is explained more thoroughly in the discussion of information extraction and judgment. The parameter α of the simplified uncertainty equation defines the initial uncertainty associated with the driver's estimate of collision potential. This parameter can be estimated by using known uncertainty in driver estimates of time-to-collision (TTC), the distance to the lead vehicle, and the distance required to stop. The parameter λ can be estimated by analyzing eye-glance behavior of drivers performing a secondary task that requires them to divert their eyes from the road for as long as they think it is safe. The duration and timing of glances as a function of headway and speed can be used to estimate this parameter. Once these constants have been estimated, this equation can be used to model how the driver looks toward and away from the driving environment.

The driver's attention distribution has significant effects on his or her ability to react to a possible collision situation. The driver's reaction time to the actions of the lead vehicle will be increased by the amount of time required to return his or her attention to the lead vehicle. This increase in reaction time includes both the time spent looking away from the road and the time required to transition attention back to the roadway. Pashler summarizes many studies of the time course of selective attention that examine how long it takes for a cue to initiate selective processing by location (*12*). The results of these studies suggest that the transition time for attention to the roadway might range between 100 and 250 ms.

This component of the model can guide RECAS design by identifying the benefit a warning can provide to a periodically distracted driver by redirecting attention to the roadway. This can be accomplished by comparing how long it would take the driver to return attention to the roadway with and without the warning.

In summary, the attention component of ARCAM converts collision potential and time since the last sampling of the roadway into a level of uncertainty that guides drivers to direct their attention to the road. It also identifies the delays associated with this process, including the time required to switch attention to the roadway.

Information Extraction and Judgment

The second component of the driver model describes the information extraction from the environment and the judgment of the need to brake. An early description of driver behavior provides a theoretical framework for explaining how drivers decide to decelerate (*13*). This theoretical framework describes the driver as attempting to move through the environment that is represented as a field of safe travel. This field is specified by visual information, and the driver moves along a path that avoids obstacles that would impede locomotion. This path follows the field of safe travel, which is a combination of all paths that the driver can take unimpeded. The field of safe travel has a positive "valence" with the center of the path having the highest positive valence, whereas obstacles have negative valences. The destination of the driver also has a large positive valence, which controls the overall course of the vehicle. The field of safe travel is not static and moves with the vehicle. It is independent of driver perceptions and describes the physical characteristics of the vehicle and the environment that govern safe travel. For longitudinal control, the field of safe travel extends to where the lead vehicle would be in the time taken for the driver to stop the vehicle. The driver uses a preferred normal deceleration as the basis for this determination. A good estimate of this normal braking level is 0.20 g (*14*).

The premise of the field theory of driving is that the driver will attempt to follow this field of safe travel, thus avoiding other vehicles and obstacles in the roadway. The driver does this through steering adjustments and velocity corrections. For steering adjustments, steering can be considered "a perceptually governed series of reactions by the driver of such a sort as to keep the car headed into the middle of the field of safe travel" (*15*, p. 122). The deceleration of the vehicle is controlled by the index of cautiousness (IC), which is the ratio between the field of safe travel (FST) and the minimum or stopped vehicle. However, this steering model must be integrated with the braking portion of driver response.

Most descriptions of drivers' response to RECAS assume a step-braking response. This element of the model will help determine how a closed-loop braking response affects the benefit of RECAS.

In summary, the response selection component of the model converts collision potential into deceleration. In addition, it specifies delays associated with moving from the accelerator to the brake and depressing the brake.

Model Outputs: Reaction Time and Response

Providing a framework for better understanding and predicting driver reaction time in rear-end collision situations is an important contribution of ARCAM. Driver information processing and motor control introduce delays in each component of ARCAM. Many studies have been conducted that examine the perception-reaction time (PRT), generating widely varying estimates. ARCAM may help reconcile these results so they can be applied to RECAS design. The PRT includes all delays associated with the model from information extraction through reaction. The time delay associated with each component of ARCAM suggests that for a braking response, the PRT is influenced by whether the driver is expecting the event or not, the specific perceptual characteristic of the situation, and the severity of the situation. When the driver is alerted to an event, the PRT will be less than if not alerted. In a study by Johannson and Rumar, it is suggested that when braking is anticipated, a correction factor of 1.35 s must be added to find the unalerted PRT (*28*). This 1.35-s correction factor was validated on Iowa driving simulator experiments in which the baseline reaction-time values were 2.34 to 2.53 s for an "unexpected" event (*29*). Based upon the model of the driver, this correction factor for reaction time may be attributed to a delay in attending to the road (attention module) relative to the alerted case.

A reexamination of the data obtained by McGehee et al. provides additional information about how a driver responds to a RECAS warning (*29*). The drivers' mean response to a RECAS warning, for a stopped lead vehicle, was 0.29 s to accelerator release, 0.90 s to brake application, and 2.32 s to maximum brake application. The mean time between brake application and maximum braking was 1.41 s for drivers with RECAS. Additionally, the 90th percentile time to brake application was 1.3 and 1.6 s for the two RECAS conditions examined in that study.

Another study that examined response to a lead-vehicle-moving scenario produced similar findings, but the mean response for accelerator release was 1.2 s instead of the 0.3 s found for the lead-vehicle-stopped scenario. This reaction time reflects a less severe lead-vehicle-moving scenario, thus allowing the driver more time to respond. Additionally, this study found that improvements in driver response were mainly the result of changes in initial accelerator release (McGehee, Lee, and Brown, unpublished data). This range of results is consistent with the predictions of ARCAM. Experimental situations will affect drivers' reaction time and response through the mechanisms of attention, perception, and motor control limits.

FINDINGS

ARCAM is a conceptual tool that can examine the rear-end collision situation and identify the implications for design and evaluation of RECAS. There are two main areas of interest in this regard: the validity of the conceptual model and the evaluation of RECAS warning effectiveness.

Validity of Conceptual Model

The closed-loop structure of ARCAM is an important contribution to its validity. Current algorithms and models assume that drivers do not adjust their response after making the initial decision. Data from recent studies examining RECAS show that drivers respond in a closed-loop fashion to rear-end collision situations. If the response to a rear-end collision were an open-loop process, it would be expected that the driver would make an initial reaction and then the response would remain unchanged; whereas, in a closed-loop process, the driver adjusts the response based upon new information. In a recent study, McGehee et al. found that 21 of 30 drivers made adjustments following the initial reaction (*29*). Figure 3 plots six variables for 7 s for one driver's response to a collision situation. The figure shows that the driver's first response is to brake. The driver then releases the brake somewhat and begins a steering maneuver; during this steering maneuver, the driver then increases brake application to avoid the collision. This response suggests that the driver is adjusting the response based upon changes in the driving environment.

Reaction-time data also provide support for the closed-loop nature of the response. Specifically, the data show that drivers adjust the brake pressure based upon the current state of the environment; they do not make a simple step-brake response when they begin braking. For example, the time between initial brake application and maximum braking is 1.4 s (*29*). This reflects a braking profile that is modulated by the driver's perception of the collision situation. This implies that the driver does indeed act as a closed-loop system, consistent with ARCAM.

The reexamination of the data in McGehee et al. provides additional validation of ARCAM (*29*). The data show that the driver does not immediately brake following the initial accelerator release; instead 0.6 s expires before the driver brakes. This delay reflects a process of information extraction and judgment. This characteristic of the model, validated with empirical data, is important because it shows that warnings may only return the driver's attention back to the roadway to obtain information rather than directing a response. The closed-loop nature of the driver's response to the RECAS warning, the delay between accelerator release and initial braking response, and the braking profile all provide validation for the conceptual model.

Effectiveness of RECAS Warnings

ARCAM has important implications for the design of RECAS. Specifically, the effectiveness of a RECAS warning depends on how drivers interpret the warning. One possibility is that the warning focuses the driver's attention to the roadway. Another possibility is that it causes the driver to immediately react. How an alert or a warning causes the driver to react has significant implications for the design of a system. For example, if the warning causes the driver to react immediately, the reaction time, from accelerator to brake, will be relatively small. However, if the warning causes the driver to process information from the environment, then that reaction time will be longer while the driver extracts information from the environment.

The model described in this paper contains several important features that support an accurate prediction of driver response. For

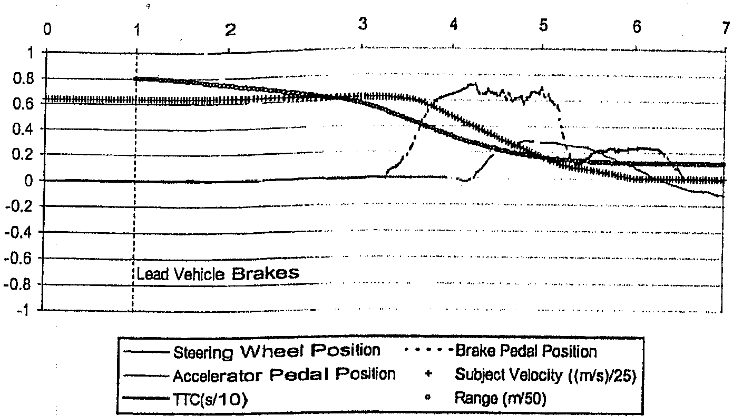

FIGURE 3 Closed-loop response to a rear-end collision situation.

example, the intermittent selective focus of attention and the uncertainty growth function describe a potential mechanism underlying inattention. These features provide a means of augmenting a RECAS warning algorithm to account for this inattention and determining the benefits that could be achieved. The information extraction and judgment process defines how τ and CER can be used to define the field of safe travel for the driver and the potential for colliding with the lead vehicle. This provides for identification of the circumstances under which drivers may misperceive the situation and RECAS will be most beneficial. The use of collision potential in directing the response selection process allows ARCAM to reflect the complex closed-loop braking profiles used by drivers. These complex deceleration profiles will allow for a more accurate prediction of the benefits of RECAS. These features provide a basis for ARCAM to improve RECAS warnings.

CONCLUSION

ARCAM brings together empirical findings from several studies to provide a solid basis for examining how the driver interacts with RECAS. Existing data validate the basic structure of ARCAM by showing that the driver operates in a closed-loop manner, adjusting the initial response as a result of subsequent observations. It also is clear that the RECAS warning causes the driver to extract information from the environment before reacting. These findings provide initial validation for the conceptual model of the driver that has been developed. The components of ARCAM provide a structure for interpreting conflicting reaction-time data and also provide several important recommendations for the design of warning algorithms and displays.

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REFERENCES

1. *Accident Facts.* The National Safety Council, Itasca, Ill., 1996.
2. Knipling, R. R., M. Mironer, D. L. Hendricks, L. Tijerna, J. Everson, J. C. Allen, and C. Wilson. *Assessment of IVHS Countermeasures for Collision Avoidance: Rear-End Crashes.* NHTSA, U.S. Department of Transportation, 1993.
3. Burgett, A. L., A. Carter, R. J. Miller, W. G. Najm, and D. L. Smith. *A Collision Warning Algorithm for Rear-End Collisions.* NHTSA, U.S. Department of Transportation, 1998.
4. McGehee, D. V., T. A. Dingus, and A. D. Horowitz. The Potential Value of a Front-to-Rear-End Collision Warning System Based on Factors of Driver Behavior, Visual Perception and Brake Reaction Time. *Proc., 36th Annual Meeting, Human Factors and Ergonomics Society,* Atlanta, Ga., 1992, pp. 1003–1005.
5. Brown, T. L., J. D. Lee, and D. V. McGehee. Analysis of Rear-End Crash Avoidance Algorithms: Demonstrating the Value of Simple Human Performance Models. Submitted to *Human Factors.*
6. Ranney, T. A. Models of Driving Behavior: A Review of Their Evolution. *Accident Analysis and Prevention,* Vol. 26, No. 6, 1994, pp. 733–750.
7. Rockwell, T. Skills, Judgment and Information Acquisition in Driving. In *Human Factors in Highway Traffic Safety Research* (T. W. Forbes, ed.), Wiley Interscience, New York, 1972.
8. Senders, J. W., J. I. Elkind, M. C. Grignetti, and R. Smallwood. *An Investigation of the Visual Sampling Behavior of Human Observers.* National Aeronautics and Space Administration, Washington, D.C., undated.
9. Senders, J. W., A. B. Kristofferson, W. H. Levison, C. W. Diettrich, and J. L. Ward. The Attentional Demand of Automobile Driving. In *Highway Research Record 195,* HRB, National Research Council, Washington, D.C., 1967, pp. 15–33.
10. Moray, N. The Role of Attention in the Detection of Errors and the Diagnosis of Failures in Man-Machine Systems, 1981. In *Human Detection and Diagnosis of System Failures* (J. Rasmussen and W. B. Rouse, eds.), Plenum Press, New York, 1981.
11. Courage, C. An Investigation of Attentional Demand in a Simulated Driving Environment. In *Mechanical and Industrial Engineering,* University of Toronto, Ontario, Canada, 2000, p. 83.
12. Pashler, H. *The Psychology of Attention.* The MIT Press, Cambridge, Mass., 1998.
13. Gibson, J. J., and L. E. Crooks. A Theoretical Field-Analysis of Automobile-Driving. *American Journal of Psychology,* Vol. 51, 1938, pp. 453–471.
14. Kiefer, R., D. LeBlanc, M. Palmer, J. Salinger, R. Deering, and M. Shulman. *Development and Validation of Functional Definitions and Eval-*

uation Procedures for Collision Warning/Avoidance Systems. Crash Avoidance Metrics Partnership, Washington, D.C., 1999.

15. Gibson, J. J. A Theoretical Field-Analysis of Automobile-Driving. In *Reasons for Realism* (E. Reed and R. Jones, eds.), Lawrence Erlbaum Associates, Publishers, Hillsdale, N.J., 1982, pp. 119–136.
16. Sussman, E. D., H. Bishop, B. Madnick, and R. Walter. Driver Inattention and Highway Safety. In *Transportation Research Record 1047,* TRB, National Research Council, Washington, D.C., 1985, pp. 40–48.
17. Aberg, L., and P. A. Rimmo. Dimensions of Aberrant Driver Behaviour. *Ergonomics,* Vol. 41, No. 1, 1998, pp. 39–56.
18. Laurent, G., and F. Gabbiani. Collision-Avoidance: Nature's Many Solutions. *Nature Neuroscience,* Vol. 1, No. 4, 1998, pp. 261–263.
19. Hoffmann, E. R. Estimation of Time to Vehicle Arrival—Effects of Age on Use of Available Visual Information. *Perception,* Vol. 23, 1994, pp. 947–955.
20. Stanard, T., and M. R. H. Smith. Testing the Tau Hypothesis Against Alternative Information Sources Used for Collision Avoidance. *Proc., 42nd Annual Meeting Human Factors and Ergonomics Society,* Chicago, 1998, pp. 1535–1539.
21. Sidway, B., M. Fairweather, H. Sekiya, and J. McNitt-Gray. Time-to-Collision Estimation in a Simulated Driving Task. *Human Factors,* Vol. 38, No. 1, 1996, pp. 101–113.
22. Wickens, C. D. *Engineering Psychology and Human Performance.* 2nd ed. HarperCollins Publishers Inc., New York, 1992.
23. Lee, D. N. A Theory of Visual Control of Braking Based on Information About Time to Collision. *Perception,* Vol. 5, 1976, pp. 437–459.
24. Liebermann, D. G., N. Schweitzer, G. Ben-David, Y. Apter, and A. Parush. A Field Study on Braking Responses During Driving: I. Triggering and Modulation. *Ergonomics,* Vol. 38, No. 9, 1995, pp. 1894–1902.
25. Schweitzer, N., Y. Apter, G. Ben-David, D. G. Liebermann, and A. Parush. A Field Study on Braking Responses During Driving: II. Minimum Driver Braking Times. *Ergonomics,* Vol. 38, No. 9, 1995, pp. 1903–1910.
26. Spurr, R. T. Subjective Aspects of Braking. *Automobile Engineer,* Feb. 1969, pp. 58–61.
27. Reid, L. D. A Survey of Recent Driver Steering Behavior Models Suited to Accident Studies. *Accident Analysis and Prevention,* Vol. 15, No. 1, 1983, pp. 23–40.
28. Johansson, G., and K. Rumar. Drivers' Brake Reaction Times. *Human Factors,* Vol. 13, No. 1, 1971, pp. 23–27.
29. McGehee, D. V., T. L. Brown, T. B. Wilson, and M. Burns. *Examination of Driver's Collision Avoidance Behavior in a Lead Vehicle Stopped Scenario Using a Front-to-Rear-End Collision Warning System.* The University of Iowa, Iowa City, 1998.