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Transportation Research Record 1403

Contents

Foreword

The 13 papers in this volume focus on driver performance and simulation. Human engineering of advanced technology to aid drivers is discussed first: topics include the design of auditory interfaces new to the world of automobiles and the design of vehicle controls and models of human performance to use in evaluating the development of high technology for drivers. Then human behavior in the driving environment is explored in studies of eye scanning and driver work load. Ways to improve information to the driver are examined from the perspective of the vehicle, through the use of daytime running lights, and from sources external to the vehicle, such as broadcasting, signs, and markings. The Record concludes with papers on simulation of vehicle dynamics and motion.

Design of TravTek Auditory Interface

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In an advanced driver information system, computer voice messages and nonverbal auditory signals provide a means of imparting information to the driver without creating a visual distraction. In the TravTek system, synthesized voice has been used extensively as a supplement to the visual display, providing route guidance instructions, navigation assistance, and traffic information. Special consideration has been given to strategies for maximizing the acceptability of synthesized voice to drivers. TravTek voice messages are designed as concise utterances that aid the driver in reaching the destination easily, quickly, and safely. Data collected from onboard computers, controlled experiments, and driver questionnaires will be analyzed to evaluate user acceptance and feature preferences.

Computer-generated voice has been widely identified as a useful way to impart information to drivers in an advanced driver information system (ADIS) (*1*). A typical ADIS may use voice to present navigation and traffic information without creating a visual distraction. There is, however, a common perception in the North American automotive community that people do not like talking cars. In the TravTek ADIS, the authors have attempted to understand the objections that drivers may have to the use of voice in cars and to develop strategies that enhance the user acceptance of synthesized voice.

TRAVTEK DEMONSTRATION

TravTek is an ADIS operational field test conducted jointly by General Motors, FHWA, the American Automobile Association, the Florida Department of Transportation, and the city of Orlando, Florida. TravTek has been in operation in Orlando with 100 vehicles available as rental cars and for use by local drivers. ADIS features of the TravTek system include route planning and guidance, real-time traffic information, navigation assistance, and an onboard services and attractions data base. Fleischman et al. (*2*) and Carpenter et al. (*3*) describe the functionality and human factors design of the TravTek driver interface. Rillings and Lewis (*4*) and Krage (*5*) provide details of the TravTek program and the architecture of the vehicle subsystem.

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VOICE FUNCTIONS IN TRAVTEK

Synthesized voice is used extensively in the TravTek system, providing route guidance instructions, navigation assistance, and traffic information. Nonverbal auditory signals are also used in a limited way as feedback for button presses, as well as prompting for screen glances when voice functions are deactivated. Voice functions are controlled by the driver through the use of four buttons on the steering wheel. These buttons are labeled "Where Am I?", "Repeat Voice," "Traffic Report," and "Voice Guide." The voice controls allow a driver to select the types of information desired through voice, allowing all voice messages to be disabled if necessary.

Where Am I?

The Where Am I? function provides information on the vehicle's current street location and the name of the next cross street ahead of the vehicle. Each press of the Where Am I? button elicits a single message with location information. Special messages have been formulated to accommodate situations in which the vehicle is not situated on a known street or no known cross streets are ahead of the vehicle.

Repeat Voice

The Repeat Voice function enables the driver to replay the most recently spoken voice message. The message, when repeated, is prefaced by the statement "The last message was . . .". The replay is a literal repeat as opposed to a functional one. Even if the information has changed since the message was originally spoken, the original text is spoken in the replay. The repeatability of a message times out after a short period, to avoid repeating messages in which the information content is extremely outdated. After the timeout, a button press of Repeat Voice produces the message "No recent message to repeat."

Traffic Report

The Traffic Report function provides a verbal traffic advisory that reports known traffic problems. Traffic data are broadcast to the vehicles once a minute from the TravTek traffic management center (TMC). Traffic data contain information on congestion problems within the TravTek map area, as well as details on incidents and construction when such information is known.

Onboard the vehicle, the traffic data are displayed on a color map using incident and congestion icons. Traffic problems are filtered for relevance to the vehicle's location and route. With each new broadcast, a voice traffic message is formulated to describe each geographically relevant traffic problem. Voice traffic messages contain information on the location, cause, and severity of traffic problems. The set of relevant traffic messages constitutes the voice traffic report. When the Traffic Report function is activated by a button press, the voice begins to speak the current traffic report, with messages ordered by urgency and proximity to the vehicle. A subsequent button press will terminate the report. While the Traffic Report function remains activated, as subsequent TMC broadcasts are received, all new, relevant traffic problems are spoken.

At the start of a trip, the Traffic Report function defaults to an off state. Voice traffic reports are spoken only if requested by the driver. When Traffic Report is switched off and then back on, the full, relevant, ordered set of traffic messages is respoken, thus enabling the driver to hear all traffic problems.

Voice Guide

The Voice Guide button enables and disables voice route guidance instructions. Voice guidance messages describe upcoming maneuvers on the planned route and indicate an off-route condition and destination arrival.

Up to three voice messages may accompany the upcoming maneuver. If the distance to the maneuver is so great that the driver need not attend to it yet, the voice guidance message specifies only the distance to the maneuver, corresponding to a straight-ahead arrow on the visual guidance display: for example, "Ahead, next turn in three and four-tenths miles." At a closer distance to the maneuver, when the driver must get into the appropriate lane in anticipation of a turn, a "near-turn" message is spoken. The near-turn message contains the distance to the maneuver and the name of the turn street and the type of maneuver (e.g., "make a hard left" or "bear right"). A typical near-turn message is "In eight-tenths miles, turn right onto the ramp to I-4 east." This corresponds with a change in the visual guidance display, which now depicts the geometry of the maneuver intersection and displays the name of the turn street. Just before the maneuver intersection, at a point at which the driver can be expected to identify visually the turn street, voice guidance speaks an "at-turn" message, which contains the same information as the near-turn message but eliminates the distance information. This informs the driver that the maneuver is imminent.

When an upcoming maneuver is followed closely by another maneuver, the message for the first maneuver alerts the driver to prepare for the second one. An example is "Bear left to follow the correct branch of Sand Lake Road, then prepare to turn right." This helps the driver position correctly after the first maneuver in anticipation of the second one.

When Voice Guide is switched off and then back on again, a distance-appropriate guidance message is spoken. In this way the driver has the ability to force the system to speak an instruction for the next maneuver at any time. The Voice Guide function is automatically enabled at the start of a trip with a planned route, as voice guidance is intended to reduce glances at the visual displays.

TRAVTEK PHILOSOPHY ON VOICE ACCEPTABILITY

The auditory mode, if implemented effectively, has great potential as a means of imparting complex information to the driver. Voice messages elaborate on the information depicted on the visual display, providing an eyes-on-the-road mode of informing the driver. Voice messages also draw the driver's attention to the fact that new information is now available, so the driver need not glance at the visual display frequently to check for an update. In TravTek, voice functions are considered to be a supplement to the visual display, which can be used as a stand-alone system.

The TravTek driver interface design team has strived to make the application of voice to an ADIS palatable to the driver. The precepts that the authors have applied to the design of the auditory interface include

- Minimizing voice "chattering" and "nagging";
- Maximizing voice intelligibility;
- Providing timely, useful information through voice; and
- Allowing significant driver control of voice functions.

Talking Cars

"People don't like talking cars." This bit of folklore has presumably arisen from negative reactions to vehicles that use voice to warn driver of open doors and unbuckled seat belts. An examination of the use of voice for such purposes reveals violations of some of the aforementioned TravTek precepts.

Drivers may not be receptive to the use of voice for system warnings unless the condition is urgent, such as a collision warning. In the case of an open door, a nonverbal auditory signal or a telltale on the instrument panel is probably enough to alert the driver to the condition. The driver may perceive the voice in this instance as nagging, because the voice only speaks to say that the driver has done something wrong. Drivers may have various reasons to suppress a voice system at times, and these wishes must be accommodated by giving the driver control over volume as well as activation of voice functions.

Past negative reactions to misapplied voice technology do not necessarily bode poorly for future well-considered use of voice on passenger cars. The initial experiences with the TravTek auditory system indicate that the computer-generated voice that provides useful information at the appropriate time may be welcome to drivers, especially for route guidance.

The TravTek evaluation plan provides a mechanism for assessing user acceptance and actual usage of the voice functions (*6*). Driver interaction data that are logged onboard the vehicle serve as one source of feedback on how drivers use the system. Drivers also express subjective reactions to their TravTek driving experience through debriefings and questionnaires. Controlled experiments were designed that may analyze benefits provided by voice guidance. By analyzing TravTek data from all these sources, the authors expect to learn a great deal about driver behavior and preferences for

ADIS features. In particular, analysis of the use of voice controls will provide a measure of the usefulness and the affective impact of the auditory system. Preliminary evaluation of TravTek guidance displays indicates that drivers use voice guidance and perceive it as very helpful and that navigation with visual guidance displays is improved when combined with voice (*7,8*).

Chattering and Nagging

As anthropomorphism is inevitable in a talking car, the authors have chosen a conservative approach to the sort of "personality" that may be attributed to this ADIS. Anthropomorphism may be lessened by designing voice systems that are somewhat machine-like in their expression. ADIS with excessively long voice messages, or messages that exceed strict bounds of usefulness, may be accused of chattering or nagging. Drivers are no more likely to take kindly to chattering and nagging cars than they do to passengers who exhibit the same charactistics.

"Auditory clutter" is the term that Stokes et al. (*9*) use to describe the overuse of the auditory channel, resulting in potential distraction from the driving task and in annoyance. To minimize auditory clutter, the authors avoid voice feedback for correct maneuvers, driving speed, and system status—uses that Davis advocates (*10*). Initial road tests of the TravTek driver interface convinced the authors to reduce further the length and number of voice messages, which had been thought to be quite minimal to begin with.

VOICE INTELLIGIBILITY

Computer-generated speech for ADISs may be either synthesized or digitized. Digitized speech has the significant advantage of intelligibility and naturalness, along with the disadvantage of prohibitive limitations in recording and storing large amounts of text. In TravTek, synthesized voice has enabled the use of a large variety of messages in an implementation that achieves an acceptable level of intelligibility.

Female Versus Male Voice

Although the TravTek voice sounds indisputably male, this should not be interpreted as a deliberate design decision. The selection of a speech synthesis product was based on hardware requirements for durability in an automotive environment. The authors had little choice regarding voice characteristics and had to settle for the voice available in a product that satisfied our constraints. Although the synthesizer does allow for programmer control over speech attributes such as rate of speech, pitch, and voice gain, it does not provide a choice between a male and female voice. It does, however, offer the choice of a large person, a medium-sized person, and a small person. The male-sounding TravTek voice is the medium person (the other two voices were largely unintelligible).

A female digitized voice was preferred for use in military aircraft in the 1960s (*11*) because it contrasted with the predominantly male voices in flight crews and control tower radio communications of that era. This motivation for using female voice clearly does not apply to automobiles, where voices coming from passengers, radio, or car phones are equally likely to be male or female. Subsequent research suggests that the human female voice is less intelligible than the human male voice (*12*). Additional research is needed to assess the relative intelligibility of male and female synthesized speech, as well as machine speech that is not characteristic of either sex.

Intelligibility of Synthesized Speech

Synthesized speech is decidedly less intelligible than digitized human voice. The reduced intelligibility has been demonstrated to stem from the absence of many prosodic features that are found in natural human speech (*13*). The prosodic element of speech is that which gives natural speech its rhythm. A state-of-the-art voice synthesizer applies some reasoning to the insertion of pauses and variations in pitch and stress; however, the inability of the system to perform a syntactic parse of input sentences severely limits the prosodic results. Many commercially available voice synthesizers provide a way to insert prosodic markers in text, giving the programmer some control over the intonational pattern of a synthesized utterance.

Similarly, a speech synthesizer typically contains a large dictionary of stored pronunciations for known words, as well as a program that generates a pronunciation for an unknown word on the basis of its spelling. In English, spelling is not a good predictive measure of pronunciation, and no known algorithms will produce consistently accurate results in pronouncing unknown English words. For the TravTek voice messages, prosody has been specified carefully to enhance intelligibility. The authors have also listened to the voice synthesizer pronunciation of all words that may be spoken by the system, including more than 12,000 Orlando street names, storing corrected pronunciations as needed. This effort has resulted in large improvements in intelligibility, and this preprocessing is considered to be essential for public acceptance of synthesized voice.

Other strategies are also effective in increasing the intelligibility of synthesized speech. Simpson and Hart discuss the importance of providing sufficient linguistic context for synthesized warnings and commands to enhance comprehension (*14*). The authors have found that in TravTek route guidance and traffic messages, the street names are the least intelligible part of the utterance. To aid in the comprehension of street names, it is useful to speak the street name suffix (e.g., "Colonial Drive" as opposed to "Colonial").

Alerting prefaces are thought to be effective in attracting the listener's attention to an impending voice message. Various studies have indicated a reduced response time for prefaced messages, despite the increased length of the messages because of the preface (*15,16*).

The mechanical-sounding characteristics of synthesized voice may have some advantages over digitized human voice in automotive applications. Because the voice does not sound human, it is easily and immediately distinguishable from other voices in the automotive environment. In this way, the perceptual contrast makes the voice somewhat self-alerting; it is obviously the car speaking. The machine-like voice also may

reduce the tendency toward anthropomorphism, as mentioned before.

USEFULNESS OF INFORMATION

Useful information in an ADIS is that which enables the driver to optimize the performance of the driving and navigation tasks. Route guidance instructions are useful if they help the driver to follow a route safely and without error. Traffic information is useful if it enables a driver to avoid congestion, minimize travel time, and drive safely in unavoidable traffic congestion. There are many open questions as to the appropriate information content of guidance and traffic messages in an ADIS.

Route Guidance

People typically include the names of turn streets in route guidance instructions. Are street names a necessary or useful piece of information? The authors believe that they are, given the difficulty of timing turn messages accurately enough to prevent erroneous turns in areas with closely spaced cross streets. Street names also help drivers to orient themselves in unfamiliar territory.

At an intersection where two streets cross at right angles, the instruction describing the maneuver is easily formulated: "turn right" or "turn left." Complex intersections entail maneuvers that are more difficult to describe unambiguously. Although this is another justification for the use of street names, it is important to note that street signs are not always easily visible. For this reason, voice guidance, graphical representation of the maneuver intersection, and error recovery are all important elements of robust route guidance. Combined in a coherent system, they work effectively to keep the driver on the planned route.

It is useful for drivers to known how far they are from their next maneuver. Individual drivers, however, differ in their abilities to reason about distance. Some football fans may find meaning in distances measured in yards, but not in fractions of a mile. Davis (*10*) and Streeter et al. (*17*) have discussed the potential ambiguity of other measures of distance. For instance, "in two blocks" may be ambiguous when the next cross street does not intersect the driven street on both sides; does it delimit a block? Upon hearing an instruction like "Turn left at the third light," will the driver count the light at the intersection he or she is passing through when the message is spoken? The authors conclude that distance expressed unambiguously (e.g., in fractions of a mile) is more likely to help drivers who can gauge it than confuse drivers who cannot.

Navigation Assistance

The Where Am I? function was designed primarily to provide assistance when the driver is navigating along a self-planned route. It helps drivers to identify the intended turn street and to orient themselves when uncertain of the current location and heading. Where Am I? can be a useful supplement to route guidance as well, identifying turn streets when street signs are missing at intersections or visibility is obscured. It also indicates navigation system accuracy without reference to the map display.

An example of the Where Am I? message is "Approaching Lee Road. Headed north on Orlando Avenue." At first glance, it may seem counterintuitive to answer the question "where am I?" by first stating what you are near, then where you are. The authors chose to word the message in this way to impart the presumably more urgent piece of information first. Cross street information is considered to be more urgent, because it may identify the location of the intended maneuver and it changes more frequently than driven street data.

The Where Am I? function is self-interrupting. It aborts its current message and restarts itself when the button is pressed during Where Am I? output. Repeated, quick button presses will result in a series of cross street notifications, with the location information clipped. This functionality enables the driver to use Where Am I? to listen to cross streets in quick succession while proceeding down the road. The terseness of the Where Am I? message further serves this purpose.

Research Issues in Traffic Advisories

There is not yet a good understanding of which pieces of information about a traffic problem are necessary and useful to drivers. Specifically, it is not clear whether knowing about lane closures, or the cause of a congestion problem, may cause drivers to modify their behavior. Perhaps it is beneficial to suppress clarification of a spectacular incident such as a fire, because it could encourage gawkers to travel to the scene. On the other hand, it also alerts drivers to the possibility of emergency vehicles in the area.

There are a variety of ways to express the severity of a congestion problem. Terms such as "heavy traffic," "sluggish traffic," "1-minute delay," "bumper to bumper," "stop and go," "slow and go," and "merging delays" are used in traffic reports broadcast by radio stations. Radio traffic reports also occasionally provide an estimate of the length of a congestion queue. More research is needed, however, to determine how drivers use an estimate of a backup queue, whether it can be reliably estimated, and how best to describe it to drivers: in miles, or number of traffic signals, or from Street X to Street Y. The word "congestion" itself may be ambiguous: do drivers interpret it consistently as slow traffic, or can it also refer to a heavy volume of traffic moving at the posted speed?

The location of a traffic problem can also be expressed in various ways. Can the relevance of the problem be assessed more easily by the driver if its location is described relative to the vehicle, or in absolute terms?

Onboard computer-generated traffic advisories can provide information on demand that is filtered for relevance to a given vehicle location and planned route. Some issues that arise in relevance filtering include the criteria that are applied to determine relevance, the upper limit on the amount of information that should constitute an on-demand traffic report, and the possibility of enabling drivers to tailor traffic reports to their own needs and interests.

TravTek Approach to Traffic Reporting

TravTek traffic advisories report lane closures and the cause of an incident when known. Congestion is characterized as heavy or moderate, depending on the degree to which travel time on the affected road varies from free-flow travel time (*18*). The location description of a traffic problem varies according to whether the vehicle is on a planned route and whether the traffic problem is related to an incident or not. The location of an incident (e.g., accident, disabled vehicle, malfunctioning signal, construction) can be pinpointed, whereas congestion is so volatile that it cannot be delimited precisely and reliably. When the vehicle is on a planned route, only problems ahead of the vehicle on the route are reported. If an on-route problem is an incident, its location is described as "[distance] ahead on [street name]," where distance is expressed in miles. A nonincident congestion problem on the route is specified as "Ahead on [street name]," which avoids an estimation of the distance to the tail of the congestion queue. When the vehicle is off the planned route, or no route has been planned, traffic problems are located as "On [Street X] between [Street Y] and [Street Z]." The visual display indicates incidents and congestion with icons on the local area map, thus clarifying the location of problems reported by the voice traffic report.

The collection, dissemination, and in-vehicle use of traffic data is a process whose design is subject to many interdependencies. The TravTek solution to onboard presentation of traffic data was largely driven by outside constraints imposed by the organization of the TravTek TMC. The design of the TMC was itself constrained by local availability of information sources. In future ADISs, it would be preferable to base the information content of traffic advisories on solid research in the usefulness of the information, constrained by the general feasibility of data collection in most large urban areas.

DRIVER CONTROLS

It is essential that drivers be allowed to select functions for which they receive voice output, control the volume of the voice, and suppress all voice messages. In the TravTek system, when a voice message is about to be spoken, the radio is muted for the duration of the voice output. Activation of the radio volume control during voice output adjusts the volume of voice messages; to adjust radio volume, the driver uses the volume control during radio output. This capability enables differing volume levels for radio broadcasts and for TravTek voice functions.

In initial testing, the authors have found that voice messages for TravTek functions are generally welcome when the driver is not listening to the radio or conversing with a passenger. Because the voice synthesizer suppresses radio output and tends to interrupt conversations, drivers may occasionally want to turn off all or some voice functions. Separate controls for voice guidance, traffic reports, and navigation assistance allow the driver to reduce the amount of voice selectively, instead of having only a single voice on/off control.

While a driver's attention is occupied by the driving task and competing thought processes, the driver may not immediately attend to a voice message that is issued automatically. Because the auditory display is inherently ephemeral, the Repeat Voice function provides a necessary mechanism to recapture information that may not be initially apprehended.

NONVERBAL AUDITORY SIGNALS

Considerable research has been done in the use of nonverbal auditory warnings in aircraft cockpits [see work by Patterson (*19*) for a comprehensive discussion]. Some of the knowledge that has accrued from aircraft research may pertain to passenger vehicles (e.g., appropriate volumes and temporal characteristics for auditory tones). However, principles guiding the use of auditory systems in aircraft must not be applied indiscriminately to passenger vehicles. It is important to remember the essential differences between highly trained cockpit personnel and automobile drivers who range widely in age, driving abilities, physical condition, and so on.

When ADISs become so commonplace to be available to untrained drivers, the meaning of auditory signals must be easily learned and retained, with minimal potential for confusion. In the TravTek system, three nonverbal auditory signals are used. Two are tied directly to driver actions: a feedback signal for touchscreen key presses, and an error tone for inappropriate steering wheel button presses (for instance, pressing Voice Guide when no destination has been entered). The third signal must be taught. When the Voice Guide function is turned off, a glance-at-the-screen tone is sounded to inform the user that new information is presented: when the next maneuver is first depicted, or when the car has left its planned route. The glance-at-the-screen tone is soft and unobtrusive; it should not startle drivers or disrupt conversations

CONCLUSIONS

Computer-generated voice is a desirable component of ADISs; however, the North American automotive community has little experience in marrying voice to cars. The TravTek auditory interface strives to maximize the acceptability of the application of synthesized speech to an ADIS. The voice messages were designed as concise utterances that help the driver reach the destination quickly, easily, and safely. Data logged on onboard computers and extracted from driver questionnaires will provide feedback on user acceptance and actual usage of the various voice functions. Further research is needed to determine the optimal information content of route guidance and traffic messages.

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A Simulation Model for Driver's Use of In-Vehicle Information Systems

WILLIAM H. LEVISON

A simulation model for predicting driver behavior and system performance when the automobile driver performs concurrent steering and auxiliary in-vehicle tasks is described. The model was used in support of an experimental study to develop evaluation methods and human factors guidelines for in-vehicle information systems. It is an integration of two computerized models: the procedural model and the driver/vehicle model. The procedural component deals primarily with in-vehicle tasks and with the task-selection and attention-allocation procedures, whereas the driver/vehicle component predicts closed-loop continuous control (steering) behavior. Given descriptions of the driving environment and of driver information-processing limitations, the resulting integrated model allows one to predict a variety of performance measures for typical scenarios. Application of the model to experiment design is discussed, and quantitative examples are provided for model calibration and for predicting the effects of in-car telephone use on steering performance.

The U.S. government is promoting an umbrella program known as intelligent vehicle-highway systems (IVHS), the goal of which is to apply advanced electronics, computing, and communications technology to improve highway efficiency and safety. This technology will include advanced in-vehicle information systems to help drivers perform a number of functions, including in-car telephoning, navigation, traffic status monitoring, on-road hazards warning, and vehicle systems monitoring. The safety of such systems is in question because of the potential for in-vehicle displays to divert attention from the primary driving task (*1–3*).

This paper describes a simulation model that was developed to predict driver behavior in support of an experimental study, performed by the University of Michigan Transportation Research Institute (UMTRI) for the U.S. Department of Transportation, to develop evaluation methods and human factors guidelines for in-vehicle information systems (*4*). Given descriptions of the tasks to be performed and of a driver's information-processing limitations, the model predicts a variety of performance measures for typical scenarios. Representative measures include lane deviations, control use and monitoring times for a variety of in-vehicle systems, and various measures of driver attention such as eye fixations times and scan frequencies, task-to-task transitions, and statistics relating to task interruptions.

The primary intended uses of this model are to aid in the design of manned simulation experiments and to help extrapolate experimental results. Preexperiment model analysis is of particular value in situations in which, because of the expense or limited access to resources, it is critical to have the experimental program well defined before starting a set of simulation or on-road studies. By exploring a range of potential experimental variables—typically, much wider than would be practical to explore in properly controlled experiments—one can use the model as an all-digital simulator to predict which choices of parameter values will yield results that are sensitive to experimental variation and which candidate experiments will tend not to show significant effects. Armed with these results, one can presumably make better choices as to which candidate experimental variables to explore, the range of values to be explored, optimal settings for other independent variables, and so on.

Similar types of postexperiment model analysis allow the extrapolation of experimental results to conditions not yet tested. One potential application is to test the generality of design guidelines developed from the experimental data base.

DESCRIPTION OF MODEL

Overview

The model presented here, which is called the integrated driver model (IDM), is an integration of two computerized models: the procedural model and the driver/vehicle model. The procedural model represents the driver of the vehicle in terms of perceptual, neuromotor, and cognitive responses (*5*). Submodels may include visual scanning and detection, auditory perceptual processing, neuromotor reaction time, and choice and decision in the selection of activities. The procedural model deals primarily with in-vehicle auxiliary tasks (i.e., tasks other than continuous vehicle control) and with the task-selection and attention-allocation procedures.

The driver/vehicle model predicts closed-loop continuous control behavior. This model, which is currently used to predict lateral path (steering) control, is based on the optimal control model (OCM) for manually controlled systems (*6*). The structure and predictive value of the OCM have been verified via extensive application to laboratory and operational manual control tasks, and the OCM has been applied successfully to the design of manned simulation studies (*7*). The driver/vehicle model is currently implemented to simulate a constant-speed steering task.

The resulting integrated model allows one to predict continuous steering performance as visual attention is intermittently diverted from the roadway to one or more monitoring locations associated with the auxiliary in-vehicle tasks. The model also allows the driver to attend visually to the roadway

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while processing auditory information. Attention is switched and tasks are selected on the basis of time-varying priorities that consider, at each decision point, the penalties for tasks not performed. The presentation of auxiliary tasks is controlled in part through dependencies on the state of the driving environment as predicted by the model and in part through scripting (i.e., state-independent time-based occurrence of events defined before the model run).

Figure 1 contains a diagram of the IDM showing the principal functional elements of the model and the major communications paths. To make maximum use of previous implementations, the continuous control driver/vehicle model and the procedural model are implemented as separate processes.

Driver/Vehicle Model

The major assumptions underlying the driver/vehicle model are the following:

1. The operator is sufficiently well trained and motivated to perform in a near-optimal manner subject to system goals and limitations.
2. The driver constructs an internalized representation ("mental model") of the driving environment in which all dynamic response processes are represented by linear equations of motion.
3. Performance objectives can be represented by a quadratic performance index (e.g., minimize a weighted sum of mean-squared lane deviation and mean-squared control activity).
4. Driver limitations can be represented as response-bandwidth limitations, time delay, and wide-band "noise" processes to account for information-processing limitations.

To obtain a model solution, the user must provide information sufficient to describe the task environment, the performance goals, and the operator's response and information-processing limitations. Because the model is a simulation model, timing parameters must also be specified. The following kinds of input must be specified for the driver/vehicle models:

1. Description of driving environment
   - Vehicle response dynamics,
   - Perceptual variables,
   - Command and disturbance inputs, and
   - Initial conditions;
2. Driver characteristics
   - Mental model of the task environment,
   - Information-processing limitations (S/N),
   - Perceptual limitations ("thresholds"),
   - Time delay, and
   - Motor lag;
3. Simulation parameters
   - Simulation update interval, and
   - Data recording interval.

The flow of information within the driver/vehicle model component is shown in Figure 2. For applications in which the vehicle is maintained at near-constant speed and undergoes relatively low lateral accelerations, the model components enclosed in boxes are implemented as linear dynamic processes for which the behavior of the system states is described by a set of linear differential equations. The vehicle response behavior element contains a description of the dynamic response of the automobile, the kinematic equations that relate turn rate and speed to lateral displacement, and any dynamic response elements that might be needed to model external disturbances.

The cue generation element accepts the system states and external command inputs to generate the set of perceptual cues assumed to be used by the driver. This element contains a linearized approximation that relates the perspective real-world scene cues to system states and command inputs. (For a constant-speed steering task, typical perceptual cues are lane error, drift rate, heading relative to the road, turn rate relative to the road, and road curvature.) These perceptual cues are then corrupted by wide-bandwidth observation noise and delay, where the observation noise reflects both a signal-to-noise type of information-processing limitation as well as perceptual threshold limitations.

The driver's adaptive response behavior is represented by the optimal estimator and predictor, the optimal control laws, and the response lag, with an additional motor noise corrupting the motor response. The mental model noted earlier is a component of the optimal estimator. The estimator and predictor construct a least-squared-error estimate of the current system state, and the (linear) optimal controller generates the optimal control response operating on these state esti-

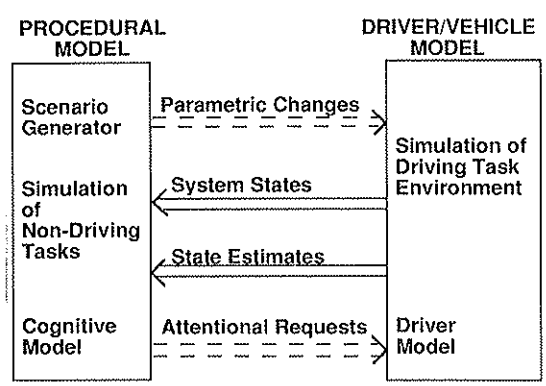

FIGURE 1 Overview of IDM.

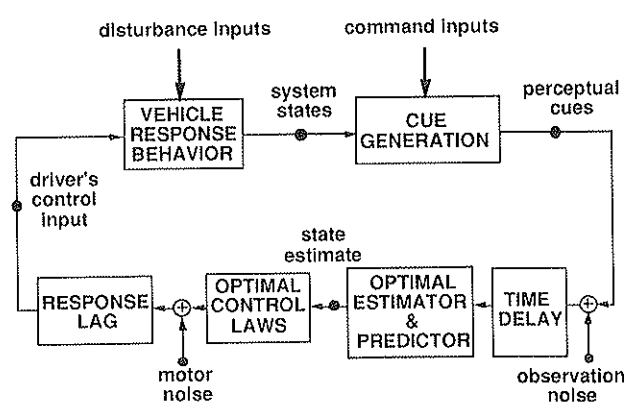

FIGURE 2 Flow diagram of driver/vehicle model.

mates. The motor noise serves to provide some uncertainty concerning the response of the vehicle to the driver's inputs, and the response lag may be thought of as reflecting a penalty for generating a high-bandwidth control response.

The form and quantification of the estimator, predictor, and controller are determined by the specific problem formulation according to well-developed mathematical rules for optimal control and estimation (*8,9*). Model outputs consist of quantities similar to those measurable in a manned simulation (e.g., time histories for all important system variables), as well as quantities that cannot be directly measured (e.g., the driver's estimate of the value of any system variable).

The driver's assumed mental model of the driving environment is a key feature of the driver/vehicle model. Typically, the driver is assumed to be sufficiently well trained in the specific driving task to allow the mental model to replicate the model of the physical environment. However, the consequences of the driver's misperception of the external world can be explored by making the mental model different from the world model in terms of parameters values or structure.

When the driver is required to share attention between the vehicle control task and one or more auxiliary tasks (e.g., look at the rearview mirror, tune the radio), performance of the control task will in general degrade. The effects of such interference are accounted for in one of two ways. For intervals in which visual attention is directed away from the roadway cues to some other visual input, the mathematical "driver" receives no perceptual inputs relevant to vehicle control, and the model continues for a short time to generate control inputs based on the internal model only.

The driver is assumed to attend simultaneously to vehicle control and to auxiliary tasks requiring speaking or listening. In this case the driver is assumed to continue to fixate visually on roadway cues, but central-processing resources are now shared between the two tasks. The effects of less than full cognitive attention to the driving task is modeled by degrading the driver's signal-to-noise ratio—in effect, by increasing the observation noise level (*10*). Either type of attention-sharing tends to decrease the portion of the driver's control response that contributes to effective control and to increase the stochastic component of the driver's control, with the net effect of degrading vehicle control performance.

Procedural Model

Besides acting as the supervisory element of the integrated model, the procedural model simulates the in-vehicle auxiliary tasks and performs task selection. First considered is the task selection algorithm, and then the overall logic of the procedural model is discussed.

Task Selection Algorithm

Task selection is based on assumptions that are generally consistent with the multiple-resource theories of Wickens and Liu (*11*). Specifically, it is assumed that

- If two or more tasks require different visual fixation points, only one such task may be performed at any given instant.
- If two or more tasks require listening or speaking, only one such task may be performed at a given instant.
- If one task requires visual inputs and another requires auditory inputs, the tasks may be performed concurrently (with presumably some performance degradation) if they require different "processing codes" (i.e., one requires spatial processing, the other verbal processing).
- Task selection is based on the perceived relative importance of competing tasks and is computed by minimizing the expected net penalty of tasks not performed.
- If an auditory and a visual task are performed concurrently, cognitive attention is allocated according to the penalty functions.
- When a task is first attended to, or first reattended to following attention to another task, attention must remain on this task for some minimum "commit time," after which the driver is free to allocate attention as described.

Note that the steering task (which requires attention to the road) is always competing for attention. The logic for selecting a task when multiple tasks compete for attention is diagrammed in Figure 3.

Model Inputs and Outputs

The following kinds of input must be specified for the procedural model:

- Description of activities (hard-coded)
  - –Models of performance versus time, and
  - –Penalty functions (penalty for not performing task);

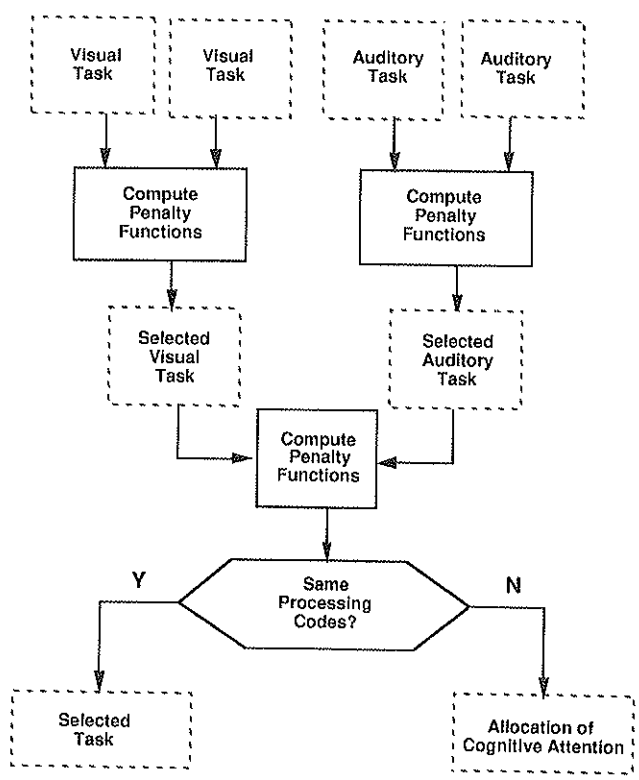

FIGURE 3 Task selection logic.

- Script of events: times at which activities are spawned; and
- Simulation parameters: simulation update interval.

The description of activities (auxiliary in-vehicle tasks) must be implemented in the computer code, unlike all other procedural and driver model inputs, which are specified at run time.

An auxiliary task may consist of one simple activity (e.g., glance at the rearview mirror) or a sequence of activities, such as the telephone task described later in this paper. An elemental activity may require visual attention (eyes) or visual and manual attention (eyes and hand).

Two categories of parameters need to be specified for each activity: parameters that relate to the performance of the task, and parameters that determine the relative importance or urgency of the task. Performance is usually defined by one or more time parameters, which may include (a) times to move eyes and hands, if necessary, in preparation for the task; (b) time to complete the task; and (c) minimum commit time following initial (re-) attention to the task. Some tasks are described by a simple task-completion time. Other tasks are defined by a rate of progress, with the driver allowed to interrupt after some commit time and later continue the task.

For tasks that consist of sequences of activities, sequencing rules need to be implemented, as do rules for which sequences of tasks must be performed as a unit before the driver is allowed to select another task. (For example, in an in-car telephoning task, the driver may be assumed to dial the entire area code before deciding whether to look back at the road or to continue dialing.)

Penalty functions for in-vehicle tasks may be specified as a single number or as a number that (typically) increases with time, up to some limit, until the task is completed. A different kind of penalty function is used for the driving (steering) task, namely, the predicted probability of exceeding a lane boundary within a "prediction time" that consists of the time required to perform the in-vehicle task segment plus an assumed time to recover control of vehicle path upon reattending to the road. This computation is based on the driver's current estimate of lane deviation, drift rate, and heading and is similar to the time-to-line-crossing metric proposed by Godthelp et al. (*12*).

The output file produced by the procedural model includes time histories of the driver's visual fixation point, the position of the driver's free (nonsteering) hand, and measures of performance for each in-vehicle task in progress (e.g., number of words read so far from the visual monitor, time elapsed since initiation of the task). As with a manned simulation experiment, posttrial analysis of model outputs can be performed to yield a variety of performance statistics, such as means and standard deviations for all continuous variables relevant to the steering task (including variables internal to the driver), statistics relating to the duration of a given in-vehicle tasks, and statistics on dwell times and intervals of inattention.

Simulation Cycle

After the model has been initialized, the simulation cycle is executed once per update interval until some stopping criterion has been reached (typically, a stopping time specified at the start of the run). The cycle begins with a check on which new tasks, if any, are to be added to the active list (the set of tasks now competing for the driver's attention). New tasks may be spawned according to the time-based script or because of completion of an antecedent subtask.

If the task currently attended to is locked up, the driver must continue to attend to that task. If the task is not locked up, the task selection algorithm is executed to determine the task to be next attended (which may be the same task). Active tasks are updated, and simulation variables needed for post-simulation analysis are recorded in the output file.

MODEL CALIBRATION

To the extent that the driving tasks of interest may differ in important respects from driving tasks modeled previously, a certain amount of initial empirical data is desired to calibrate the model for the baseline experimental condition. Calibration data may be needed for the driving task, the auxiliary in-vehicle tasks, or both, depending on the amount of preexisting data relevant for model calibration.

The continuous control component of the IDM has been validated against a considerable body of laboratory tracking data and has been found able to replicate these data with nearly invariant values for driver-related independent model parameters for idealized cueing conditions (*13*). These data provide an initial selection of independent model parameter values, which may be modified as necessary to account for the nonideal control environment associated with real-world driving tasks.

The procedural component of the IDM is new and is therefore in need of a more substantial calibration effort. To the extent that specific data are lacking for the in-vehicle tasks of interest, one may use data obtained from the human performance literature (e.g., times to make eye and hand movements, times to read words of text, times to read numbers, etc.) and later refine relevant model parameters as additional empirical data become available.

As an example of a typical calibration exercise, the calibration exercise performed for the Green and Olson in-vehicle display project just before preparation of this paper is summarized. Data from four subjects were provided for the baseline driving task performed on the UMTRI driving simulator. This simulator contained a steering wheel as an input device and a relatively sparse visual scene roughly approximating nighttime viewing conditions. The highly simplified vehicle response dynamics, although not a true representation of automobile steering response behavior, provided a workload representative of a driving task (*14*). The subject's task was to remain near the middle of the lane while driving at constant speed on a road having a sinusoidal curvature with a period of about 26.5 sec and a zero-peak lateral deviation of about 4 ft. The data base used for model calibration consisted of one 4-min trial from each of four subjects.

To calibrate the model, first the task-related model parameters were set to reflect the simulator dynamics and roadway curvature. Then driver-related model parameters were selected as follows:

- Response delay was set to 0.2 sec, on the basis of laboratory tracking data.
- An information-processing metric (implemented as a noise-to-signal ratio) was quantified, on the basis of laboratory tracking data.
- Perceptual noise terms were specified to reflect a visual or indifference threshold of 0.305 m (1 ft) and 0.305 m/sec (1 ft/sec) for path error and path error rate. These numbers were set substantially higher than associated with idealized laboratory tracking displays to reflect the relative difficulty of obtaining precise information from the simulated perspective roadway display.
- A trade-off between allowable path error and allowable steering wheel activity was modeled by adjusting an effective driver response bandwidth parameter.

Within-trial mean and standard deviation scores for path error and wheel displacement were computed for each of the four experimental trials, and intertrial means and standard deviations of the standard deviation scores were computed. Model runs were then generated for various values of the bandwidth parameter until an acceptable joint match to the average path error and wheel deflection scores was obtained. The following table shows that model predictions matched the experimental standard deviation scores to within two standard deviations (and to within 10 percent):

Variable	*Experiment*	*Model*
Path error (m)	0.210 (0.22)	0.195
Path error (ft)	0.689 (0.072)	0.640
Wheel deflection (degrees)	17.7 (1.15)	19.1

Figure 4 shows 2-min segments of the wheel deflection time histories generated by one of the subjects and by the model using the parameters calibrated as described. Because the human controller is represented as a mathematically linear system plus noise, and because the road curvature was sinusoidal, the wheel response is expected to consist of a sinusoidal component of the same frequency as the road sinusoid, plus a stochastic disturbance about this sinusoid. Figure 4 shows that this qualitative description appears to fit both the model and the experimental data, which offers additional validating evidence of the model as a predictor of performance trends. The discrepancies between the high-frequency components of the model and experimental time histories reflect the fact that, by definition, the model cannot replicate (other than statistically) the stochastic component of the driver's time history.

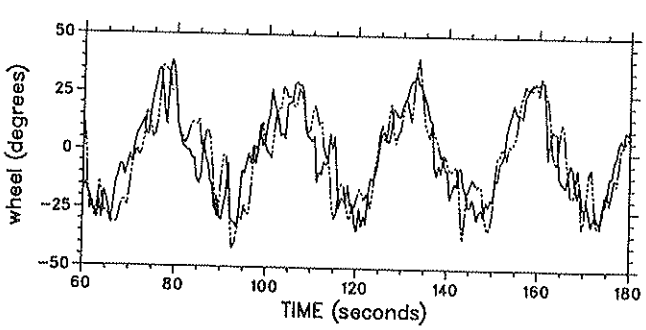

FIGURE 4 Experimental and predicted wheel time histories: solid curve = subject; dashed curve = model.

APPLICATION OF MODEL TO EXPERIMENT DESIGN

Three kinds of independent model parameters are most likely to be varied when the IDM is used to help design experiments involving in-vehicle displays: (a) the in-vehicle tasks, (b) factors influencing the difficulty of the primary driving task, and (c) driver performance capabilities. The in-vehicle tasks are presumed to be the primary variables of interest and would be programmed into the IDM for testing. Driving-task parameters such as roadway curvature profile, speed profile, wind gusts, and vehicle dynamics may or may not be of interest as experimental variables. If not, and if the experimenter is free to select one or more of these variables, the IDM can be useful in selecting parameter values that provide a driving workload (or range of workloads) that results in a reasonable sensitivity of driving performance to the in-vehicle tasks.

Finally, the model can be used to predict the extent of driver population effects on performance trends by suitably varying driver-related parameters of the driver/vehicle model. For example, one might represent the older driver as having one or more of the following: larger response delay, less aggressive response behavior, less efficient information-processing capability, and larger commit time after switching attention.

To illustrate how the model might be applied in this manner, a modeling activity is reviewed that was performed for the in-vehicle display project in progress at the time this paper was written. The model results presented in the following were obtained without the benefit of knowledge of results to generate some a priori performance predictions for subsequent comparison with data.

The model was run for the baseline driving-only condition described earlier, and for one of the experimental tasks involving in-car telephone usage. The telephone task modeled here involved the following steps:

1. Flip to the next page of an index-card telephone directory on the seat next to the driver.
2. Read the name of the person to be called. (For this condition, the subject knew the telephone number from memory and needed to be prompted only as to the person to be called.)
3. Pick up the handset.
4. Dial 1 + area code.
5. Dial the exchange.
6. Dial the last four digits.
7. Press the Call button.
8. Conduct a 30-sec conversation.
9. Press the End button.
10. Set the telephone down.

Model analysis was based on the assumed performance times given in the following table for the component activities underlying the 10 steps listed:

Activity	*Performance Time (sec)*
Eye movement	0.2
Hand movement between buttons on handset	0.2
Hand movement between devices	0.4
Flip page	1.0
Read name	0.8
Pick up, set down handset	0.4
Push button	0.2

A hand (thumb) movement of at least 200 msec was assumed prior to entering each digit of the telephone number. Minimum dialing times were thus 1.2 sec for the three-digit exchange and 1.6 sec for four-digit combinations.

Except for the 30-sec conversation, the mathematical "driver" was required to time-share visual attention between the simulated roadway scene and the telephone. (The driver was assumed to obtain no useful roadway information while looking at the telephone.)

The driver was assumed to perform each of the visual and manual tasks in the preceding list without interruption. When a task was completed and a subsequent visual or manual task became current, the model determined whether the driver should continue with the next telephone task segment or glance at the road for at least a predetermined minimum interval (400 msec). Similarly, if the driver was looking at the road while an in-vehicle visual task was pending, the model determined whether it was appropriate for the driver to resume the telephone task sequence. The decision algorithm was as follows:

1. Predict the probability of exceeding a lane boundary over a prediction time that consists of the time required to perform the next telephone task segment plus an assumed time to recover control of vehicle path upon reattending to the road.
2. If the probability exceeds 1 percent, attend to (or continue to attend to) the roadway cues; otherwise, attend to the telephone task.

The driver was assumed to obtain roadway cues while conversing, but with some performance decrement. While the conversation was in progress, the model allocated cognitive attention between the driving and conversational tasks according to instantaneous driving performance. [See elsewhere for a discussion of how the effects of cognitive attention-sharing on continuous control performance are modeled (*10*).] Attention allocation was quantized to the nearest 0.25, with the restriction that the driver always allocated at least 25 percent attention to the driving task.

The model predicted an increase in root-mean-square lane error of about 60 percent: 0.19 m (0.62 ft) for the baseline task, 0.32 m (1.05 ft) for the experimental driving plus telephone condition. Figure 5 shows the path error time histories for the baseline (solid curve) and telephone task (dashed curve). Because the same random number sequence was used to produce the stochastic portion of the driver's response, the differences between the two curves reflect the effects of the concurrent telephone task and are not confounded with run-to-run variability.

As expected, larger error peaks are shown for the experimental task. Comparison of this figure with the cognitive attention timeline of Figure 6 shows that performance decrements were predicted for the portions of the task when conversation was in progress, as well as when visual attention was shared between driving and telephone start-up tasks. For this curve, a value of 1 indicates full attention to the road, a value of 0 indicates full visual attention to the telephone task, and values between 0 and 1 indicate a reduced level of cognitive attention to the roadway cues while conversing. According to this timeline, the "driver" made three minimal 0.4-sec glances and one 0.8-sec glance to the road while performing the preconversation telephone tasks.

This discussion is intended to illustrate the kinds of performance predictions available from the model.To make a more definitive prediction of performance trends, a number of model runs per condition would be made with different random sequences in order to account for run-to-run variability of the type expected in an experiment. Then a statistical analysis would be performed on the model predictions—just as would be done with experimental data—to predict whether performance differences across experimental conditions are likely to be significant.

DISCUSSION OF RESULTS

Because its predecessor (the optimal control model) has been in existence for about two decades, the driver/vehicle component of the IDM is supported by a substantial amount of validation data. Although the calibration data presented in this paper are not sufficiently rich to allow identification of all the independent driver-related parameters, these parameters have been shown to be individually identifiable from laboratory tracking data using specialized identification techniques (*13*). There is thus a firm foundation for quantifying some of these parameters on the basis of past data. Furthermore, the ability to match performance in a variety of control situations with a near-invariant set of parameter values tends to validate the basic model structure.

In contrast to the driver/vehicle model, the recently developed procedural model component is not similarly sup-

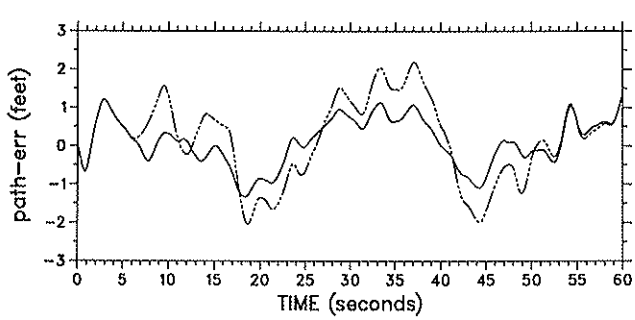

FIGURE 5 Predicted path error trajectories for baseline and experimental conditions: solid curve = steering only; dashed curve = steering while telephoning (1 ft = 0.305 m).

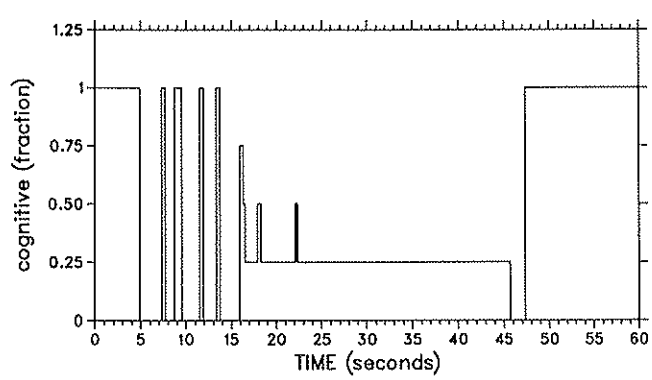

FIGURE 6 Predicted attention to driving task while performing concurrent telephone task.

ported by data. This is particularly true of the task selection procedure and associated penalty functions, for which the goal was to develop algorithms that are plausible and consistent with what is known about task-sharing behavior and with approaches used by others in modeling multiple-task performance (*11,15,16*). Validation of this aspect of the model awaits the availability of experimental data against which to test model behavior.

The model need not mimic all relevant aspects of human response behavior to meet the intended uses that have been suggested here, which are to help design experiments and to extrapolate experimental results. Instead, it is enough that the model be able to reliably predict performance trends resulting from changes in the task environment and to do so with a minimum of preexperiment calibration and with a well-defined set of procedures for quantifying independent model parameters. This is still a tall order, and validation data will be needed to test the model's capabilities in this respect.

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Eye Scanning Rules for Drivers: How Do They Compare with Actual Observed Eye Scanning Behavior?

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The U.S. driver education and training literature was reviewed to identify rules and recommendations with regard to driver eye scanning behavior and strategies, where drivers ought to fixate their eyes when driving, specifically when driving through a curve. In addition, driver eye scanning behavior was recorded and analyzed for nine drivers driving through right curves with radii of 73.15 m (240 ft) (unlighted Interstate entrance and exit ramps, 270-degree turns) at night with low beams. An instrumented car with a corneal reflection technique television eye scanning system was used. Each driver made a number of runs through the curves at an average speed of 41.8 km/hr (26 mph), and the driver eye fixation sequences were analyzed for three to eight runs per driver, yielding 51 analyzed runs. Of most importance for the eye fixation sequence analysis were the eye fixation positions on the curves ahead of the car. Besides the eye fixation sequences analyzed in this study, previously analyzed spatial and temporal eye scanning data from the same subjects were used to compare the eye scanning rules with the actual observed eye scanning behavior. Matrices and histograms were established to indicate the conditional frequencies for forward- and backward-progressing eye fixation sequences, given a previous type of eye fixation sequence. The results showed that the expected number of consecutive forward eye fixations (including forward-ending eye fixations) is 1.89, while that of backward eye fixations (including backward-ending eye fixations) is 1.26. The results of the exploratory study indicate that drivers use both forward and backward eye fixation sequences and that there appears to exist no predictable, simple, systematic eye fixation sequence patterns within a driver (within a run or between runs) or between drivers when driving through a curve. Since no such sequence was discovered, it may be tentatively concluded that various eye fixation sequences and strategies provide adequate visual input for proper curve driving. Therefore, there is probably no need for very specific recommendations for objects- or sequence-oriented eye fixation for curve driving, or even for driving on a straight section of a highway.

The U.S. driver education and training literature contains a number of recommendations with regard to driver eye scanning behavior and strategies and specifically with regard to where drivers should fixate their eyes when driving. One of the earliest sets of perceptive driver training rules was provided by Smith et al., who recommended to "aim high at steering, have a wide picture, keep your eyes moving, keep yourself an out and make sure they see you" (*1*). The American Automobile Association proposed and discussed the "brief glance" technique for drivers to avoid a dangerous condition known as "captured attention" (*2*). Aaron et al. proposed and explained driver seeing habits (*3*) that were the same as the rules published previously by Smith et al (*1*). They recommended that drivers should develop a habit of scanning the entire traffic scene (about 300 degrees) and that their eyes should move from left to right in a continuous effort to assess the potential hazards.

Bishop et al. explained the techniques of "systematic seeing" and indicated that systematic seeing involves three important steps: "center on the travel path, scan and search the traffic scene, and check mirrors and instruments" (which, according to the authors, can be thought of as an extension of scanning and searching) (*4*). They explained that for centering on the travel path, one's reference point on a straight road should be in the middle of the path, and on curved roads and turns, it should be through the curve or turn to the point at which the vehicle will be when the turn is complete; the same rules should be followed when driving at night (*4*). Some of the other recommendations given by Bishop et al. are to "scan and search the scene by looking far ahead and near and on both sides of your vehicle, look away from your visual reference point." They also proposed several ways to make the best use of vision for centering and scanning: "Use central vision only on pertinent events, look at each event in the traffic scene briefly, limit the number of times you look at each event in a traffic situation, avoid looking at former events and keep all previous information in mind." Night vision and the factors affecting it were further discussed, and it was recommended that drivers should scan the darkened areas when driving at night. To lessen the likelihood of being blinded temporarily by the glare of oncoming headlights, they recommended that one "look at the edge of the pavement ahead of your car until the oncoming vehicle has passed."

In another publication Davis et al. discussed two basic seeing rules that should be made a habit: "Center on a target 12 seconds ahead, and keep your eyes scanning and searching" (*5*). The authors explained that "the eyes should move from the target 12 seconds ahead to the left and to the right, they should then move to the rear view mirrors, then to the instrumented panel, and finally they should move back to the target ahead" and recommended to reduce the speed and stay in the lane. Johnson et al. specifically discussed driving on two-lane highways and curves (*6*). The authors proposed taking these steps when approaching a curve: "Take quick glances across the curve to identify oncoming traffic, maintain proper lane position by glancing ahead at your intended path of travel, evaluate the sharpness of the curve, slow down to a suitable

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speed before entering the curve, accelerate gently after entering the curve, and once around the curve, resume a safe speed." They also explained an "orderly visual search pattern," which is a process of searching critical areas in a regular sequence. Moreover, they recommended that drivers should develop the technique of "selective seeing," a process of selecting and identifying only those events and clues that pertain to a driving task.

On looking at the rules and recommendations found in the U.S. driver education and training literature, it appears that most of these recommendations do not make any distinction between driving through a curve or a straight section of a highway, between daytime and nighttime driving, and between driving on the road alone or with other traffic present. Most of these recommendations, however, make general statements about where to look in the driving scene and, very important, suggest moving the eyes frequently to scan and search the traffic scene. Some of these recommendations stress the importance of short eye fixations, brief or quick glances, and limitations of the number of fixations at a specific feature in the driving scene.

Only a few previous studies reported in the literature have investigated driver eye scanning behavior on straight and curve sections of a highway. One such study by Shinar et al. concluded that "drivers rely on different visual cues, for directional and lateral control, on curves than they do on straight roads" (7). The authors stated that drivers, instead of paying close attention to the focus of expansion as is done on a straight road, should concentrate intermittently on the position of the roadway ahead and the road edge (or lane markings) closer to the car when on a curved road. Moreover, they concluded that "drivers start scanning curves for directional cues as they approach them and resort to direct foveal fixations of the roadway close to the car for lateral placement cues." Most of the driver eye scanning behavior studies usually provide average and standard deviations for the spatial and temporal eye scanning measures, but very few provide detailed density plots of spatial eye fixation or frequency distributions of eye fixation duration.

No studies have been found that would provide any information about the eye fixation sequences that drivers make when driving either on a straight road or through a curve. In addition, there may be problems with regard to the accuracy of the spatial and temporal eye scanning summary measures provided in some of the previous curve eye scanning studies. This is not surprising if one considers the difficulties involved in the spatial and temporal analysis of the eye fixations when driving through a curve. Since there is no fixed visual reference point in curve driving (such as the focus of expansion in straight driving), one must work with an imaginary focus of expansion as the environmental reference point. The imaginary focus of expansion in curve driving for a given eye position in the curve is defined as a point on the horizon line where a pair of imaginary straight, extended, left, and right edge lines of the driving lane meet, assuming that a driver's sagittal plane coincides with the center of the visual field and is tangential to the curve radius.

It is extremely difficult to determine accurately the correct horizontal location of the imaginary focus of expansion along the horizon on the television screen on the basis of a limited field of view of the curve perspective (given by the left and right edge lines of a driver's driving lane). Depending on the accuracy with which one determines the imaginary focus of expansion for each eye position in relationship to the perspective view of the left and right edge lines of the driving lane, the calculated mean of the horizontal eye fixation distribution can be more or less wrong. Furthermore, depending on the assumed accuracy of the perspective view of the curve as it is seen by the drivers, the results and statements with regard to the horizontal overall average of the eye fixations may not be accurate. Figure 1 shows the correct perspective views for curves with two different radii of curvature. It should be noted that because a driver's eyes are located at a certain distance above the pavement of the flat road, the edge lines of the driving lane in the curve do not touch the horizon line as indicated incorrectly in figures published by some authors.

If one would know, with a reasonable degree of accuracy, the spatial and temporal eye scanning behavior characteristics and the eye fixation sequences of fairly experienced drivers (assuming that experienced drivers have developed adequate, sufficient, and possibly near-optimal eye scanning sequence patterns), one should be able to evaluate the validity of the driver eye scanning behavior rules and recommendations found in the U.S. driver education and training literature and, if warranted, propose new rules. It was the purpose of this study to determine in an objective and quantitative manner the type of eye fixation sequence (EFS) patterns that drivers exhibit in terms of fixating successively farther away, or closer toward

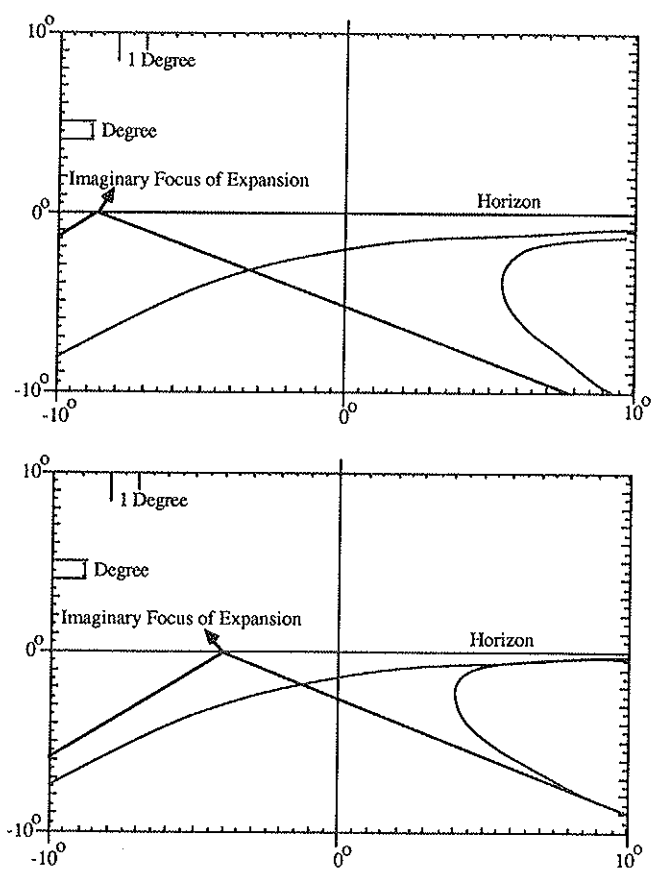

FIGURE 1 Perspective views of typical right curves: *top*, radius = 200 ft; *bottom*, radius = 1,000 ft.

the car when driving through a curve, and compare them with the rules and recommendations given in the driver education and training literature.

DATA ANALYSIS

The curve eye scanning behavior data used in this analysis were collected as part of a study conducted by Zwahlen (*8*). Driver eye scanning and performance data were collected at night for Interstate highway entrance and exit ramps (270-degree right curves, both dry and wet pavement) with radii of 73.2 m (240 ft) and widths of 4.9 m (16 ft). An instrumented car (VW 412, automatic transmission, four doors, 4000 low beams) with an in-car television eye scanning recording system, a lane trucker, and other electronic sensors and equipment (corneal reflection technique television eye scanning system) was used. Nine young subjects with an average age of 22.3 years (standard deviation = 2.3) with an average driving experience of 6 years (6,000 mi/year) were paid to participate in the experiment. All the drivers were fairly familiar with the experimental car and the television system used for the eye scanning behavior measurements since they usually drove from Athens, Ohio, to the experimental site on Route I-70; usually before running the actual experiment, all the drivers were made to drive in and around Athens by wearing the helmet with the television system components.

Each driver serving as his or her own control made a number of runs through the curves at an average speed of 41.8 km/hr (26 mph). The prevailing traffic conditions on I-70 and the entrance and exit ramps caused some of the runs to be performed at very low speeds (because of slow-moving vehicles ahead). For this reason, eye fixation sequences for an unequal number of runs per subject (three to eight) were analyzed, yielding 51 analyzed runs. Lateral positions were also measured for all the experimental runs, but since the scope of this paper is limited primarily to the analysis of the driver eye scanning behavior, no lateral position data are presented.

The exact sequence and spatial coordinates of all eye fixations on the road ahead, or the adjacent flat road environment up to a radius of 88.4 m (290 ft), were determined. Only 0.7 percent of the eye fixations during curve driving were on a vehicle ahead. All forward and backward eye fixation sequences were determined for each run and also recorded as a function of each previous eye fixation sequence. Conditional matrices and histograms indicating the frequency of forward or backward EFSs (including forward and backward ending EFSs) consisting of a number of eye fixations were prepared to quantify the eye fixation sequences. The sequences were examined for each run, then for all the runs for a given driver, and finally for all runs for the entire group of drivers. These data were previously analyzed in terms of eye fixation distributions (spatial analysis) and in terms of eye fixation durations (temporal analysis) for night driving on both tangential and right curve (entrance/exit ramps) Interstate sections (*9*). The two-dimensional eye fixation distributions indicated a single mode located at $x = 0.5$ degrees and $y = -0.5$ degrees for tangent sections (focus of expansion at 0, 0; $N = 11{,}780$) and at $x = 14.5$ degrees and $y = -1.7$ degrees for the right curve (imaginary focus of expansion 0,0; $N = 8{,}884$). The average fixation durations were 0.43 sec (2.3 fixations per sec) for the tangent section and 0.29 sec (3.4 fixations per sec) for the right curve (standard deviations = 0.35 and 0.16 sec, respectively). These results indicate that more eye fixations are needed in curve driving, which is a visually more demanding task than straight road driving. Figure 2 shows the cumulative relative frequencies as a function of the fixation durations (in seconds), and it can be seen that the fixation durations for curves are considerably shorter than those for straight sections.

DEFINITIONS OF EYE FIXATION POINT, EYE FIXATION SEQUENCE, AND EYE FIXATION

An eye fixation point is defined as the point on a feature of an object or of the curve environment (except the sky) on which a driver has fixated his or her eyes for a short duration of time (about 0.1 to 0.5 sec) in such a way that visual information can be obtained with the greatest resolving power for visual detail (fovea). The coordinates of the eye fixation points for the features of the objects or of the curve environment can be determined mathematically, provided one knows the coordinates of the surfaces (usually assumed to be a horizontal and level plane), the horizontal and vertical angles of the eye fixation direction, and the coordinates of a driver's eye position. Figures 3, 4, and 5 illustrate the graphical definitions

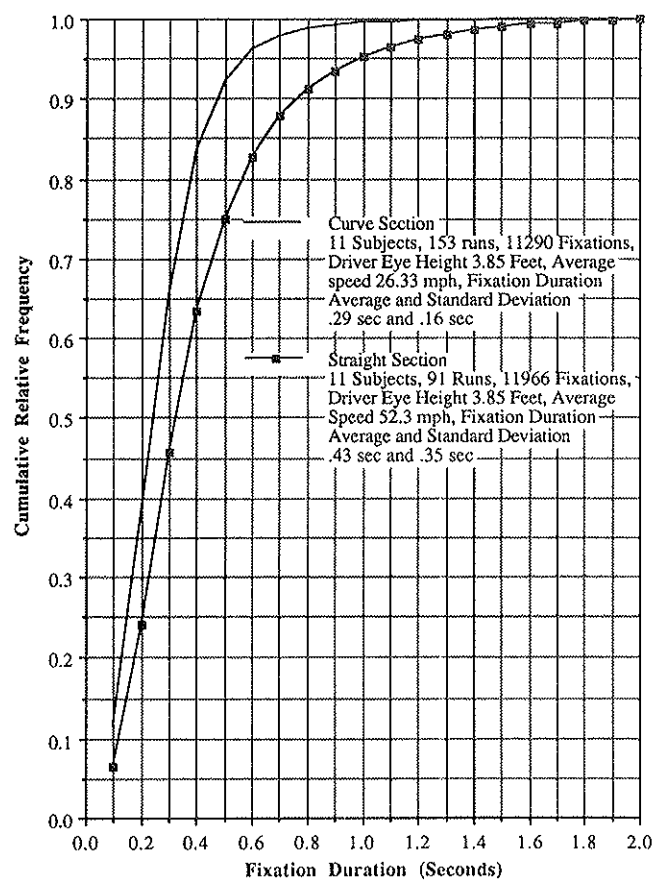

FIGURE 2 Cumulative relative frequencies as function of fixation durations.

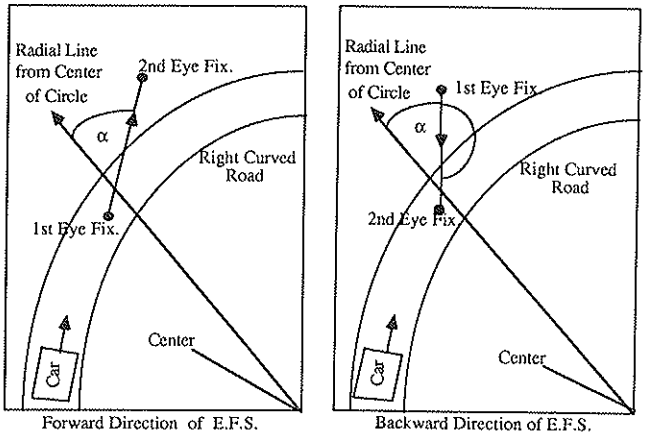

FIGURE 3 Graphical definition for direction of single EFS: *left*, 0 degrees ≤ α < 180 degrees; *right*, 180 degrees ≤ α < 360 degrees.

for the direction of single EFS, for forward and backward EFSs and for forward ending and backward ending EFSs, respectively. A forward or a backward ending EFS was obtained whenever there was no eye fixation point visible on the TV screen (eye blink or out of view) after the last eye fixation point, or when the next eye fixation point was either above the horizon or outside the 88.4-m (290-ft) curve radius region. Figure 6 illustrates and defines some typical eye fixation sequences observed when a driver drives through a curve.

In this study, the definition of an eye fixation when a driver's eye spot moved within the same object was made dependent on two factors: (a) the length of time of the shorter of two adjacent "would-be" fixations (separated by a saccade) and (b) the magnitude of the direct distance (saccade) between the two would-be fixations in the visual plane. Keeping in mind a reasonable trade-off between accuracy and analysis time, it was decided that in general, the longer the duration of the shorter of the two would-be fixations, the smaller the magnitude had to be of the direct distance between them in the visual plane in order to define both as separate eye fixations. On the other hand, the shorter the duration of the shorter of the two fixations, the longer the magnitude of the direct distance between them in the visual plane in order to define them as separate. If these criteria were not met in a specific case, the shorter of the two fixations was incorporated into the larger fixation, making up one eye fixation. If a driver's eye spot moved enough (a few degrees) to indicate that the foveal attention shifted to a different object, it was defined automatically as a new fixation regardless of the duration and magnitude of the saccade distance. However, if one would define an eye fixation such that many fixations are incorporated into one large fixation, the fixation durations increase significantly, thereby resulting in an error in the summary measures of the temporal distributions.

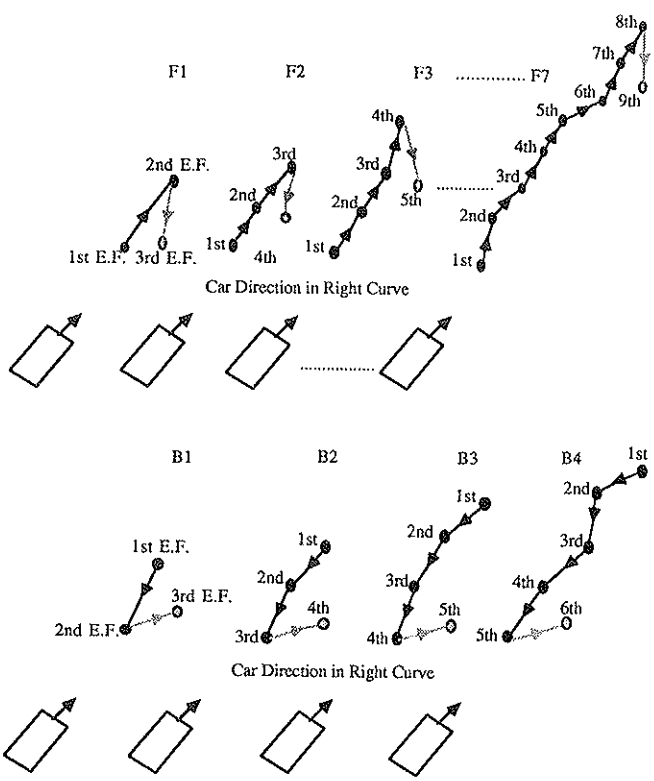

FIGURE 4 Graphical definitions for forward sequences (*top*) and backward sequences (*bottom*.)

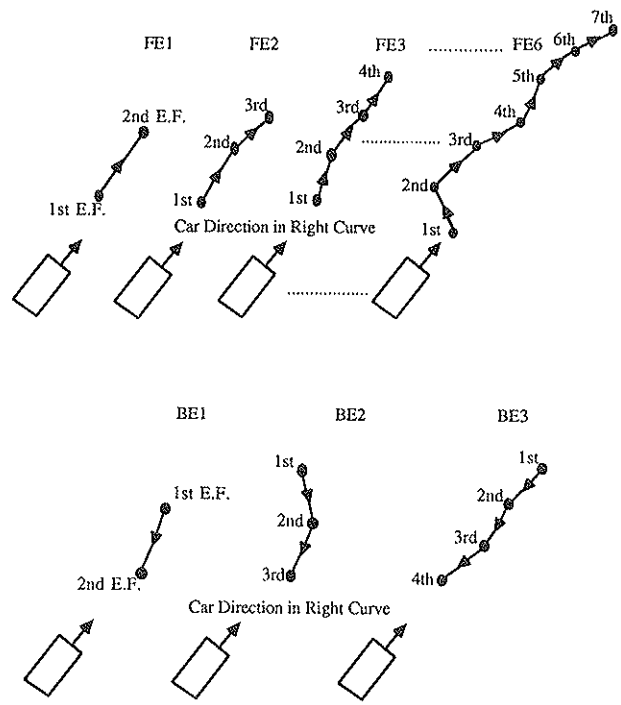

FIGURE 5 Graphical definitions for forward ending sequences (*top*) and backward ending sequences (*bottom*.)

Two computer programs were written in FORTRAN. The first one plots a top view for each 90-degree section (total three sections, 270 degrees) of the right-hand curve, a point at which each eye fixation intersects with the horizontal plane, a point for each head position of the driver, and a line between each set of two corresponding points indicating a driver's eye fixation direction from the head to the fixation point (intersection with horizontal plane). These fixation direction lines were plotted only if the eye fixation intersection points with the horizontal plane were within a selected maximum radius

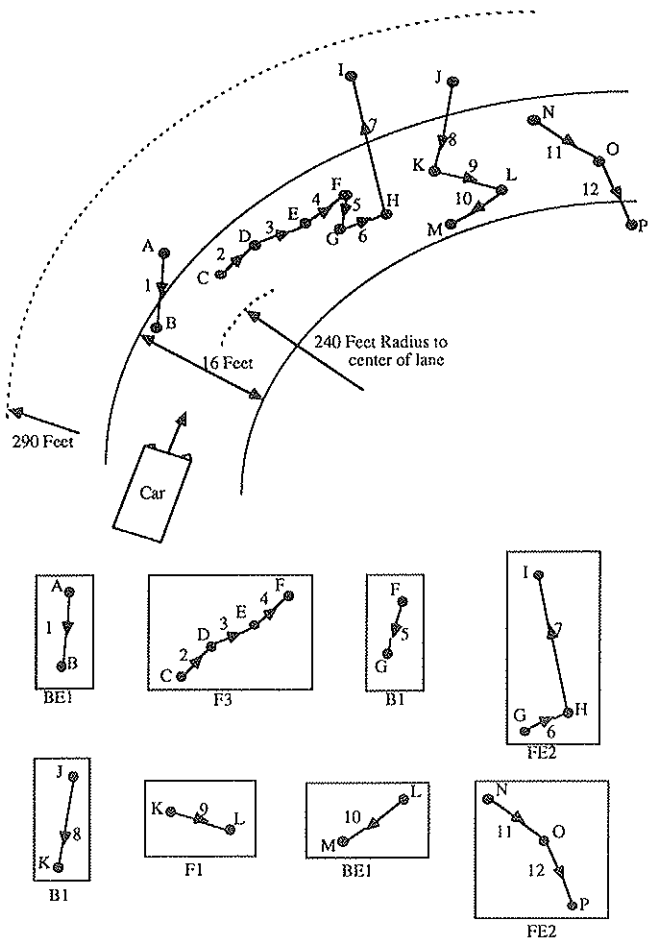

FIGURE 6 Example of eye fixation sequence analysis.

of 88.4 m (290 ft). The second program plots the top view for each 90-degree section, each eye fixation point below the horizon and within the 88.4-m (290-ft) radius only, and draws straight lines connecting the consecutive eye fixation points. These two top-view plots for eye fixation direction and consecutive eye fixation obtained for each run along with the definitions provided in this paper represented the basis upon which the conditional eye fixation sequences were determined.

RESULTS

The results indicate that there appears to be no discernible simple, systematic eye fixation sequence pattern within and between the runs of a single driver, as well as between the runs of different drivers. Therefore, the data obtained from all the runs for all the subjects were combined for further analysis. The results indicate that the drivers made a maximum of seven consecutive forward eye fixations and a maximum of four consecutive backward eye fixations. Table 1 presents the summary matrix of forward, backward, forward ending, and backward ending eye fixation sequences for all 51 runs as a function of the eye fixation sequence that the subjects exhibited before. It can be seen from Table 1 that 643 eye fixation sequences—which resulted in 1,013 (forward or forward ending = 613, backward and backward ending = 400) eye fixation directions (based on 2,175 eye fixation points)—were analyzed.

On the basis of the EFS results for fixations ahead of the car below the horizon and within a curve radius of 88.4 m (290 ft), the expected number of consecutive forward fixations (including forward ending fixations) is 1.89, and the expected number of consecutive backward fixations (including backward ending fixations) is 1.26. The ratio between forward and forward ending sequences is 3:1 and that of backward and backward ending sequences is 6:1, indicating that the forward sequences occur about three times as often as the forward ending sequences and that the backward sequences occur six times as often as the backward ending sequences. Figures 7 and 8 further illustrate the conditional probabilities as given in Table 1. It can be seen in Figure 7 that the relative frequencies of a forward or forward ending EFS appear to be independent of the previous number of eye fixation points of the backward or backward ending EFS. There is about 50 percent probability that an F1 sequence will follow a previous backward or backward ending EFS. Similarly, there are about 25, 15, 5, 2, and 2 percent probabilities that an F2, F3, F4, F5, and F6 sequence, respectively, will follow a previous back-

TABLE 1 Summary Matrix of Eye Fixation Sequences

		Forward Seq.							Backward Seq.				Forw. End. Seq.						Backw. End. Seq.			
	Previous \ Present	F1	F2	F3	F4	F5	F6	F7	B1	B2	B3	B4	FE1	FE2	FE3	FE4	FE5	FE6	BE1	BE2	BE3	Total
Forward Seq.	F1								107	28	3								18	5	1	162
	F2								53	14	3								10	1		81
	F3								30	4	3	1							5	1	1	45
	F4								13	2									2			17
	F5								4										1			5
	F6								5		1											6
	F7								2													2
Backw Seq.	B1	103	46	30	11	5	5						32	13	10		1	1				257
	B2	18	9	6	1			2					8	6		2						52
	B3	2	4	2	1								3	2								14
	B4	1												1								2
Total		124	59	38	13	5	5	2	214	48	10	1	43	22	10	2	1	1	36	7	2	643

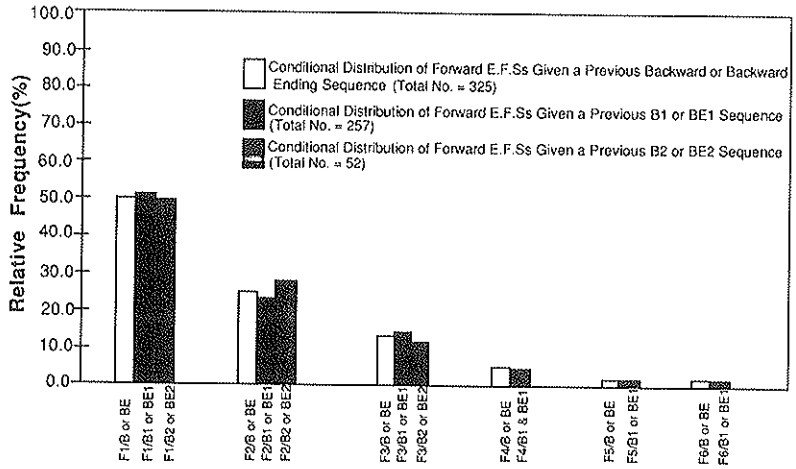

FIGURE 7 Relative frequencies of forward EFSs given a previous backward EFS or backward ending EFS (shown only if their sum is greater than 5).

ward or backward ending EFS. Similarly, in Figure 8 it can be seen that the relative frequencies of backward or backward ending EFSs also appear to be independent of the previous number of eye fixation points of the forward or forward ending EFS. There is about 80 percent probability that a B1 sequence and about 18 percent probability that a B2 sequence will follow a previous forward or forward ending EFS.

DISCUSSION OF RESULTS AND CONCLUSIONS

The results of this study indicate that drivers use both forward and backward eye fixation sequences. There appears to be no predictable, simple, systematic EFS patterns within a driver or between drivers, such as a repeating sequence of one or two fixations far ahead (possibly for perception of curvature, directional control, and obstacle detection) followed by one or two fixations closer toward the car (possibly for lateral control) when driving through a curve. Therefore, fairly experienced drivers appear to have much freedom in choosing what they want to look at in the driving scene and what combinations of EFSs they want to use to get the necessary visual driving information, without impairing their successful driving performance through a curve, or even on a straight section of a highway. Because no such pattern was discovered and because each of these fairly experienced drivers exhibited different combinations of EFSs on each run, it may be tentatively concluded that many different EFSs and strategies must provide adequate visual input for proper curve driving and that there is probably no need for very specific objects or sequence-oriented eye fixation recommendations for driving on a curve or a straight section of a highway.

Moreover, looking at the results of the spatial and temporal eye fixation analysis (*9*), it would appear that drivers make

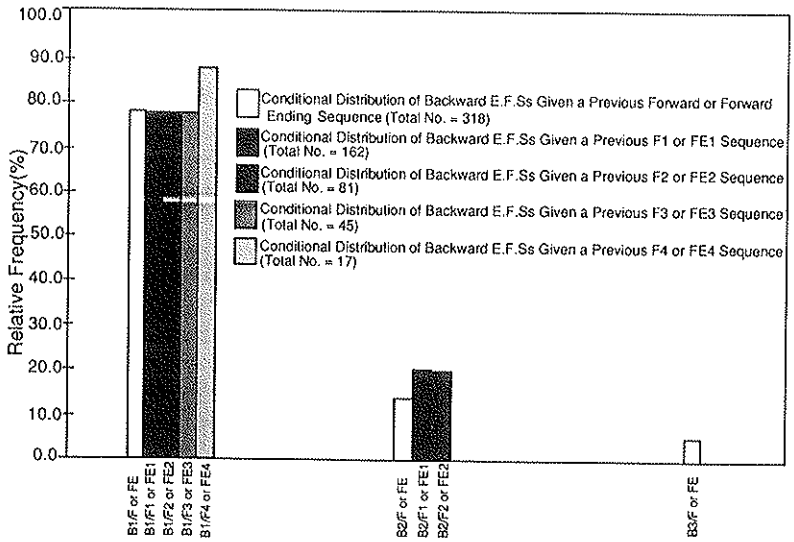

FIGURE 8 Relative frequencies of backward EFSs given a previous forward EFS or forward ending EFS (shown only if their sum is greater than 5).

considerably more eye fixations on curves than they do on straight roads. One may conclude that curve driving appears to be much more demanding in terms of acquiring and processing visual information than does driving on a straight section of highway; very little spare visual capacity is left for the driver. Traffic engineers might also note this fact and limit the placement of traffic signs in curves as much as possible, especially traffic signs placed along the inside of the curve.

The observed forward and backward eye fixation sequences, the cumulative eye fixation duration frequencies, and the spatial eye scanning data published by Zwahlen (*9*) appear to support, to some degree, some of the recommendations and rules given in the U.S. driver education and training literature. However, some of these rules cannot be supported by the results and might be inherently dangerous if one follows them consistently and accurately, especially when driving through a curve at night.

For example, "aim high at steering" (*1*) is a general recommendation since it does not make any distinction between driving on a straight road and on a curve, or during the day and during the night. Looking at the EFS results and the spatial eye fixation distributions for straight road and curve driving at night published by Zwahlen (*9*) and assuming that the eye scanning behavior of the test drivers who participated in the study is fairly well learned and close to an optimal information acquisition process, one can state that drivers cannot always "aim high at steering" since they make backward EFSs toward the front of the car, especially during curve driving at night. The spatial eye fixation distribution results also indicate that drivers do fixate once in a while relatively close in front of the car during straight road and curve driving at night. Overall, a recommendation of "aim high at steering" that is qualified by adding "wherever and whenever possible and feasible" appears to have some validity and merit when looking at the eye scanning behavior results and would give a driver a longer preview time, which is desirable from the point of view of control systems and tracking. According to the spatial eye fixation results and the EFS analysis, in curve driving at night, the test drivers appeared to not maximize their preview time or forward fixation distance across the curve (beyond the major illumination of the lowbeams) and instead followed a strategy of placing most of their eye fixations anywhere from fairly far ahead in the curve (but still mostly within the low-beam illumination pattern) to closer in front of the car on the curve surface or on the immediate curve environment ahead.

The recommendation to "have a wide picture" (*1*), although somewhat nonspecific, is fairly well supported by the spatial eye fixation data shown elsewhere (*9*), especially for curve driving at night, which shows a larger horizontal dispersion of eye fixations (horizontal eye fixation average = 12.79 degrees to the right of the imaginary focus of expansion with a standard deviation of 3.79 degrees) than does straight road driving at night (horizontal eye fixation average = 0.84 degrees to the right of the focus of expansion with a standard deviation of 1.92 degrees) if one assumes that the horizontal width of the "wide picture" is about 10 degrees. It is assumed and fairly well established that drivers acquire detailed visual information only when fixating their eyes on an object or a road feature and not when moving their eyes from one fixation point to another. Therefore, to "have a wide picture" a driver would probably have eye fixations over a certain area of the visual field in order to get visual details about the most important objects or road features in the driving scene. It should be noted that the most important road features and objects are below the horizon within a rectangle of about 30 degrees horizontal ahead and from the horizon to 6 degrees below for both straight roads and curves, which is not a large area considering the extent of a driver's whole visual field ahead.

"Keep your eyes moving," according to the authors, involves glancing near and far, to the right and left, in the mirrors and at the instrument panel, and looking ahead after each glance. This recommendation appears to be partially validated by the EFS analysis, the cumulative eye fixation duration frequencies, and the spatial results shown elsewhere (*9*). If one wants to move his or her eyes frequently, the eye fixation durations must be rather short, which is supported by the temporal eye scanning behavior results (saccade durations of usually much less than 0.1 sec) especially for curve driving situations, where the average fixation duration is only 0.29 sec. Furthermore, the spatial results indicate that drivers do move their eyes over a certain region of the driving scene for straight road driving (most of the time within ±3 degrees horizontal and ±3 degrees vertical around the focus of expansion) and a moderately larger area (most of time within a rectangle from 6 to 18 degrees horizontal and −4 to 0 degrees vertical from the imaginary focus of expansion, centered on the outer curve lane-marking stripe) for driving through a right curve with a 73.2-m (240-ft) radius at night. Overall, the results indicate that drivers do look ahead after making fixations close to the front of the car but not in a systematic and consistent pattern, as is suggested by Smith et al. (*1*). "Keep yourself an out" and "make sure you are seen" are general recommendations (*1*) and are suited more for strategic driving rules, which do not recommend specific eye fixation patterns or sequences to be followed by drivers.

The brief-glance technique is the one that has been claimed to avoid the dangerous condition known as captured attention (*2*). Again, this technique does not distinguish between the various driving situations (curves, straight roads, day, night, traffic, etc.). However, the recommendation is similar to "keep your eyes moving" (*1*) and thus appears to be partially validated as a rule by the EFS analysis results, the cumulative eye fixation distribution frequencies, and the spatial results shown elsewhere (*9*). The rule does stress fixation durations, which should be brief instead of long, and the cumulative fixation duration frequencies for curve driving indicate that there are practically no glances with durations of more than 1.1 sec.

Aaron et al.'s statement that drivers should develop a habit of scanning the entire traffic scene and that their eyes should move in a continuous effort to assess the potential hazards is again similar to "keep your eyes moving" (*3*), but according to the spatial eye fixation results given by Zwahlen (*9*) the horizontal extent of the recommended scanning activity (about 300 degrees) appears much too large for both straight road and curve driving at night. And no reference is made with regard to any vertical scanning activity (ahead of the car). Again, a driver acquires detailed visual information during a continuous string of discrete eye fixations rather than during a continuous movement of the eyes. The eyes move very quickly between two successive fixation points with no sig-

nificant detailed visual information intake during these times.

It should also be remembered that a driver obtains detailed visual information around the center of the fixation point (circular area, visual cone). The size of this visual circular area is dependent on the fineness of the visual detail that needs to be obtained and the amount of detailed information in that circle. For very fine visual information and a large density of such information around the fixation point, the diameter of such a visual cone can be from less than 1 degree to a few degrees. Information about larger objects (if they are sufficiently conspicuous) will be picked up by the visual system outside this visual cone and, if it is of interest to a driver, the information will most likely trigger a movement of the eyes to this object (saccade) with a subsequent eye fixation or several subsequent eye fixations to acquire, process, and verify the visual information at a detailed level within a driver's expectation and memory framework.

The recommendation to "center on the travel path" (*4*) is fairly well supported by the spatial results published by Zwahlen (*9*) that indicate a single mode (largest number of fixations in a 1- × 1-degree cell) located at $x = 0.5$ degrees horizontal and $y = -0.5$ degrees vertical for tangent sections (from focus of expansion, mostly on the road surface ahead) and at $x = 14.5$ degrees horizontal and $y = -1.7$ degrees vertical for a right curve with a 73.2-m (240-ft) radius (from imaginary focus of expansion, mostly on the illuminated curve surface ahead). However, these modes contain only about 13.5 and 3.9 percent of the total number of fixations for straight road and curve driving, respectively, which indicates that even though the drivers have a relatively large number of fixations at one point, a larger percentage of the fixations are spread around the mode cell and many of them on the travel path. "Scan and search the traffic scene" (*4*) is again similar to "keep your eyes moving" and thus is partially validated by the results of the EFS analysis and the results of Zwahlen (*9*). "Check mirrors and instruments" (*4*) is a useful recommendation especially before slowing down, stopping, or changing direction. However, from the results of Zwahlen (*9*), mirrors and instruments were looked at very infrequently during straight road driving and practically never while driving through a curve at night since very few slowing, stopping, or direction-changing maneuvers were executed.

"Look at each event in the traffic scene briefly" (*4*) is also similar to "keep your eyes moving" and can be partially validated by the results of this study, the cumulative fixation duration frequencies, and the results published elsewhere (*9*). "Scan darkened areas when driving at night" (*4*) is very vague in terms of specific scan locations. This recommendation cannot be supported by the spatial results of Zwahlen (*9*), which indicate that drivers have a large portion of their eye fixations within or close to the illuminated pavement surface of the curve at night or on the road pavement surface ahead. "Look at the edge of the pavement ahead of your car until the oncoming vehicle has passed" is also a general recommendation that helps drivers lessen the likelihood of being temporarily blinded by the glare of an oncoming car's headlights. Whereas this rule appears reasonable and most likely useful, there was no opposing traffic present in the immediate next lane on the straight road sections (four-lane highway) or in the curve (one-directional exit ramp) to investigate its validity.

"Center on a target 12 seconds ahead" (*5*) is one of the few recommendations in which the authors make a clear distinction between driving on a straight section and on a curve, although nothing was mentioned about night driving. The results of the EFS analysis and the spatial results given by Zwahlen (*9*) indicate clearly that a driver cannot consistently center on a target 12 sec ahead. Again, the same comments as discussed before with regard to the recommendation "aim high at steering" would apply here. "Keep your eyes scanning and searching" (*5*) is similar to "keep your eyes moving," and the same comments apply. "Take quick glances across the curve to identify oncoming traffic" is somewhat supported by the spatial eye fixation results (*9*), especially for curve driving at night, which indicate that drivers once in a while make eye fixations across the curve. Again, it should be noted that the curve in the experiment was one-directional and precluded opposing traffic, which could represent a potential hazard.

"Orderly visual search pattern" (*5*) is a process in which drivers are recommended to search critical areas in a regular sequence. An example of this process is "glance ahead, check rear view mirror, glance ahead again, search the sides of the roadway intersections, glance ahead again, check speedometer and gauges, and glance ahead again." The results of the EFS analysis do not indicate any systematic eye fixation patterns when driving through a curve that would indicate that drivers acquire visual information through such an orderly sequential search pattern.

Selective seeing is the process of selecting and identifying only those events and clues that pertain to a driving task. Although one would hope that drivers follow a selective seeing procedure, there was no objective way to investigate whether the drivers who participated in the study used such a selective seeing procedure. Moreover, it should be reiterated that the results of the EFS analysis do not show any consistent pattern of eye fixation sequences from run to run within a driver or between drivers, which could suggest a consistent selective seeing process. One might question whether the spatial and temporal eye scanning behavior results between daytime and nighttime (under low-beam illumination) are much different from each other. A comparison with daytime eye scanning results for straight road driving given by Zwahlen indicates small differences between the eye scanning behavior of drivers during daytime and nighttime straight road driving, with the only exception that the daytime horizontal eye fixation dispersions are somewhat larger than the nighttime horizontal eye fixation dispersions (daytime horizontal standard deviation = 2.45 degrees, nighttime standard deviation = 1.92 degrees (*10*). Furthermore, Zwahlen provides temporal eye scanning behavior results (averages and standard deviations of fixation durations when looking at curve warning signs, and Stop Ahead and Stop signs) for day and night driving that indicate that there is no consistent trend in terms of average fixation durations between daytime and nighttime driving (*11,12*).

Overall, a few general recommendations or rules with regard to eye scanning behavior when driving through curves or when driving in general—such as "aim high at steering wherever and whenever possible or feasible"—might be helpful to a novice driver. However, it would be highly desirable that the need for such rules as well as the conditions for which

they apply would be carefully researched and justified and that such rules would be carefully developed and validated on the basis of driver eye scanning behavior studies conducted in representative driving environments under representative conditions with a sufficiently large group of representative drivers.

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Subsidiary Task Measures of Driver Mental Workload: A Long-Term Field Study

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Two auditory subsidiary task measures of driver mental workload, delayed digit recall and random digit generation, were evaluated in a 4-year field trial. Vanpool members performed the tasks for 2-min periods while traversing a mix of rural secondary roads, limited access expressways, high-density limited-access urban drives, and downtown city streets on a daily commute from upstate New York to New York City. The delayed digit recall task presented a sequence of random digits to the driver at 2-sec intervals for a 2-min period. The driver was required to recall the digit before the last one presented during the interdigit interval. Errors were scored for digits missed or omitted. The random digit generation task required the driver to verbalize a random sequence of digits from 1 to 9 for a 2-min period. The randomness of the generated sequence was determined by computer analysis. Data collected included the roadway being traversed, time of day, traffic conditions including density and estimated speed, weather, brake applications, and drivers' subjective difficulty ratings. Subsidiary task degradation was a conjoint function of traffic density, average speed, and uncertainty (estimated by the number of brake depressions). Weather conditions moderated these variables. Subjective difficulty ratings correlated with objective criteria of traffic density and speed. Unpredictability of traffic appeared to be the major determinant of perceived difficulty. The digit recall task correlated (r = .834) with a calculated driver workload index based on brake actuations divided by the square root of speed.

A major problem in the study of complex perceptual motor tasks such as driving an automobile is the direct determination of the mental workload imposed on the operator. The concept of mental workload is based on the dual assumptions that

- The act of responding to stimuli takes a finite amount of effort, and
- The total amount of effort that an individual can expend is limited.

For most vehicle control tasks, significant increases in task difficulty may produce few measurable changes in error rate as the operator attempts to hold performance constant by allocating more resources to the task. When all available resources are committed, any further increase in difficulty results in a sharply increased error rate.

The workload that can be handled before performance begins to deteriorate defines maximum capacity for a particular individual. At lower levels of workload, that portion of the individual's resources not committed to the task represents spare capacity. Because of the slow increase in error rate below the break point, the fraction of total capacity allocated to the task is difficult to determine from an examination of error rate alone. By requiring the operator to perform a subsidiary task that uses the unallocated resources, estimates of both spare capacity and primary task workload can be derived. Thus, spare capacity measures, although indirect, offer a means of evaluating operator workload in the less extreme range of operating conditions, before overt errors occur.

Subsidiary tasks have been used by researchers in the estimation of spare capacity and primary task workload for four decades (*1–5*). So many subsidiary tasks have been used, in such specific contexts, that the body of research offers insufficient guidance to the worker who desires general-purpose subsidiary tasks for comparing various implementations of man-machine systems across a variety of conditions (*6–8*).

To be effective, a subsidiary task should meet the following basic requirements:

- Interact minimally with the primary task within the range of conditions covered in the experiment,
- Have more performance degradation as a function of decreased capacity than the primary task, and
- Show performance changes as a monotonic or predictable function of spare capacity.

The ideal subsidiary task would have a number of practical attributes as well. It would

- Use alternative input-output modalities to the primary task (this is implied in the first basic requirement)—since most man-machine control tasks are visual-motor, good subsidiary tasks tend to use auditory inputs and verbal outputs;
- Require minimum learning on the part of the subjects;
- Be resistant to change as a function of repetition;
- Permit transient as well as continuous changes in spare capacity to be measured;
- Require minimum equipment; and
- Be easy to score.

In the course of a U.S. Department of Transportation study on automobile stability and handling, a variety of subsidiary tasks using an oral response mode were screened. They included digit span, mental arithmetic, self-paced generation of random digits, and delayed recall of random digits. Delayed digit recall and random digit generation met most of these

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criteria and were used in the ensuing investigation (*5*). After the conclusion of the study, other responsibilities intervened and the author discontinued active research on subsidiary task techniques of measuring mental workload.

Commuting to New York City from the surrounding suburbs is uncertain at best. In 1987, in anticipation of a transit strike, several large corporations subsidized employee car- and vanpools. One of the author's graduate students, in his capacity as director of transportation services for a large insurance company, made it possible for the author to conduct a continuing field evaluation of the two subsidiary tasks used in the previous experiment.

METHOD

Overview

Drivers in two commuter vanpools performed two subsidiary tasks (delayed digit recall and random digit generation) while traversing a mix of rural secondary roads, limited-access expressways, high-density urban drives, and downtown city streets on a daily commute from upstate New York to New York City. Data were gathered from 1987 through 1991. Four different vehicles were used during the study, a 1986 Dodge Caravan, a 1987 Plymouth Voyager, a 1988 Dodge Caravan SE, and a 1991 Chevrolet Astrovan LT.

Subjects

The vanpools consisted of six adult men at a time. Driving responsibility rotated on a daily basis. All members lived in the towns of Cortlandt and Yorktown in northern Westchester County and worked in mid-Manhattan. Over the 4-year duration of the study, the membership in each pool changed as the original members moved, changed jobs, changed working hours, or went on vacations or sabbaticals. By the end of 1991, 20 drivers had completed nine full trip trials of each task over the four roadway types, a total of 2,880 two-minute task samples.

Subsidiary Task

Delayed Digit Recall

A sequence of random digits from 1 to 9 was presented to the driver at 2-sec intervals for a 2-min period. The driver was required to say the digit before the last one presented during the interdigit interval. Errors were scored for digits missed or omitted. Each trial consisted of a set of 60 random digits. Before inclusion in the experiment subjects were trained on the task in a no load situation until a criterion of 98 percent accuracy (one or fewer missed digits) was achieved. Training took no more than two or three trials.

Random Digit Generation

During selected 2-min trials, the driver was requested to call out digits from 1 to 9 in random order at a self-paced rate. In past experiments, subjects generally selected a rate averaging two to three digits per second. In these experiments the rate of digit generation did not appear to vary despite major changes in loading on a primary task. Subsidiary task performance was evaluated by determining the randomness of the digit sequence. Evaluation criteria suggested by Wagenaar (*9*) were incorporated into a computer program. Digit frequency, shifts in the autocorrelation function, and comparison of the subject's digit digram frequencies with those of a mathematically random sequence were used in the analysis. The index of randomness used in this study was the χ^2–estimate of the probability that the observed distribution of digrams matched those of an expected Poisson distribution of a true random sequence of the same length.

Roadway Characteristics

Both commutes started at 7:00 a.m. in northern Westchester County, one in Yorktown Heights, the other in Peekskill. Members were picked up by 7:30, and the designated driver took his position. Each van traveled rural secondary roads (NY-129, Croton Avenue, Furnace Dock Road, and NY-9A) before entering the limited-access road system. Posted speeds on the rural roads ranged from 48 to 72 km/hr (30 to 45 mph). Traffic density was moderate, two to four cars visible. During the warm months, foliage screened driveways. Depending on starting location, the average one-way distance on secondary roads was 24 to 28 km (15 to 18 mi). After leaving the secondary roads, the vans entered the New York Thruway, a high-speed limited-access expressway. The posted speed limit was 89 km/hr (55 mph), but traffic exceeded the limit by 8 to 16 km/hr (5 to 10 mph). During the commuting hours, traffic density was moderate, four to eight cars visible but all moving in the same direction. Thruway distance was approximately 26 km (16 mi). At the city limits, the Thruway changed into a high-density limited-access urban drive, the Major Deegan Expressway. The vans crossed the East River to FDR Drive. Posted speeds on both roads are 80 km/hr (50 mph), but actual speed ranged from 100 km/hr (62 mph) to a bumper-to-bumper crawl depending on traffic conditions. Observed traffic density was extremely high during commuting hours, 20 or more cars visible. The limited-access urban drive distance was 23 km (14 mi). Downtown city streets comprised the final lap. Bidirectional traffic, cross traffic, pedestrian traffic, buses, taxicabs, and traffic lights required constant alertness and mandated low speeds and repeated brake applications. Depending on destination, city street distance was 5 to 8 km (3 to 5 mi). The roadway sequence was repeated in reverse order every evening.

Data Collection Method

The driver was requested to perform the assigned subsidiary task for a 2-min period during each of the four roadway conditions on the inbound commute. The process was repeated on the outbound commute. The same subsidiary task was used for all trials of a given commute. The tasks were alternated at each complete rotation of drivers, about every 2 weeks. Task stimuli were presented and responses recorded with paired

cassette tape recorders. An event counter was wired into the brakelight circuit of each van, incrementing the count each time the brake was depressed.

At the conclusion of each trial, the driver was asked to rate the difficulty of the drive on a 10-point scale. In addition to initiating the task, the observer noted the roadway being traveled, time of day, traffic conditions including vehicle density and estimated speed, weather conditions, drivers' difficulty rating, and the starting and ending count on the event counter. Observer notations were made during and at the conclusion of each 2-min trial. No specific instructions were given to the observer to average density and speed observations for the trial period, but observers appeared to do so as a matter of course. As a backup, the observer snapped a picture of the roadway through the front window with a point-and-shoot camera equipped with a date and time recording back. This proved unnecessary and expensive and was dropped after several weeks. Initially, the observer was either the author or a graduate student. Several months into the experiment, vanpool members participated as observers using prepared data forms. Interobserver reliability was assessed by comparing the speed and traffic density estimates on known stretches of roadway. The estimates of all observers were similar. The author monitored data gathering periodically during the duration of the experiment.

Design Limitations

Roadway type is the only variable that can be considered independent in the classical experimental sense. Sequence of presentation, time of day, and traffic conditions (including speed and density) were largely determined by the invariant nature of the commute. A rough form of ABBA counterbalancing was provided by the reverse presentation of conditions on the homeward leg. Weather conditions, a factor that could be expected to influence driver workload, varied by season, but the long duration of the experiment had the effect of randomizing it over subjects. For safety reasons, data were not collected during extremely bad weather.

RESULTS

Observer data on roadway traffic density, average speed, and brake actuations for all drivers are given in Table 1. Even though the roadways clearly vary in all dimensions contributing to driver workload, no apparent differences in driver performance were noted during the course of the experiment. Data were collected on 180 days over 4 years. During that time the vans traveled more than 36,000 mi. Five serious driving errors were recorded: three resulting in moving violation summonses (two for failure to observe stop signs, one for speeding), and two in minor paint-scraping incidents in dense traffic. It is certainly true that an external observer might have noted occasional deviations from prudent driving practice; no consequences resulted from these errors. Such constancy implies that the driver was allocating resources or modifying driving behavior to stabilize performance.

Traffic density, as estimated by the number of vehicles visible through the front window, was dependent both on the nature of the roadway and the time of day. The commute, starting at the beginning of rush hour, encountered progressively greater traffic as the roadways converged on New York City. Peak density was observed on the urban limited-access drives. The number of vehicles observed varied greatly from moment to moment as traffic was slowed by bottlenecks and construction sites. City street density was largely regulated by traffic lights and pedestrian movement and varied substantially less than did the density on urban drives.

Speed limits were posted on all roadways, but actual driving speed appeared to be determined by the conjoint interaction of roadway characteristics, traffic density, weather, and the driver's comfort level. At the gross observational level, speed adjustment appeared to be the primary way of maintaining a comfortable workload. Drivers exceeded the posted limit on rural roads and expressways and dropped below the posted limits on urban drives and city streets.

The number of brake actuations was also determined by roadway characteristics, traffic density, and weather. In contrast to speed, the driver has little choice about braking. A high rate of brake actuation reflects a similarly high degree of uncertainty and unpredictability in the driving situation. Expressway driving, with good visibility, gentle curves, and constant speed allowed minimal use of the brake. City driving, by contrast, required brake actuation on an average of every 7 sec.

The subjective assessment of task difficulty confirms the direct observations. Table 2 presents a summary of driving difficulty ratings and subsidiary task measures for the different roadways. The driving difficulty rating is the mean value of all ratings for a given condition, taken just after the completion of the subsidiary task. The ratings are based on a scale of 1 to 10, where 1 is referenced to an extremely easy driving experience and 10 is referenced to an almost impossible, anxiety-provoking experience. The ratings are completely subjective, but the low standard deviations attest to considerable agreement. Rural driving and expressway driving were viewed as relatively unstressful, urban driving was near the midpoint of the range, and city driving was considered both stressful and unpleasant.

TABLE 1 Observed Roadway Characteristics

Roadway Type	Vehicle Density	Density Std. dev.	Av. Speed (kph)	Speed Std. dev.	Brake Actuations	Brake Std. dev.
Rural road	2.7	.92	53.3	3.96	5.5	1.46
Expressway	6.7	2.01	100.9	8.59	1.6	1.07
Urban drive	17.2	7.71	66.9	5.61	6.6	2.67
City street	10.1	2.45	19.0	1.76	17.1	4.52

TABLE 2 Driver Response Data

Roadway Type	Difficulty Rating	Rating Std. dev.	Digit recall Task errors	Recall Std. dev.	Random[1] Task Index	Workload[2] Index
Rural road	2.74	.73	2.60	.81	.165	.751
Expressway	2.76	.72	1.54	.64	.165	.154
Urban drive	4.22	1.32	5.29	.89	.082	.806
City street	6.15	1.84	9.48	1.54	.082	3.898

[1]Index = probability of "true" random sequence. Low load and high load conditions grouped.
[2]Workload index = (brake actuation rate) / $(\text{speed})^{0.5}$

The ratings are confounded with time of day. Rural and expressway driving took place both in the morning when the driver was fresh and near the end of the commute when an evening's relaxation could be anticipated. By contrast, urban and city street driving difficulty assessments might have been influenced by driving frustration and work fatigue. The present data analysis procedure does not provide a means of isolating morning and evening commutes to provide an estimate of fatigue effects. However, if the concept of mental workload is treated as an integrative construct, incorporating all psychological, emotional, and physical moderators of behavior, then such unconfounding is unnecessary. An analysis of variance (ANOVA) showed that the differences in difficulty ratings of the four roadway types were significant at $p < .001$ level.

Table 2 also gives a summary of errors made in each condition on the delayed digit recall subsidiary task. Delayed digit recall was sensitive to transient aberrations in the traffic flow, the driver forgetting or omitting responses during periods of heaviest load. Digit recall was quite accurate during rural and expressway driving; urban and city driving showed a higher error rate. The errors in these latter regimes appeared to be due to subjects' omitting or dropping digits during unanticipated avoidance maneuvers or brake applications. Indeed, the number of times the van was cut off by a vehicle abruptly changing lanes on city streets could be estimated by looking at the sequence of errors on this task. An ANOVA showing that the digit recall error differences for each roadway type were significant at the level $p < .001$.

Errors made on the delayed digit recall task correlate highly ($r = .784$) with subjective assessments of driving difficulty. Figure 1 plots the average difficulty rating across all conditions against the average delayed recall error rate for the 20 subjects.

The random digit generation task failed to discriminate between the four roadway conditions, although it was quite effective at separating the two conditions with low average difficulty (rural and expressway driving) from the two conditions with high average difficulty (urban and city driving). Direct observation of the driver's performance provided the reason for this insensitivity. During all of the driving regimes, the driving task appeared to be composed of two components: (a) a steady-state driving workload dictated by roadway conditions, speed, and traffic density and (b) a transient workload determined by the degree of uncertainty and unpredictability in the driving situation. The steady-state driving task may have been moderately difficult as a whole, but there were occasional moments of high difficulty. The integrative nature of the random digit generation subsidiary task tended to bury these moments of high difficulty, averaging them over the entire duration of the digit sequences. An ANOVA confirmed that the random digit generation task can discriminate between the low and high average workload situations at about the $p = .01$ level of significance.

A metric combining steady-state and transient conditions provides a reasonable estimate of driver workload. An empirical index of workload was established by dividing the number of brake actuations per 2-min test period by the square root of the observed speed. The results of this calculation averaged across all drivers for each roadway type are given in Table 2. An ANOVA showed that the workload index differed by roadway types at the $p < .001$ level of significance.

Figure 2 compares difficulty ratings, digit errors, and the workload index for the four roadway types. The workload index, derived from directly observed driver actions, tracks the subjective difficulty index quite well. The workload index correlates at a moderate level ($r = .389$) with the subjective driving difficulty ratings and at a higher level ($r = .834$) with errors on the digit recall task. Errors on the digit recall task prove to be a sensitive estimate of both subjective difficulty and the calculated workload index. This high degree of relationship lends confidence to the assumption that the digit recall subsidiary task provides a good measure of spare capacity and can be used to infer primary task workload.

DISCUSSION OF RESULTS

This experiment confirmed the fact that subsidiary tasks can provide a useful measure of spare capacity in the field and can, by inference, provide an estimate of driver mental workload. The two tasks used in this experiment have entirely different characteristics and should be matched to the specific problem at hand. The random digit generation task is of rel-

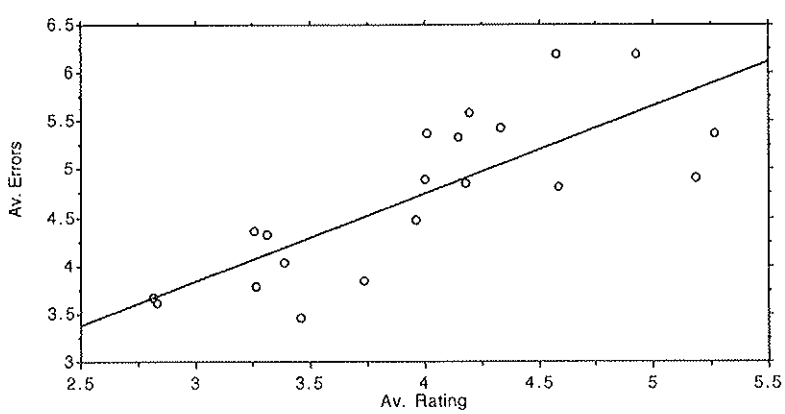

FIGURE 1 Delayed digit recall errors by ratings of subjective driving difficulty ($y = .914x + 1.099$, $R^2 = .615$).

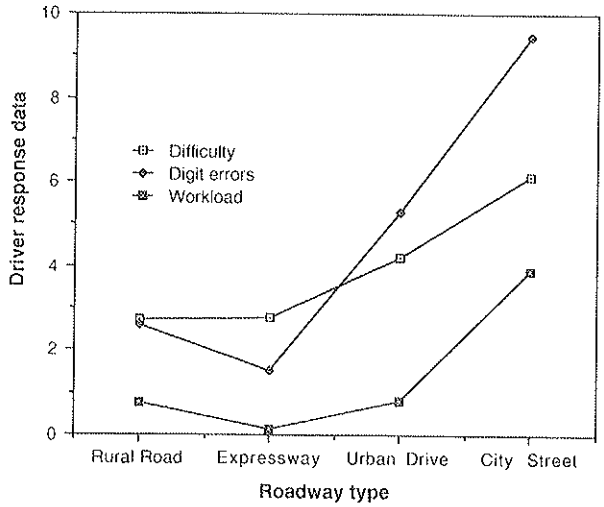

FIGURE 2 Driver response measures by roadway type.

atively little use in dealing with control situations in which primary task difficulty varies transiently over a significant range, such as is typical of "real world" automobile driving. It is of use, however, in evaluating the effect of general loading conditions or steady-state environmental stressors. The unstructured and self-paced nature of the task, coupled with its algorithmic method of scoring, suggests that it could also be useful as a simple measure of driver alertness and physical state.

In contrast, the delayed digit recall task is clearly sensitive to gradations of primary task loading. The high correlation between this task and the driving difficulty ratings suggests that a reasonable estimate of the driving difficulty and consequent mental workload imposed by a given vehicle-roadway combination can be derived by a practical subsidiary task. The experimental workload index,

$$\text{workload} = \text{brake actuation rate/speed}^{0.5}$$

is a parsimonious metric combining transient (brake actuations) and steady-state (square root of speed) conditions and offers a simple but directly observable estimate of subjective driving difficulty.

Interestingly, both subsidiary tasks appeared more sensitive to primary task loading in the field than on a simulator. The allocation of portions of total mental capacity to the tasks at hand requires a judgment call on the part of the individual. Since the consequences of a driving error on a simulator are considerably less serious than the consequences of an error on the roadway, the simulator driver may choose to allocate more capacity to the subsidiary task, decreasing simulated driving performance. No such tendency was noted in this experiment.

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Effect of Ambient Lighting and Daytime Running Light (DRL) Intensity on Peripheral Detection of DRL

KENNETH ZIEDMAN AND WILLIAM BURGER

Daytime running lights (DRLs) have been proposed to reduce the frequency and severity of traffic accidents by enhancing the conspicuity of vehicles to other drivers. DRL regulations have been enacted in several countries and are being considered in the United States. Although various studies of DRL effectiveness have been conducted, only one has included the range of ambient illumination conditions encountered in the United States. The project reviewed methodologies appropriate for the study of DRL effectiveness and conducted a study of DRL effectiveness under a wide range of ambient illumination. A peripheral detection experiment was conducted in which subjects responded to a DRL test vehicle approaching at a 20-degree peripheral angle while the subjects were performing a central attention task. DRL intensities were 0, 200, 400, 800, and 1,600 cd. Ambient illumination levels varied from about 11 000 to more than 110 000 lx (1,000 to 10,000 fc). Only the 1,600-cd intensity resulted in a statistically significant increased peripheral detection distance. Improved peripheral detection distance was limited to ambient illumination levels below 43 040 lx (4,000 fc). The mean improvement in detection distance for 1,600-cd intensity and ambients less than 43 040 lx (4,000 fc) was about 75 m (247 ft), or about 3 sec of driving time at 88 km/hr (55 mph).

Daytime running lights (DRLs) for automobiles and motorcycles have attracted the attention of the traffic safety community for many years as a means of increasing the daytime conspicuity of vehicles to other road users (*1–7*). Several European countries have required DRLs for a number of years (*8,9*), Canada has recently implemented a DRL requirement (*10,11*), and the European Economic Community is considering a uniform DRL requirement (*12,13*). The U.S. Department of Transportation has conducted various DRL studies to assess the applicability of DRLs to the U.S. environment (*14–16*).

A substantial amount of DRL research has been conducted, including studies of accident experience before and after DRL implementation (*8,9,17,18*), fleet studies in which DRL-equipped vehicles have been compared with non-DRL-equipped vehicles (*19–21*), observational studies in which observers have made judgments of various DRL configurations (*22*; D.W. Moore, DRL tests in various U.S. cities, SAE Lighting Committee Correspondence, 1985–1986), and experimental tests of DRL performance using detection distance or other performance measures (*15,16,23–29*).

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However, this body of work includes only a few experimental studies that provide quantitative relationships among DRL parameters such as intensity, environmental parameters such as ambient illumination, and performance measures such as detection distance or conspicuity.

The issue of DRL effectiveness as related to ambient lighting levels is especially important for DRL use in the United States and other countries that have a significant amount of territory at lower latitudes and, therefore, higher ambient illumination levels than encountered in most European countries. For instance, Sweden and Finland, which pioneered DRL application, have typical ambient levels about one-tenth those of the United States. Only one study studied DRL performance over an ambient range that is typical of the U.S. environment (*15*).

DRL EVALUATION METHODOLOGIES

The predominant experimental and observational methodologies used in DRL evaluation have been judgment or comparison techniques, decision making, central detection, and peripheral detection.

DRL judgment studies, in which the effectiveness of various DRL configurations are ranked or rated by observers, tend to be conducted under uncontrolled conditions and cannot provide quantitative performance measures that can be used to evaluate DRL accident reduction potential.

Gap acceptance studies and similar decision-making approaches pose methodological problems and can be very difficult to conduct, especially when one is attempting to measure gap acceptance behavior of unsuspecting drivers. However, such studies may be extremely useful for evaluating DRL effectiveness in a more natural situation than is provided by the typical controlled experimental task.

DRL central visual detection studies are of limited value because of the very long DRL detection distances typically found for direct viewing of DRL-equipped vehicles. However, some conditions will exist in which improved central detection due to DRL is relevant (e.g., driving under glare conditions or when the other vehicle is viewed against masking backgrounds).

Peripheral detection studies were judged to be the best technique for relating DRL conspicuity (i.e., initial noticeability of the other vehicle) to ambient illumination and DRL intensity. However, performance is sensitive to the peripheral

angles at which targets are presented, central task demands, and deviations of observers' gaze direction.

DRL PERIPHERAL DETECTION EXPERIMENT

The purpose of the experiment was to determine DRL peripheral conspicuity as a function of ambient illumination and DRL intensity. A secondary purpose was to examine the effectiveness of DRL as a function of driver age.

Test Site and Subject Station

The test site was a concrete taxiway at the Camarillo airport (Ventura County, California) that was about 15 m (50 ft) wide. It provided a straight east-west "roadway" of more than 762 m (2,500 ft). A connecting ramp at the far end of the runway provided a turn-around area for the test vehicle. The terrain surrounding the taxiway was essentially flat, with low mountains in the far background.

Six subject chairs were located in a line at the east end of the test area. The DRL vehicle approached the subject station from the west. The central task display was located at a 20-degree angle to the north of the vehicle path and at a distance of about 16 m (53 ft) from the subjects' station. The peripheral angle deviation from the nominal 20 degrees for the two end subjects was less than 1 degree at a distance of about 150 m (500 ft). The experimenter's station was behind the subject station.

An overview of the test area configuration is given in Figure 1.

Method

Groups of six subjects were run simultaneously. The DRL vehicle started each trial from a distance of 762 m (2,500 ft) or greater and approached at 40 km/hr (25 mph). The data collection period started when the vehicle was 701 m (2,300 ft) from the subject station and ended when it was 38 m (125 ft) away.

Central Task

The central task display used six vehicle lamp assemblies 12 cm (4 in.) in diameter (Grote Type 5064 with Type 1156 32-cd lamps), three with red lenses and three with amber lenses. Five of the lamps were mounted around the edge of a circular panel 0.73 m (2 ft) in diameter and the sixth was mounted in the center. One light at a time was flashed in random sequence with a timing of about 0.5 sec on, 0.5 sec off. The subjects' task was to count (silently) only the yellow flashes. The light flashes were easily visible under all lighting conditions. Subjects wrote down their flash count at the end of each run on a score sheet.

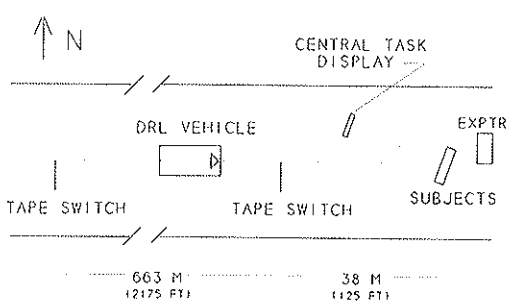

FIGURE 1 DRL test area configuration (not to scale).

DRL Detection Task

Each subject was provided with a quiet response switch and was instructed to press the switch when the vehicle could be seen out of the corner of his or her eye during a trial. Subjects were instructed to respond to any aspect of the vehicle that would lead them to believe another car was approaching if they were actually driving.

Experimental Plan

Twenty-four subjects were used, divided into four subgroups, each consisting of three "old" and three "young" subjects. Each subgroup was run for two half-day periods: a morning and an afternoon period. Two subgroups were run morning first, and the other two were run afternoon first. Thus, the entire set of runs required four days.

Each half-day run was divided into four blocks of runs. Each block consisted of 10 runs, with 2 runs at each of the five DRL intensity levels. The sequence of intensity levels was randomized within each block (with the constraint that each level was to occur twice). A run took 3 to 4 min, so an entire block required 30 to 40 min. A rest period was taken between blocks. The amount of time between when subjects were alerted to the start of each run and when the DRL vehicle actually started was varied to avoid subjects' basing responses on the time from when they were first alerted.

As all subjects in each age group received all DRL intensity conditions, intensity was a within-group variable. Age was a between-group variable. The basic design is a repeated measures design in which each subject received repeated trials at each level of DRL intensity.

Independent Variables

Independent variables were as follows: (a) DRL intensity: 0, 200, 400, 800, 1600 cd (each lamp of a two-lamp system), (b) ambient lighting environment, and (c) age: younger (18 to 30 years) and older (55 years and older).

Several measures of the ambient lighting environment were recorded: (a) horizontal illuminance (HILLUM) measured in footcandles, (b) vertical illuminance (VILLUM) measured in footcandles, (c) sky luminance (SKYLUM) measured in foot-Llamberts (fL), and (d) road luminance (ROADLUM) measured in foot-Llamberts.

Ambient lighting conditions were varied by testing on selected days (for example, on overcast days to obtain lower ambients) and because successive runs under the same DRL

intensity conditions occurred throughout the day and, therefore, under a range of ambient conditions.

Photometric Measurements

HILLUM was recorded at the end of each run. VILLUM, SKYLUM, and ROADLUM were recorded about 12 times each test day, from just before the first run to just after the last run. Illuminance was measured with a Minolta T-1 illuminance meter with a cosine-corrected sensor. Luminance was measured with a Minolta LS-100 luminance meter with a circular 1-degree field of view. Sky luminances were taken just above the horizon terrain along the path of the DRL vehicle. Road luminances were measured with the 1-degree field approximately centered at a point about 150 m (500 ft) west of the subject station.

Dependent Variables

Dependent variables were (a) DRL vehicle distance for the peripheral detection task, and (b) amber light count for the central task.

Procedures

A subject group arrived at the test site at about 7:30 a.m. for a morning test period and at about 1:30 p.m. for an afternoon test period. On the first test occasion, printed instructions were handed to the subjects and read to them while they were asked to read along.

Emphasis was placed on the importance of paying attention to the central task, not looking to the side during or between test runs, and maintaining a consistent detection criterion in regard to DRL vehicle detection responses. Subjects were instructed to respond as soon as they became aware of an approaching "vehicle," but they were not instructed to respond to any particular aspect of the approaching vehicle.

Several practice trials were given before the first test trials. Subjects were given the opportunity to ask questions or make comments after each practice trial.

A bonus award was given for the most accurate flash count over each block of 10 trials in order to encourage motivation for the flash-count task and to generally increase subject interest in the overall test situation. Subjects were paid a base amount of $180 for participation in the two half-day sessions plus an additional $10 for the most accurate flash count.

Subjects were encouraged during the rest periods to comment on any difficulties they had in following procedures and to indicate after each trial if they thought that they responded inappropriately.

Apparatus

DRL Vehicle and Test Lamps

The test vehicle was a 1984 Volkswagen Rabbit fitted with a black plywood panel 0.38 × 1.4 m (1.25 × 4.5 ft) mounted vertically in front of the grill. The DRL lamps were mounted behind and flush with circular cutouts in the panel. The lamps were clear Types 4412 (SAE J-583) 27.5 cm (5.25 in.) in diameter and have a nominal H,V intensity of 11,000 cd, a vertical beam width of 6 degrees, and a horizontal beam width of 40 degrees. These lamps were chosen for their relative uniformity of vertical and horizontal beam pattern. The lamp mounting height was 0.67 m (2.2 ft), and their center-to-center distance was 1.2 m (3.6 ft). The Volkswagen Rabbit was painted a flat gray over the areas visible to the subjects to minimize responses to specular reflection. The black panel simulated the dark grill area of many (although not all) cars.

DRL Lamp Calibration and Control

DRL intensity was adjusted by the use of a set of four adjustable resistors for each lamp; power was provided from the vehicle electrical system through a voltage regulator for each lamp. A switch box next to the driver allowed the driver to select lamp intensity.

The lamps were calibrated and the resistors set at the proper values by measuring the illuminance generated on a vertical grid perpendicular to the vehicle longitudinal axis. Details of the calibration and beam pattern are given in the project final report (*16*). Although the lamp intensity decreased slightly as the test vehicle approached the subjects because of the increase in vertical angle at which the lamps were viewed, the estimated intensity difference would be less than 10 to 20 percent.

Test Control and Data Recording

A laptop computer interfaced with a digital/analog input/output device was used to (a) randomly select the sequence of central task lights and control the on/off period of flashes, (b) record the times of tape switch crossings of the DRL vehicle, and (c) record the time of each subject's vehicle detection switch-press.

Subjects

Subjects were recruited from the Ventura County area. The criteria for subject selection were

- Young (18 to 30) or old (55 and older),
- Vision within standards for California driver's license,
- Current driver's license,
- Currently driving at least 4,000 mi/year, and
- Not taking prescription drugs that might affect performance.

The mean age of the old and young groups were 65.7 and 22.5 years, respectively.

DATA ANALYSIS

Detection Distance Conversions

Detection distance was calculated for each subject on each trial by using the times of tape switch crossings and time of subject response, assuming a constant DRL vehicle speed. Analysis of the variation in average speed from run to run indicated that speed variation was likely to be small within a run.

Data Quality and Missing Runs

Extensive data screening was performed to test for data quality. One young subject was a "no-show" and could not be replaced; 31 other cases were lost due to various problems such as admitted inadvertent responses. The final data set consisted of 1,809 data points from 23 subjects.

Data Transformations

Several transformations of the raw detection distance distributions were examined to match statistical test requirements, and various relationships between detection performance and transformations of the photometric data were examined. The latter included various measures of target "contrast" in an effort to examine independent variables that might be better correlated with detection performance than the individual illuminance and luminance variables.

Statistical Methods

Data analysis was complicated by the uncontrolled nature of the ambient illumination conditions. Each group of subjects to some extent experienced a different range and quality of ambient conditions. In general, such confounding was more of a problem for the lower ambient levels, as all subjects were exposed to the higher ambient levels for a number of blocks, but some subjects had much less exposure to the lower levels than did others.

Emphasis was placed on correlational analyses and extensive use of descriptive statistics for overall data examination, in addition to analysis of variance methods.

RESULTS

Photometric Data

The lighting environment during the testing periods can be summarized as follows:

- Overcast conditions occurred during the entire morning on one of the test days and on the early-morning hours on two other test days, resulting in more or less diffuse illumination with relatively low HILLUM values during these test blocks.
- Clear sky with the sun behind subjects illuminating the front of the test vehicle normally occurred by the later morning test blocks.
- Sun more or less overhead to in front of the subjects illuminating the rear of the test vehicle occurred during the afternoon test blocks.

Generally, HILLUM levels were below 11 000 lx (about 1,000 fc) at the beginning of the test day, increased to about 110 000 lx (about 10,000 fc) at midday, and then decreased to about 54 000 lx (about 5,000 fc) at the end of testing.

VILLUM incident on the plane of the vehicle front increased from about 11 000 lx (about 1,000 fc) at the beginning of the morning testing, reached peak values of 86 000 lx (about 8,000 fc) at about 10:00 a.m., and then decreased to about 21 500 lx (about 2,000 fc) at the end of testing. During the afternoon, the vehicle front was in shadow for much of the time.

ROADLUM remained relatively constant at about 10,000 cd/m^2 (about 3,000 fL) after about 10:00 a.m., following an initial rise from about 700 cd/m^2 (about 200 fL) at the beginning of testing.

SKYLUM increased monotonically from about 3,400 cd/m^2 (about 1,000 fL) at the beginning of testing to about 27 000 cd/m^2 (about 8,000 fL) at the end of testing.

HILLUM is shown plotted versus time of day for the 4 study days in Figure 2.

The lighting conditions encountered in this study were complex but typical of viewing in the natural environment.

Central Task Performance

A flash-count error score was formed by subtracting the number of reported flashes from the number of actual flashes for each subject on each trial. The overall error rate was very small; 95 percent of all trials resulted in errors of one count or less. As the flash-count task was judged to be fairly difficult and require concentrated attention, it was concluded that subjects were unlikely to have glanced in the direction of the DRL vehicle to any significant amount. The possibility of such glances cannot be ruled out entirely, as a glance could occur in less than 0.5 sec and as eye movements were not recorded or observed (the experimenter did check for subject head

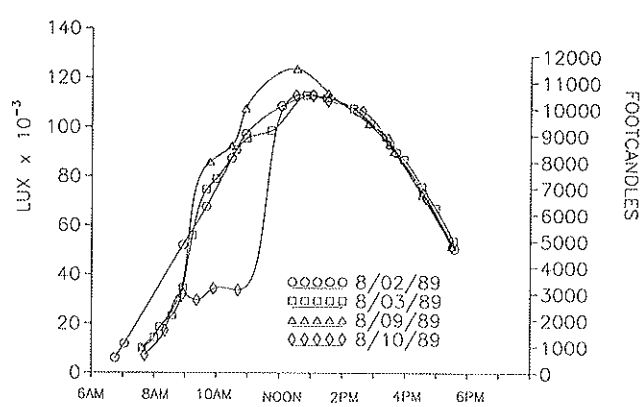

FIGURE 2 Horizontal illuminance versus time of day.

movements during the observations periods, however.) No significant correlations were found between the flash count score and other performance measures.

Detection Performance

General Trends

Mean detection performance across all subjects versus DRL intensity is shown in Figure 3. Both detection distance (DETDIST) and delta detection distance (DELDIST) measures are shown (DELDIST for each case in the detection distance for that case minus the overall subject's mean detection distance for all cases).

The results are shown separately for low ambient trials, that is, HILLUM less than 43 040 lx (4,000 fc), high ambient trials, i.e., HILLUM greater than 43 040 lx, and all trials. (The threshold of 43 040 lx to divide low and high ambients was determined after examination of various groupings of ambient levels for the various photometric measures.)

A mean improvement in DELDIST of about 75 m (247 ft) is shown for the low ambient, 1600-cd condition and about 22 m (72 ft) for the low ambient, 800-cd condition. Only a small trend is shown for improved DELDIST for the high ambient conditions, and only at 1600-cd level.

The same variables are plotted in Figure 4, but with age category as a parameter instead of ambient category. The older subjects show a trend toward better performance than the younger subjects, an unexpected result, that is discussed later.

Analysis of Variance

Three-way analyses of variance (ANOVAs) were run to test the effects of DRL intensity, subject age, and ambient level (categorized into low and high ambient). The ANOVAs were run for DETDIST as well as for three transformations of DETDIST. Transformations were examined as the distributions of DETDIST were found to be nonnormal (skewed in the direction of longer values). The transformations examined were (a) DELDIST, the difference between each DETDIST score for a subject and that subject's overall mean score; (b) LOGDIST, logarithmic transformation of DELDIST; and (c) DELLOG, the log of each DELDIST subtracted from the mean of the logarithmic transformations of individual scores.

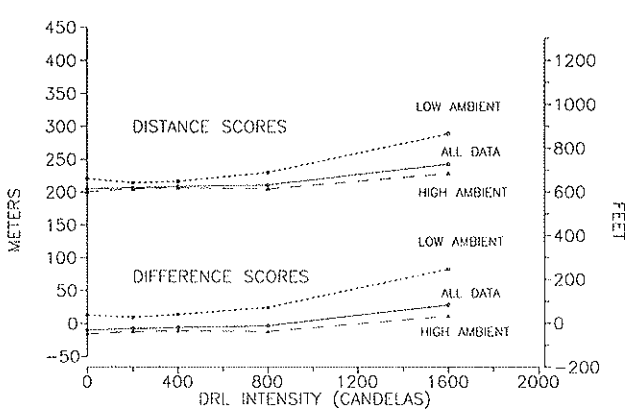

FIGURE 3 Ambient level and detection distance.

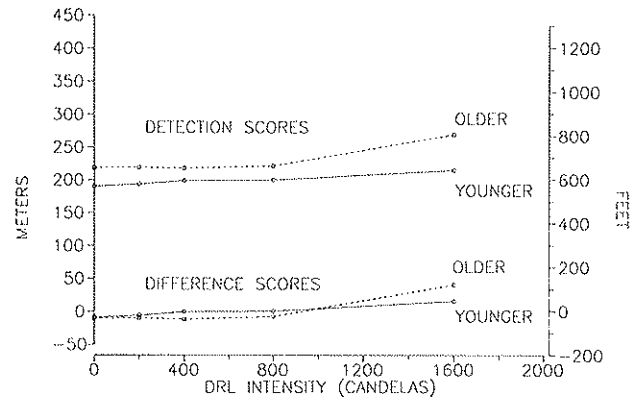

FIGURE 4 Age and detection distance.

For all measures, DRL intensity and ambient level were significant main factors. Subject age was significant for all measures except DELDIST. Significant interactions were also found for all detection distance measures except for LOGDIST. The presence of interaction terms made the ANOVA results somewhat difficult to interpret. However, the main effects of DRL intensity and ambient level were consistent across all transformations of detection distance scores.

Comparison of Individual Means

Comparison among individual DETDIST and DELDIST means at each DRL intensity were performed separately for the low and high ambient categories. The results indicated that significant improvement with DRL intensity occurred between the 1600-cd case and all other intensities but that no other comparisons were significant.

Comparisons of individual means for DETDIST between low and high ambient levels at each DRL intensity show a significant difference only at 1600 cd. However, significant differences between low and high ambients were found for DELDIST scores at each DRL intensity value. Thus, subjects performed relatively better at the low ambient levels than at the high ambient levels regardless of DRL intensity level.

Regression Analysis

Linear regression functions for DETDIST versus HILLUM are shown in Figure 5 for each DRL intensity. Only the 1600-cd DRL intensity shows an obvious nonzero slope.

Linear regression functions for DETDIST versus DRL intensity categorized into low and high ambients are shown in Figure 6. Little or no trend was found for an increase in mean detection performance for the high ambient condition, but an increase did occur for the low ambient condition.

Summary of Peripheral Detection Distance Results

In summary, DETDIST and DELDIST scores showed effectiveness of DRL at ambient levels below 43 040 lx (4,000 fc)

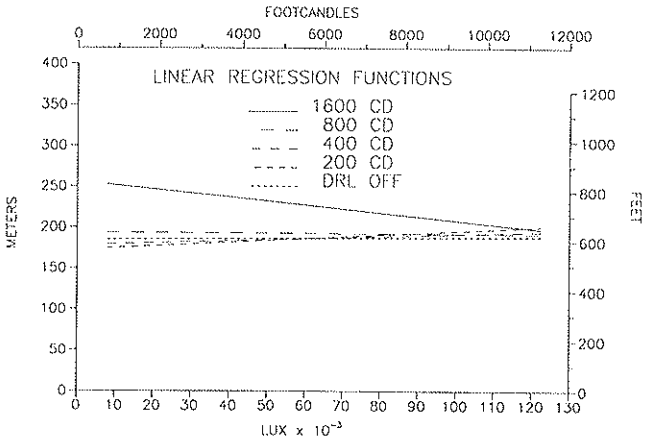

FIGURE 5 Detection distance versus horizontal illuminance.

for DRL intensities of 1600 cd (although a trend toward effectiveness was found at 800 cd).

Relationships Between Detection Performance and Other Photometric Measures

Analyses similar to those discussed were performed to examine the relationship between detection performance and photometric measures other than HILLUM, including various visibility index functions such as ratios of DRL intensity to road luminance and sky luminance. However, no other measure or transformation was found that correlated with detection performance to any greater extent than did HILLUM.

In general, although specification of DRL effectiveness in terms of horizontal illuminance alone might be misleading under some conditions, it was concluded that horizontal illuminance does provide an adequate measure for system evaluation of DRL effectiveness.

Comparison with Other Studies

A study by Kirkpatrick et al. used a range of DRL intensities and a detection task similar to the present study (*15*). Kirkpatrick et al. used a 15-degree angle between a central vision task and the approaching vehicle rather than the 20-degree angle used in this study, and the central task consisted of counting a single flashing light instead of the multiple-light display used in this study. A DRL intensity range of 250 to 2000 cd was used by Kirkpatrick et al.

A comparison of mean detection distance versus DRL intensity for the two studies is shown in Figure 7. The two data sets are remarkably similar, given the many sources of variation in such experimentation. A comparison between the two studies with data categorized into low and high ambients (as defined earlier) also showed general agreement.

Hörberg (*29*) reported a peripheral detection (DRL vehicle at 20 degrees) study under twilight conditions in which illuminance varied from 100 to 2000 lx (about 9.3 to 186 fc). His results showed that a 300-cd DRL enhanced detection below illuminances of about 800 lx (about 74 fc). Because his highest ambient level was several times less than the lowest level typically encountered in the present study a direct comparison is not possible. However, a rough comparison can be made by considering only runs in the present study with HILLUM below 10 760 lx (1,000 fc).

A total of 30 such runs existed: 10 at a DRL intensity of 1600 CD and 5 at each of the other DRL intensities. These data suggest that for HILLUM less than 10 760 lx (1,000 fc), detection was improved at DRL intensities as low as 400 cd, with a large mean increase in detection distance occurring at 1600 cd. Thus, the present results are in agreement with Hörberg at the lower ambient levels.

DISCUSSION OF RESULTS

The experimental task used in this study required detection of the DRL vehicle in the near periphery of the observer's visual field. The 20-degree angle selected is large enough to be outside the visual cone of immediate priority to the driver but still within an area of concern for possible hazards. The nature of the task used emphasizes the role of DRL in attracting attention (conspicuity) as opposed to providing improved perceptual information to the driver once a DRL vehicle is noticed and attended to. Because of the lower probability of detection at a 20-degree angle than at, say, within a 5-degree range, the results of this study will be conservative—

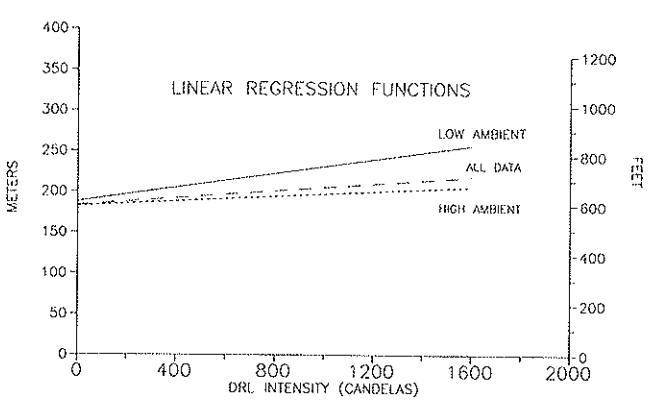

FIGURE 6 Detection distance versus DRL intensity.

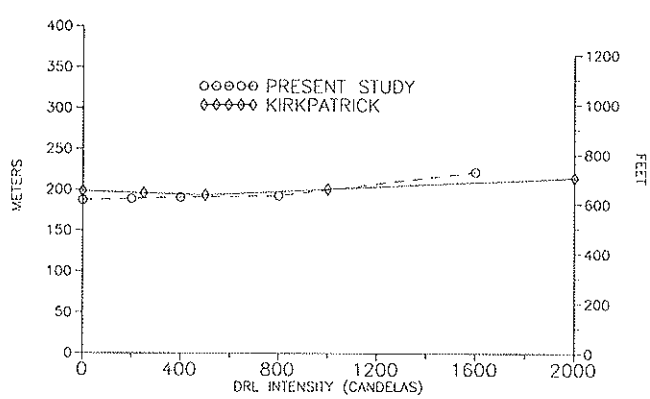

FIGURE 7 Comparison of present study with study by Kirkpatrick et al. (*15*).

that is, DRL intensities and ambient conditions for which DRL proved beneficial in this study will almost certainly enhance conspicuity for comparable conditions in which a DRL vehicle occurs at angles smaller than 20 degrees. Examination of DRL effectiveness at peripheral angles greater than 20 degrees is of interest; the single angle used in this study represented a compromise between including additional viewing angles versus obtaining an adequate number of data points for each DRL intensity.

The subjects' focus of attention on the flashing light task required more concentrated attention than one would expect from a "typical" driver who would normally be scanning the visual scene in front of him or her. Thus, many drivers would have been likely to detect the DRL vehicle at longer ranges or, possibly, at lower DRL intensities than are indicated by these results. However, the attention required in this study is not unlike that needed by a driver in a difficult traffic situation or a driver who is distracted or otherwise occupied by driving or nondriving tasks.

This study did not address the issue of DRL effectiveness for scenarios in which the driver's task primarily involves perceptual and decision-making functions. For example, the issue of DRL usefulness in assisting passing maneuvers in the face of oncoming traffic would involve questions of distance, speed, and time estimation as well as detection of an oncoming vehicle.

The results for age are difficult to interpret given the known degradation in visual performance with age. It was noted during the study that the older age group consisted primarily of professionals who were retired but still active and who appeared to be highly motivated. Thus, motivational factors might have compensated for any decrease in visual function due to age.

CONCLUSIONS

For the DRL intensity levels evaluated in this study, 1600 cd was the minimum intensity required for achieving increased peripheral detection over a range of ambients that are representative of much U.S. driving.

Within the range of DRL intensities studied, DRL was primarily effective for enhancing peripheral detection at lower ambients, although a trend toward improvement does occur at higher ambients.

For the low ambient range and 1600-cd DRL, a mean improvement in detection distance of 75 m (247 ft) was found. This corresponds to about 3 sec at 88 km/hr (55 mph), a substantial amount of additional time for a driver to perceive and respond to a possible hazard.

A horizontal illuminance level of 43 040 lx (4000 fc) appears to be a reasonable division between low and high ambient conditions.

By themselves, the results of this study suggest that 1600 cd should be considered a minimum level for DRL intensity under conditions of higher ambients. However, a final decision as to the appropriate DRL intensities for any geographical area must also consider the amount of accident reduction likely as a function of ambient levels, the distribution of driving miles versus ambient level, possible glare problems at twilight and dawn ambient levels, cost of DRL implementation and maintenance, compatibility with the international standards community, and other trade-offs between DRL benefits and costs.

ACKNOWLEDGMENTS

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Broadcast Parking Information: Behavioral Impacts and Design Requirements

JOHN POLAK, PETROS VYTHOULKAS, AND IAN CHATFIELD

For the past 2 years Nottinghamshire County Council, in collaboration with local radio stations, has been running an experimental broadcast parking information service during the Christmas period that provides drivers with up-to-the-minute information on occupancy, queues, and parking alternatives. The results of a study designed to investigate the impact of the service on motorists' travel and parking behavior are presented. The study involved a mail-back survey distributed to drivers at city center parking lots, on-street parking areas, and peripheral park-and-ride sites. The results of the study indicate that awareness of the service is high but that its impact on parking behavior is more limited. Although substantial use is made of the service by drivers en route to the city center, there is little evidence that this mode of use results in any significant impact on parking behavior or experienced search and queueing time. By contrast, the minority of drivers who use the broadcast service at the pretrip stage on average enjoy significantly reduced search and queueing time and are more likely to divert to park and ride. Drivers' tolerance of searching and queueing and the nature of their knowledge of parking alternatives are important factors conditioning the use and impact of the broadcast service.

In European cities, congestion associated with searching or queueing for parking spaces is a large part of the overall level of urban congestion. Recent studies of parking behavior in five British and German cities found that on average between 10 and 25 percent of total in-vehicle time is occupied in searching or queueing for parking (*1*). These empirical findings are reinforced by simulation studies carried out by Hoffmann that indicate that reductions in travel times of up to 20 percent could be achieved by more efficient routing of vehicles to parking lots (*2*).

Parking congestion can arise for a variety of reasons, including local inefficiencies in road layout, poor parking lot design, and drivers' lack of awareness of prevailing levels of occupancy in key parking lots or alternative parking and travel opportunities. In the latter case, systems designed to provide travelers with improved information on the parking system have the potential to reduce parking congestion by enabling the more efficient use of existing capacity. In Europe there is considerable interest in the scope for advanced parking management systems based on in-vehicle, roadside, and broadcast information (*3*).

Although the potential impact of such systems is substantial, their success will depend crucially on how travelers acquire, use, and respond to the provided information. A growing body of work highlights the need for improved understanding of the behavioral impact of traveler information systems, both as an input to the system design process and as a requirement for comprehensive evaluation (*4,5*).

This paper presents the results of a study into the behavioral impact of a broadcast parking information system that has operated for the past 3 years in the city of Nottingham. The system operates during the Christmas period and is based on local radio broadcasts providing drivers with up-to-date information on parking lot occupancy, queue lengths, and alternative parking opportunities.

BACKGROUND

Motivation

Nottingham experiences an abrupt and substantial increase in traffic volume and parking lot occupancy in the 10 to 12 weeks before Christmas. Traffic flows increase by 10 to 15 percent over their level in an average month, and the average midday occupancy in city center multistory parking lots increases from 75 percent in June to 93 percent in December. Long queues develop regularly outside the most popular city center parking lots and have become a significant source of inconvenience and delay. Sometimes these queues extend as far as 300 m, reducing the capacity of upstream junctions and causing increased congestion and accident risk to general traffic. Experience has shown that conventional methods of regulation and enforcement (e.g., increased police and warden activity) are of only limited effectiveness in combating queueing. Moreover, such measures can only address the problem once it has occurred rather than prevent it in the first place.

Despite the severity of the queueing problem at the most popular parking lots, studies carried out by the county council have shown that even in periods of peak parking demand, up to 500 spaces can be available in other (less popular) city center parking lots, in addition to up to 3,600 spaces at four (two daily and two Saturday only) park-and-ride sites. Therefore, there appeared to be scope for reducing the problems of parking congestion in the center of Nottingham if motorists could be encouraged to make more use of this existing but underused capacity.

Broadcast Information Service

The aim of the broadcast information service was to help drivers to avoid spending long periods searching and queueing

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at the most congested parking lots by providing information to encourage them to divert to less crowded city center parking lots or use the park and ride. The service operated from the beginning of October to the middle of January between 9:00 a.m. and 1:00 p.m., Monday through Saturday, and involved close cooperation between Nottinghamshire County Council and two local radio stations, Radio Nottingham and Trent FM. Information was presented in a fixed-format message of 1 to 2 min and delivered three times an hour on Radio Nottingham and twice an hour on Trent FM. Each message consists of four components:

- A list of parking lots with queues and the estimated queueing times,
- A list of parking lots with spaces available,
- Current occupancy status of all park-and-ride sites, and
- Two or three pieces of "helpful advice" at the presenter's discretion from a list supplied by the county council.

The information on parking lot queues was provided by the highway authority by means of closed-circuit television monitoring of the entrances of all key parking lots. The observed queue lengths were used to estimate expected queueing times, using the results of a survey of queueing times at the most popular parking lots during the morning peak parking periods that was carried out before the service was introduced. The parking lot information was collated and presented by a member of staff of Radio Nottingham stationed in the Urban Traffic Control Center. The availability of the service was advertised by roadside signs placed on all the main radial roads entering Nottingham.

BEHAVIORAL IMPACT STUDY

Objectives

The main objective of the study was to investigate drivers' awareness and use of the broadcast information service and to determine its impact, at an individual level, on their parking behavior and experienced parking outcomes. Given the emphasis of the service on providing improved information, there was a particular concern to explore the role played by drivers' prior knowledge and experience of local parking circumstances in conditioning their use of and response to the service.

Methodology

The survey was carried out over a 3-week period starting at the end of November 1990 and involved a combination of on-street personal interviews and mail-back surveys. This approach enabled a large sample of travelers to be contacted to establish awareness and use of the service by different groups while also providing the scope for a more detailed exploration of behavioral factors and impacts.

The initial contact interview collected basic journey and personal details and brief information about drivers' awareness and use of the information service, in general and on the specific day of interview. To contact a sample of drivers with a range of parking preferences and experiences, interviewing was carried out at a selection of city center parking lots, park-and-ride sites, and on-street parking locations. Recruitment was restricted to individuals who had driven into Nottingham on the survey day and who did not have access to private or reserved parking facilities. Quota sampling was used to ensure adequate representation of all relevant categories of journey purpose, parking type used, and planned duration of stay. As a result of the sampling and quota procedures used in recruitment, the contact sample is not necessarily representative of the characteristics of all travelers to Nottingham. Respondents who completed the initial contact interview were given a stamped envelope containing a longer mail-back questionnaire, structured in four sections.

The first section collected a more detailed description of the journey being made at the time of interview, focusing in particular on the way in which they searched for a parking place and their parking preferences, since these were considered likely to be significant factors in conditioning traveler response to the broadcast information.

The second section of the mail-back questionnaire investigated travelers' knowledge of parking conditions in Nottingham, using a map showing the nine major city center parking lots included in the broadcast service. Drivers were shown the map and asked to indicate whether they knew about, had ever used, and could name each parking lot (Figure 1). This device furnished insight into the range of drivers' experiences of different parking lots and their perceptions of their own knowledge of parking and, importantly, enabled the contrast of these perceptions with a relevant objective measure of parking knowledge.

The third section of the mail-back questionnaire explored drivers' attitudes toward the broadcast information service and the effect of the service on travel and parking behavior, including the choice of mode and journey timing.

The final section focused on attitudes toward possible extensions and enhancements of parking information services and is not discussed in this paper.

RESULTS

Sample Characteristics

A total of 1,584 car drivers were contacted in the initial on-street interviews, of which 627 returned the mail-back questionnaire, a response rate of almost 40 percent. More than 70 percent of the sample consists of shoppers arriving during the period of peak parking lot occupancy between 9:00 a.m. and 1:00 p.m. and staying for fewer than 4 hr. Almost half the sample visited the city by car once or more a week, and almost 30 percent visited less than once a month. The overwhelming majority of the less frequent visitors were engaged on shopping journeys, many specifically associated with Christmas. Almost 90 percent of respondents parked off the street either in city center multistory parking lots (49 percent) or at park-and-ride sites (40 percent). On-street parking was used mainly by those visiting the city on personal or employers' business and staying for fewer than 2 hr.

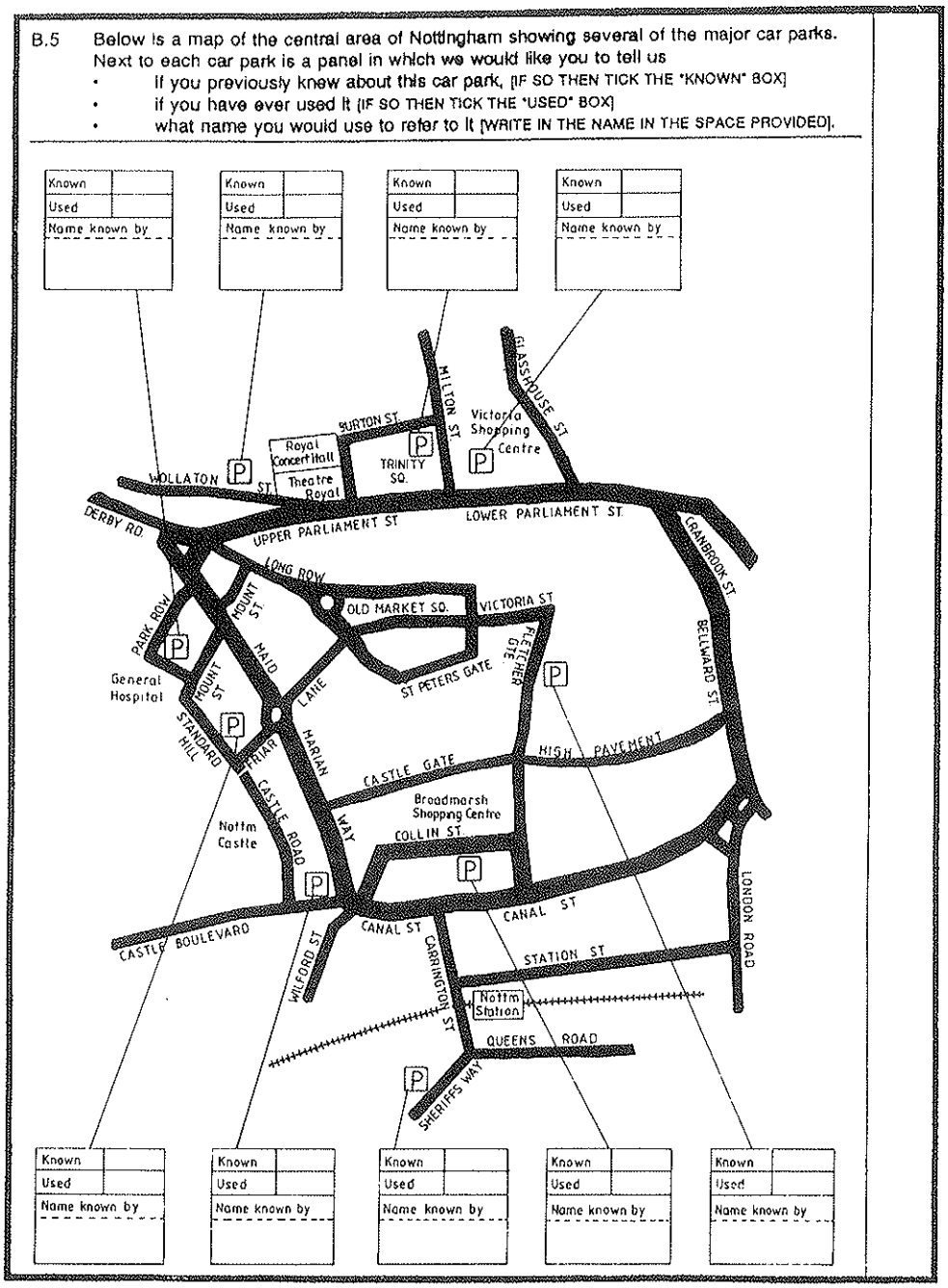

FIGURE 1 Map shown to drivers of nine major city center parking lots included in broadcast service.

Awareness and Use of Broadcast Service

Figure 2 summarizes the results concerning awareness and use of the broadcast service. Sixty-three percent of the drivers in the sample were aware of the broadcast service. As expected, awareness of the service was strongly related to local radio listening behavior: 92 percent of regular listeners were aware of the service, but only 56 percent of those listening occasionally or not at all were aware of it. Awareness was also related to the frequency of parking in Nottingham: 68 percent of those parking more than once a month were aware of the service compared with only 51 percent of those parking less frequently ($\chi^2 = 35.6$, $p < .0001$). This finding is to be expected because frequent travelers will receive greater exposure to efforts to promote the service.

Among personal factors, age has the only significant effect: 65 percent of those between 25 and 45 were aware of the service compared with only 55 percent in the younger or older groups ($\chi^2 = 12.9$, $p < .005$). This probably reflects the age profile of the listening audience of the local radio stations, although no independent data were available to confirm this. Most of the respondents who were aware of the service first

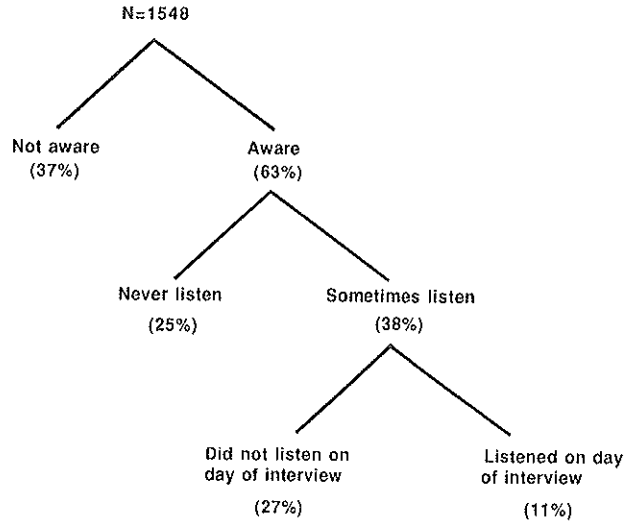

FIGURE 2 Pattern of awareness and use of broadcast service.

learned about it either by listening to the radio (32 percent) or by seeing the roadside signs advertising the service (23 percent); word of mouth (5 percent) was the only other significant method of dissemination.

Of those aware of the service, 56 percent claimed to have used it, which represented 38 percent of the total sample. Radio listening behavior was again a major conditioning factor, with more than 80 percent of regular listeners (who were aware of the service) claiming to use it, compared with only 32 percent of occasional listeners. Frequent travelers also made much greater use of the service (59 percent versus 48 percent for infrequent travelers, $\chi^2 = 8.3, p < .004$).

Users of the service tend to be selective, with only 18 percent deliberately tuning in to the service every time they travel to Nottingham during the Christmas period. Another 23 percent tune in only when traveling on a day or at a time when they expect to encounter serious parking congestion. The remaining 69 percent of users attend to the information only if they happen to hear it on the radio. Just over 28 percent had listened on the day of interview, which was 11 percent of the total sample.

Most (74 percent) of those who listened to the broadcast service on the day of interview first did so in their vehicles en route to the city center. However, a significant proportion of drivers used the service at the pretrip stage, and there was a marked difference in listening behavior according to the type of parking used: those using park and ride were much more likely to have first used the broadcast service at home ($\chi^2 = 11.4\ p < .001$):

	When first listened to service (%)	
Type of parking used	*Pretrip*	*En Route*
City center ($N = 87$)	16	84
Park and ride ($N = 61$)	41	59

Those who actively seek information from the service are also much more likely to listen at the pretrip stage or to combine pretrip and en route listening ($\chi^2 = 12.1, p < .06$).

Two factors appeared to be responsible for the decision of drivers who were aware of the service not to use it. The most common explanation (cited by more than 45 percent of such nonusers) was that they believed themselves able to find a parking space without assistance. In addition, just over 40 percent did not listen to the relevant local radio stations and although aware of the broadcast service did not want to retune their receiver. Only 4 percent of deliberate nonusers stated that they had tried the service but found the information not useful or unreliable, confirming the general pattern of satisfaction among users of the service.

Parking Search and Queueing Behavior

Characteristics of Existing Behavior

Figure 3 shows the variation throughout the day in the time that drivers reported they spent searching and queueing for different types of parking.

Average search and queueing times at multistory parking lots increase sharply after 10:00 a.m., reaching a peak of almost 20 min near midday and diminishing rapidly thereafter. A similar pattern of variation is evident in the time spent searching for on-street parking, although the peak is reached earlier and the absolute level is lower. Overall, drivers using city center multistory facilities spend an average of 5.0 min searching and queueing for parking, which, at an individual level, accounts for between 10 and 21 percent of their total journey time. Those using city center on-street parking spend significantly longer searching ($F = 21.92, p < .0001$), but when queueing time is taken in account, they experience less overall delay in parking. As expected, those using park and ride report insignificant amounts of search and queueing time.

Besides asking respondents how long they had actually searched or queued for parking, the survey also collected information about how long they were prepared to search and queue before seriously considering giving up. Across the sample the average search and queueing "budget" was 12.9 min,

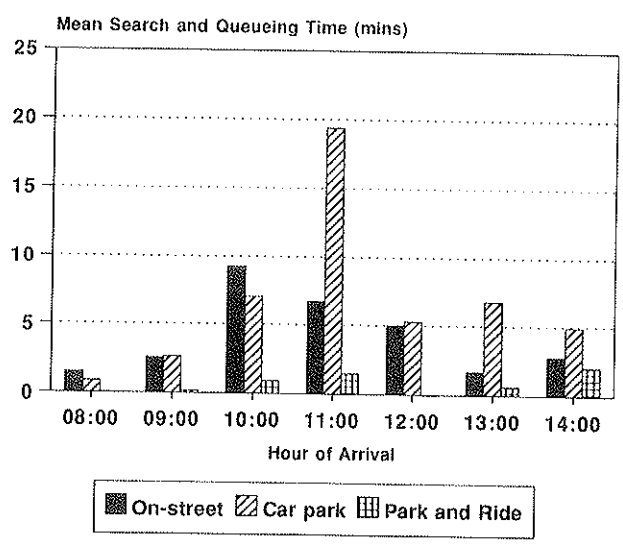

FIGURE 3 Mean search and queueing time by time of arrival.

and an analysis of variance revealed significant variations according to journey purpose ($F = 10.79, p < .01$) and type of parking chosen ($F = 40.5, p < .0001$):

Factor	*Budget (min)*
Journey purpose	
Commute	9.0
Shopping	12.8
Other	15.1
Chosen parking	
On street	18.8
Multistory lot	16.5
Park and ride	7.1

It appears therefore that drivers' tolerance of search and queueing is conditioned by the characteristics of the journey and is itself an important factor in conditioning the choice of parking. In particular, the evidence suggests that during periods of parking congestion, park and ride tends to attract those with a relatively low tolerance of search and queueing and that, conversely, most of those who choose to park in the city center during such periods are willing to spend considerable time searching and queueing for parking.

Impact of Broadcast Service on Search and Queueing Time

To determine whether drivers using the broadcast service derive any real advantage in terms of reductions in their search and queueing time, a regression model was estimated relating actual search and queueing time for the surveyed journey to a number of independent variables, including the mode of use of the broadcast service on the day of interview. Table 1 sets out the variables included in the model and summarizes the estimation results.

These results indicate that the two dominant factors influencing drivers' experienced search and queueing time are the time of arrival (acting as a proxy for overall parking demand) and whether park and ride is used. Within this context, however, those who use the broadcast service at the pretrip stage of their journeys enjoy an average reduction of almost 2.5 min in their experienced search and queueing time compared with nonusers of the service, whereas those who delay their use of the service until the en route stage enjoy no significant advantage. The results also show that those who park often in Nottingham enjoy much lower search and queueing times than those who visit less often. The magnitude of the searching and queueing budget also has a statistically significant but numerically small impact.

Structure of Parking Decision Making

Analysis of the responses to the mail-back questionnaires revealed that the vast majority of drivers decided on what type and location of parking they would use before setting out on their journey and that with few exceptions drivers succeeded

TABLE 1 Estimation Results of Regression Analysis of Influences on Parking Search and Queueing Time

Variable	Coefficient (and t-statistic)		
Search and queueing budget	0.079	(7.90)	*
Use of broadcast service on day of interview			
Did not listen	-.-		
Listened first at home	-2.462	(-2.11)	*
Listened first en-route	0.396	(0.56)	
Time of arrival			
08:00-09:00	-.-		
09:00-10:00	-0.609	(-1.20)	
10:00-11:00	1.789	(3.15)	*
11:00-12:00	5.097	(7.67)	*
12:00-13:00	1.106	(1.00)	
13:00-14:00	0.448	(0.69)	
Frequency of parking in Nottingham			
< once per month	-.-		
>= once per month	-1.257	(-3.11)	*
Type of parking chosen			
Park and Ride	-.-		
City Centre	4.039	(10.30)	*
Constant	-0.098	(-0.22)	
Diagnostics			
N	1583		
F	28.21		
df	(1573,10)		
R^2	0.152		

Note: variables marked with an asterisk are significant at the 5% level

in achieving their planned parking. Overall, only 5 percent claimed to set out with no clear idea about where to park, and only 17 percent failed to park where they originally intended. Those intending to park on the street appeared the most susceptible to diversion, with almost 17 percent ultimately using the park and ride and 6 percent parking in a multistory lot.

Although most travelers succeeded in finally parking as they intended, there is considerable variation in the strategies they used to achieve this (Table 2).

Those traveling for work and shopping purposes are least likely to engage in search, with only 11 and 13 percent, respectively, doing other than going directly to a (reasonably) certain space. By comparison, 25 percent of those traveling on personal business and other purposes searched for parking. There is only a small incidence of drivers diverting to park and ride because of parking congestion in the city center, confirming the predominance of the pretrip component of decision making.

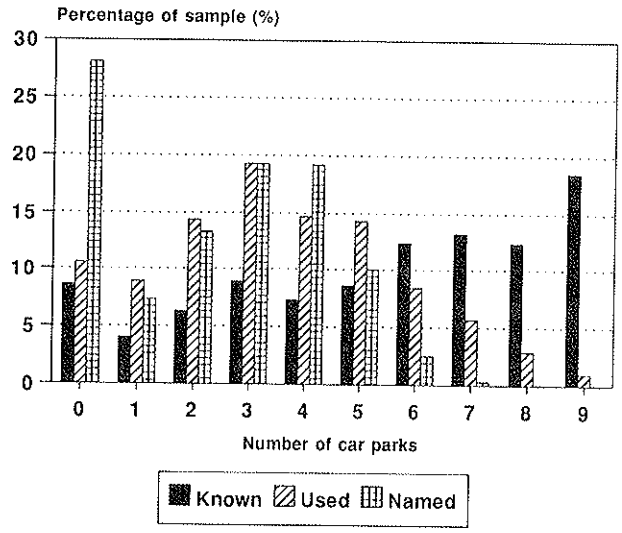

FIGURE 4 Distribution of parking experience and knowledge.

Knowledge of Parking in Nottingham

Figure 4 shows the overall distribution of knowledge and experience of parking in the city center. The distribution of drivers' perceived knowledge is highly skewed. Most drivers claim to be aware of several alternative city center parking lots: more than 70 percent claim to know four or more, and just under 20 percent claim to be aware of all nine; fewer than 10 percent admit to knowing none at all. By contrast, actual experience of the use of different parking lots is much more limited, with fewer than 33 percent of all drivers having personal experience of four or more different parking lots. Overall, the median number of parking lots claimed to be known by drivers is six, whereas the median number actually used is three.

Although these findings are by no means inconsistent (since knowledge of parking may be acquired from sources aside from personal experience), the magnitude of the divergence between claimed levels of knowledge and reported experience suggests that at least some drivers may systematically overestimate the real level of their effective knowledge of parking opportunities in the city center.

There is even greater divergence between drivers' perceived parking knowledge and their ability to correctly name different parking lots. Name-oriented knowledge shows a strongly bimodal distribution, indicating the existence of two categories of traveler. The first category, consisting of more than 28 percent of the sample, includes those unable to name any of the parking lots correctly, and although this lack of name-oriented knowledge is significantly higher among infrequent visitors ($\chi^2 = 9.9$, $p < .002$), even among those visiting the city center at least once a week, almost 25 percent do not possess any name-oriented knowledge. (The scoring of the respondents' attempts to name specific parking lots accounted for misspellings and other reasonable variants of the correct name.) Among the rest of the sample, most know the names of three or four parking lots.

There is also considerable variation in drivers' knowledge of different parking lots, with the larger, more popular ones being known, used, and correctly named by a large majority

TABLE 2 Parking Search Strategies

Search Strategy	Journey purpose (%)		
	Work (N=70)	Shop (N=99)	Other (N=146)
"I went directly to a place where I was reasonably certain I would find a space"	76	35	54
"I followed my usual route to my destination which takes me past two or three of my favourite spaces"	6	4	11
"I went directly to my destination and then drove around looking for somewhere to park nearby"	4	4	9
"As soon as I arrived in Nottingham I was on the lookout for an on-street space"	3	0	2
"When I found how difficult parking was in the city centre I went back to the Park and Ride"	0	3	3
"I went directly to the Park and Ride"	11	54	21

of travelers, whereas smaller, less popular facilities are in some cases almost completely unknown by their formal name. Thus, drivers' knowledge and experience of parking in Nottingham is not only partial and in important respects inaccurate, but it is also nonuniformly distributed over the parking stock. It is particularly significant to note that those parking lots that are most well known are precisely those that are most prone to severe congestion and that, conversely, parking lots that are less well known tend to be underused.

Effect on Travel and Parking Behavior

The table that follows shows the proportion of users of the service who have been influenced in different ways by the information provided by the service:

Dimension of Influence	*Percentage of Users Affected (N = 216)*
Parking location in the city center	45
Use of park and ride	40
Time of day of travel	22
Type of parking in the city center	19
Day of week of travel	9
Mode of travel	8

As might be expected, the broadcast service appears most effective in influencing the choice of parking type and location within the city center and diversion to park and ride. The former effect may operate either at the pretrip stage or en route; the results of the analysis of parking search behavior just presented suggest that the latter is principally a pretrip effect. Interestingly, there is also evidence that the service has influence on the timing of some journeys, reinforcing the evidence that the service has a significant pretrip impact.

To gain greater insight into the factors that predispose travelers to be influenced by the service, a binary logit choice model was developed that relates whether or not travelers were influenced by the service on the day of survey to a range of personal and journey-related factors. Several specifications of the model were explored, and Table 3 presents the estimation results for two of the most successful formulations developed.

It was decided to concentrate on only the respondents that claimed to be influenced on the day of survey (rather than the larger number that claimed to be influenced generally) so that the specific journey information collected in the survey could be used and the errors of recall and other biases could be reduced.

In both formulations a positive coefficient value indicates the increasing probability of being influenced by the service. Because of the decision to concentrate on only those travelers who were influenced on the day of travel, the estimation data set consisted of only 54 individuals; therefore the results must

TABLE 3 Logit Model of Factors Affecting Influence of Parking Information Service on Traveler Behavior

	Coefficient (and t-statistic)	
Variable	Model 1	Model 2
Gender		
female	-.- -.-	-.- -.-
male	1.055 (1.5)	1.294 (1.7)
Age		
> 45	-.- -.-	-.- -.-
<= 45	1.670 (2.0)	1.451 (1.6)
Journey purpose		
Other	-.- -.-	-.- -.-
Commute	-3.874 (-2.2)	-4.529 (-2.4)
Shopping	-1.176 (-1.2)	-1.490 (-1.4)
Frequency of parking in Nottingham		
>= once per month	-.- -.-	-.- -.-
< once per month	1.422 (1.6)	1.552 (1.6)
Number of car parks known	-0.674 (-2.4)	-0.744 (-2.4)
Number of car parks correctly named	1.318 (2.6)	1.473 (2.6)
Search behaviour		
Searched in Centre	-.- -.-	-.- -.-
Direct to City Centre CP	-.- -.-	1.274 (1.3)
Direct to Park and Ride	-.- -.-	1.674 (1.7)
Constant (No influence)	1.523 (1.2)	2.417 (1.7)
Diagnostics		
N	54	54
Rho-square	0.23	0.28
Rho-square bar	0.20	0.25

be treated with some caution. Despite this caveat several interesting observations emerged.

Both gender and age appear to have a moderate effect on the propensity to be influenced, with males and those under 45 being more likely to change their behavior than females or older age groups. Khattak et al. report similar results in the context of their study of route diversion in response to traffic incident reports (*6*). Commuters are much less likely to change their behavior than either shoppers or other travelers, possibly reflecting the relatively better overall parking conditions experienced by commuters. Those parking infrequently in Nottingham are also more likely than frequent parkers to be influenced by the service. Those prepared to search for parking within the city center (as opposed to going directly to a parking lot or the park and ride) are less susceptible to influence.

Possibly the most interesting aspect of the modeling results is evidence that they provide for the strong influence of drivers' knowledge of parking on their propensity for being influenced by the service. The results show that the propensity for being influenced by the service decreases with increasing perceived knowledge but increases with increasing levels of name-oriented knowledge. This suggests that travelers who believe that they have a good knowledge of parking in Nottingham may tend to discount the advice of the service, perhaps believing that they know better, but that those who do possess high levels of name-oriented knowledge may be better able to interpret and use the broadcast messages to avoid parking congestion.

SUMMARY AND IMPLICATIONS FOR SYSTEM DESIGN

The survey results have provided a number of important insights into the parking behavior of drivers in Nottingham and the nature of the impact of the broadcast information service.

The results confirm the existence of significant parking congestion in the center of Nottingham that, during periods of peak demand, can add upward of 15 min to normal journey times. Although severe, this congestion is spatially and temporally localized, and over the day as a whole parking conditions in Nottingham are not markedly worse than in many other European cities. Thus, the target audience for the broadcast service is a relatively small and well-defined group, distinguished principally in terms of their intended times of travel and choices of parking. This has provided the opportunity for the specific customization and targeting of the service, in terms of its content, timing, mode of delivery, and promotion.

As a consequence of the careful effort to position the broadcast service with regard to its target audience, there is a high level of awareness of the service, especially among regular radio listeners. It is significant that very few respondents reported that they had difficulties in tuning into the service; this was rarely cited as a reason for not using it. These results imply that in circumstances in which it is possible to identify a specific audience group, local radio can be an effective way to disseminate parking information.

However, although awareness of the service is high, the results of the survey suggest that its impact on parking behavior is more limited. In particular, although substantial use is made of the service by drivers en route to the city center, there is little evidence that this mode of use results in any significant impact on parking behavior or experienced search and queueing time. By contrast, the minority of drivers who use the broadcast service at the pretrip stage on average enjoy greatly reduced search and queueing time and are more likely to divert to park and ride.

The explanation for the differential impact of the broadcast service at the pretrip and en route stages is to be found in the structure of drivers' decision-making processes. The survey found that drivers' decisions about the choice of parking type and location are made predominately at the pretrip stage and that with few exceptions drivers succeed in parking in the place that they initially meant to. Once they have embarked on a journey, few drivers appear to be prepared to modify their initial parking intentions, even when informed of severe parking congestion. In particular, most of those arriving during the period of peak parking congestion and intending to use city center multistory parking lots appear to be prepared to tolerate substantial amounts of searching and queueing in order to achieve their intended parking. There is some evidence that drivers arriving during periods of peak demand become conditioned to expect and therefore are less sensitive to parking congestion. There are, however, significant variations in drivers' tolerance of search and queueing, with those drivers opting to use park and ride displaying a significantly lower tolerance of parking congestion.

Overall, it appears that to have a significant impact on parking behavior, the broadcast service must influence drivers' parking intentions before they set out on their journeys; the service cannot depend on inducing en route diversion. This finding implies that a greater orientation toward the requirements of home-based listeners, in order to encourage more use of the service at the pretrip stage, may well result in a greater impact on parking behavior. Further research would be required to identify these specific requirements.

The survey also demonstrated that drivers' knowledge and experience of parking, particularly with regard to the key aspect of parking lot names, are significant factors in conditioning their use of and response to the service. The results suggest that to be motivated to use the service in the first place, drivers must be willing to concede that the service is in principle able to offer them helpful advice and that, by implication, their own knowledge of parking may be incomplete or inadequate. But the results also show that the impact of the information provided by the service is greater among those with higher levels of name-oriented knowledge, suggesting that the interpretation of the information provided by the service is assisted by greater contextual knowledge of parking. If this is so, then the impact of the service might be enhanced by measures to improve driver familiarity with parking lot names: for example, using clearer signing at parking lots themselves or distributing parking lot maps.

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Motorist Information Needs and Changeable Message Signs for Adverse Winter Travel

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The information needs of motorists during adverse winter travel conditions were evaluated. Commuters traveling on Interstate 80 between Laramie and Cheyenne, Wyoming, and Interstate truck drivers were the primary sources of field data. During poor winter travel conditions, motorists were asked to evaluate wind, visibility, and pavement conditions and to assign a severity rating between 1 (ideal conditions) and 6 (road closed). The survey participants also indicated their desired road and travel information for changeable message signs. The results indicated that motorists have generally consistent adverse winter travel information needs. Pavement condition was the primary information desired. Visibility was the secondary needed information; however, when pavement condition was poor, visibility information became more important. The local commuters most often sought road and travel information from the winter travel advisory phone. The primary source for Interstate truckers was the citizens band radio. The changeable message sign was indicated as an important source by almost 70 percent of the local commuters and 40 percent of the Interstate truckers surveyed.

On December 11, 1990, 12 motorists were killed and 50 others seriously injured during a 99-vehicle pileup due to heavy fog on rural Interstate 75 in Tennessee. As a result, the National Transportation Safety Board heard testimony claiming that highway agencies do not do enough to warn the public about the hazards of driving in adverse weather conditions and singled out changeable message signs (CMSs) as a countermeasure for further study (*1*, p. 32).

The purposes of this study were to evaluate motorist information needs during adverse winter travel conditions and determine how to best meet information needs using CMSs. Local commuters, Interstate truck drivers, and other motorists traveling on Interstate 80 in southeast Wyoming were surveyed during the winters of 1990–1991 and 1991–1992.

The specific objectives of this research were as follows:

1. To identify information needs and consistencies within user groups for particular adverse winter travel conditions,
2. To determine the priority of winter travel information needs, and
3. To develop CMSs to be displayed for different adverse weather travel conditions.

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STUDY AREA

The area studied in this project was a 66-km (41-mi) section of Interstate 80 between Laramie, elevation 2185 m (7,165 ft), and Cheyenne, lowest elevation 1849 m (6,062 ft), in southeast Wyoming. The study area is prone to high winds, poor pavement conditions, and limited visibility during the winter. The summit, elevation 2635 m (8,640 ft), is a point 7 mi east of Laramie. The terrain is mostly flat with open plains near Cheyenne and becomes more hilly and rolling approaching the summit to the west, where the terrain turns mountainous. A steep downgrade of 5 to 7 percent occurs from the summit to Laramie. The extreme differences in elevation and terrain often cause hazardous driving conditions to occur only on isolated sections. Motorists' desired information in terms of worst condition or overall condition and consistency of the information requested was of interest in this project.

The CMSs evaluated are drum-type signs with three lines of copy; they are located on the outskirts of Laramie and Cheyenne. Each drum or line has six possible messages with a capacity of 24 characters. The last line consists of two six-sided drums set end to end that have the capacity to hold an 18- and a 6-character message, respectively. Each drum can be rotated separately to display the appropriate message.

The individuals surveyed were asked to evaluate the road and travel conditions within the study area during poor winter conditions and give indications as to what road and travel information would help them make travel decisions. To aid in surveying the motorist, road and travel conditions were classified as discussed in the following section.

CLASSIFICATION AND ANALYSIS METHODOLOGY

Different levels of time, wind, visibility, and pavement were chosen to describe the road and travel conditions (see Table 1). A dependent variable reflected the severity rating of the road and travel conditions. For this dependent variable, a linear rating scale was established, where 1 was an ideal driving condition and 6 was a condition in which the motorist believed that the road should be closed. The road users were asked to rate the severity of the road and travel conditions on the rating scale and then identify the level of each independent variable that best described the road and travel conditions encountered. Severity rating was then modeled as a

TABLE 1 Road and Travel Conditions

Time	Wind	Visibility	Pavement	
day	calm, breezy	clear	dry	snowpacked
night	strong, gusty	limited	wet	slick/spots
		very limited	slushy	icy

function of time, wind, visibility, and pavement and their interactions.

For each trip made during adverse travel conditions, the motorists were also asked to list their desired winter travel information needs with respect to the CMS. Other data were gathered to profile the population characteristics, vehicle type, and information sources being used to determine road and travel conditions.

DATA COLLECTION PROCEDURE

Field data were collected using travel diaries and interview forms. The travel diary respondents were commuters between Laramie and Cheyenne. A total of 235 diaries were sent to volunteers during spring 1991, and an additional 270 diaries were sent out during fall 1991. A citizens band (CB) radio interview process was used to reach noncommuters. A total of 337 interviews were conducted, consisting primarily of Interstate truckers.

Three supplemental surveys were sent to diary users during the course of the study. The first survey was designed to identify the messages of primary benefit to the motorist. The second survey evaluated the use of a six-point road rating system considering both the degree of adversity and length of condition. The final survey evaluated combinations of three-line messages for different adverse winter travel conditions.

STUDY RESULTS

For analysis purposes, the field population was separated into consistent groups by vehicle type and origin using vehicle license plates. Two analysis groups were defined as follows:

- Locals: passenger vehicles with local Wyoming license plates (County 2 or 5 and noncommercial diary users), and
- Trucks: all commercial freight vehicles.

The local drivers primarily used at-home information sources (phone, 80 percent; radio, 61 percent; and TV, 50 percent) to receive road and travel information (see Table 2). CMSs were identified as an information source by 69 percent of the local drivers. Despite receiving information about adverse travel conditions, 63 percent of the local drivers indicated that they would travel if the road were open, regardless of the conditions. This indicates that local drivers are using the information sources not to decide whether to travel but as a gauge of the severity of the conditions expected when traveling or as a guideline for route selection.

TABLE 2 Information Sources Used by Local and Truck Groups

	Percent	
Source of Information	Locals	Trucks
Road and travel phone	80	23
CMS	69	40
Radio	61	63
Television	50	21
CB Radio / Other drivers	24	72
Others	< 30	< 40

The truck drivers indicated that they receive their road and travel information primarily from the CB radio. Through communication with other drivers using the CB radio network, truck drivers are able to gather information at various points along their routes. This system and the regular broadcast radio account for most of their information sources. Forty percent of the truck drivers also indicated their use of the CMS as a source of road and travel information.

Information desired by the motorist revealed consistencies in the type of information needed for particular adverse travel conditions. Related key words were consistently requested on particular dates investigated during poor winter conditions. Descriptions of the wind conditions were consistent throughout the dates investigated, with requests for wind warnings ("Strong/high wind") and wind speeds ("Wind gusts to *xx* mph"). Specific words used consistently for describing visibility conditions were "snowfall," "fog," and "blowing snow." The message reduced visibility was recommended for mixed visibility conditions. For pavement conditions, consistent requests were made for terms such as "icy," "slick in spots," and "snowpacked." The key words "icy" and "snowpacked" often occurred together to describe the same condition, but "icy" was used more often.

The local drivers indicated that pavement conditions are the principal influence on the perception of the severity of adverse travel conditions. Visibility conditions were found to be the secondary influence. The results of the supplemental surveys established a set of messages designed for the CMSs in the study area (Table 3). On the basis of the road users' desired information priority, the first line of the CMS was reserved for pavement information. The second line was reserved for visibility and wind information. The message "Reduced visibility" was added to identify conditions not described by "Heavy fog ahead" and "Blowing snow." The road rating information on the third line was derived from the adjectives obtained in the second supplemental survey. The appropriate road rating selection may be determined by using the Severity Rating condition matrix (see Table 4), where 3 = poor, 4 = very poor, and 5 = severe. The condition matrix in Table 4 summarizes the severity ratings derived from a regression model containing the independent variables of wind, visibility, and pavement. The message "Advise no light trailers" was intended to be displayed with a strong wind warning and was therefore listed on the first line. Messages that were not specific to weather advisory were included in the displays.

TABLE 3 Candidate CMS Messages

Drum Number	Position	Message
1	0	Blank
	1	Icy Road Ahead
	2	Slippery in Spots
	3	Drifting Snow
	4	Advise No Light Trailers
	5	I-80 Closed
2	0	Blank
	1	Reduced Visibility
	2	Blowing Snow
	3	Heavy Fog Ahead
	4	Wind Gusts To
	5	Fasten Seatbelts
3	0	Blank
	1	40 KPH[a]
	2	56 KPH
	3	64 KPH
	4	72 KPH
	5	86 KPH
4	0	Blank
	1	Conditions: Poor
	2	Conditions: Very Poor
	3	Conditions: Severe
	4	Chain Law in Effect
	5	Return to Laramie or Return to Cheyenne

[a] 1 km = 0.62 mi

The message "Return to Cheyenne" or "Return to Laramie" was intended to be displayed with the "I-80 closed" message and was placed on the third line of the display. The message "Chain law in effect" was also included on the third line to be displayed when chains were required for travel on the Interstate.

Respondents indicated that if a combination of snow and fog was present, then the message "Reduced visibility" is more appropriate than "Heavy fog ahead." When respondents were presented with a combination of heavy snowfall and blowing and drifting snow, the message "Blowing snow ahead" was preferred 2 to 1 over "Reduced visibility." When slushy road conditions occurred, 85 percent requested "slippery in spots" to describe this condition.

CONCLUSIONS

The specific conclusions from the major findings are

1. The CMS is an important source of adverse winter travel information for rural Interstate motorists.
2. Pavement condition was the primary factor affecting the perception of the severity of adverse travel conditions for both local commuters and truck drivers. Visibility conditions were secondary and of greater importance as pavement condition became more adverse.
3. A three-point rating scale will meet motorist winter travel information needs when adverse conditions exist: poor, very poor, and severe.

TABLE 4 Severity Rating Matrix

Wind	Pavement	Visibility		
		Clear (0)	Limited (1)	Very Limited (2)
Calm (0)	Dry/Wet (0)	2[c]	2	4
	Slick in Spots/Slushy (1)	3	3	4
	Snowpacked/Icy (2)	4	4	4
Strong(1)	Dry/Wet (0)	2	3	4
	Slick in Spots/Slushy (1)	3	3	4
	Snowpacked/Icy (2)	4	4	5

[b] $RATING = 1.7 + 0.9P + 0.6V + 0.2V^2 + 0.2W - 0.3\,(V*P)$; $R^2 = 0.565$

[c] 2 = Good, 3 = Poor, 4 = Very Poor, 5 = Severe

4. Local motorist ratings of adverse conditions reflected the length of condition. As the length of adverse conditions decreased, condition adjectives requested decreased from severe to very poor to poor.
5. Local commuters primarily obtained adverse road and travel information from at-home sources.
6. Interstate truck drivers primarily used the CB radio for adverse road and travel information and supplemented this by using broadcast radio and CMS information.
7. Local commuters desired to travel regardless of road and travel conditions.

RECOMMENDATIONS

The majority of local user information concerning adverse winter travel conditions was received primarily through the road and travel phone number, the radio, and the television. These at-home sources have the potential to give highly detailed road and travel information that may deter the motorist from traveling in adverse winter conditions. If more reliable winter travel information could be provided to the motorist through these media, then perhaps fewer motorists would risk traveling and consequently lessen the chance of an adverse weather-related accident.

The CB radio network was the primary source used by the truck drivers. Investigation of a similar noninteractive system for passenger vehicles on a linear radio network would be of benefit. Monitoring CB radio for gathering road and travel information at various locations along a section of highway has potential. Assessing the reliability and accuracy of this information, as well as its applicability to other information sources, is recommended for further study.

Although local motorists prefer to receive road and travel information from at-home sources and truck drivers prefer information from CB radios, the CMS has the potential to be a very effective means of communication to the driver. Further efforts should be made to evaluate the effect of weather advisory CMSs on the reduction of weather-related accidents and the ability of a weather advisory CMS to invoke a positive response to adverse travel conditions from a driver who is unfamiliar with the surrounding area.

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Motorist Interpretation of MUTCD Freeway Lane Control Signals

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The results of a human factors laboratory study designed to investigate current motorist interpretations of lane control signals in a freeway driving environment are presented. Subjects were recruited to view a drawing of a freeway scene that included a sign structure supporting lane control signals over each lane. The type of symbols displayed over the lanes were then varied. Subjects were asked what they believed each signal indicated about the condition of the lane under the signal and what the correct driving response would be to that signal. The results of the study showed that most subjects interpreted the green arrow as indicating that a lane was open and that they would proceed in that lane as normal. The red X was most commonly interpreted as indicating that the lane was closed and that drivers should exit that lane. However, interpretations of the yellow X, defined in the *Manual of Uniform Traffic Control Devices* as a transition signal between the green arrow and the red X, were not as consistent. More important, the interpretation of this symbol was shown to be dependent on what other symbols were present in the overall display configuration at a given point on the freeway.

According to the *Manual of Uniform Traffic Control Devices* (MUTCD), "lane-use control signals (LCS) are special overhead signals having indications used to permit or prohibit the use of special lanes of a street or highway or to indicate the impending prohibition of use" (*1*). The MUTCD allows the use of four LCS displays:

- A downward green arrow, to indicate that the lane is open and that a driver is permitted to drive in the lane over which the arrow is located;
- A steady yellow X, to indicate that a driver should prepare to vacate the lane because a signal change is being made to a red X (similar to the use of yellow indications at intersection traffic signals);
- A flashing yellow X, to indicate that a driver is permitted to use the lane over which the signal is located for a left turn (applicable to arterial streets only); and
- A red X, to indicate that the lane over which it is displayed is closed to that direction of traffic and that a driver shall not drive in that lane.

In the United States, LCSs are most commonly used for controlling reversible lane operations on arterial streets, bridges, and tunnels. However, the MUTCD does allow LCSs on freeways when it is desired to keep traffic out of certain lanes at certain hours, to indicate that a lane ends at the terminus of a freeway, and to indicate that a lane is temporarily blocked by an accident, stalled vehicle, or the like.

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Motorists traveling on freeways may also see LCSs used for purposes other than the active management of the main travel lanes. In Houston, Texas, for example, freeway drivers see LCSs installed over the high-occupancy vehicle reversible transitways in the median of the freeways to indicate the proper direction of traffic flow and on toll facilities at toll plazas to indicate which booths are open to traffic, which are closed, which give receipts or require exact change, and so forth.

Concern over the actual motorist interpretations of, and response to, currently accepted LCSs in a freeway driving environment prompted the Texas Department of Transportation (TxDOT) to sponsor research on freeway LCSs in order to develop improved design, installation, and operations guidelines for their use. This paper presents the results of an evaluation of current motorist interpretations of existing LCS symbols in a freeway driving environment.

BACKGROUND

Previous human factors research on motorist comprehension of LCSs has been limited. One study was performed by Forbes et al. more than 30 years ago (*2*). Various LCS symbols were tested to indicate a need to exit a given lane or to indicate that a given lane could be used for travel. On the basis of the results of their studies, the researchers concluded that a red X was most often associated with the desired interpretation (to exit a lane) and least often associated with an undesirable interpretation (to stop in the lane). Meanwhile, a green upward arrow was correctly interpreted as indicating that a lane was available for travel by almost all subjects. However, the results also suggested that the experimental method used affected the relative distribution of what were defined as desired and undesired interpretations. Specifically, an open response format (where motorists are not given predefined choices to choose from) resulted in more undesired interpretations of the red X.

The researchers also evaluated subject interpretations of a yellow X. Overall, they found subject interpretations of the symbol to be somewhat ambiguous. Subjects interpretations ranged from "do not drive in the lane" to "warning (take caution) in lane" to "drive slow in lane."

In the 1970s Dudek et al. conducted human factors research for the design of real-time motorist information systems (*3*). One topic of research was the potential use of arrows and X's on a trailer-mounted roadside sign to indicate which freeway lanes were closed or blocked and which ones were open. They found that the color of X's and arrows displayed on a sign

board did not affect motorist comprehension of which lanes were supposedly closed on the freeway. However, comprehension was improved dramatically if the title "Lane Condition" or "Lane Blocked" was at the top of the sign. However, it must be remembered that this research was limited to roadside sign designs. Placing the LCS directly over each travel lane visually anchors the signals to the lanes, providing an interpretation cue that is not inherently present in roadside signs.

Recently, Lavellee et al. performed limited research of lane control signal comprehension with Canadian motorists (*4*). In general, the results of that research were similar to those of Forbes et al. with respect to the red X and green arrow. Unfortunately, they did not examine comprehension of a yellow X.

As can be seen, the data base regarding motorist interpretation of LCSs is limited. Data are needed on the current motorist understanding of LCS displays in a freeway driving environment. Furthermore, one of the more important issues regarding freeway LCSs that has not yet been evaluated is the degree to which interpretations of individual symbols are dependent on what other symbols are displayed at a location. In actual freeway applications, motorists are exposed to an entire LCS display configuration, from which they must assess the condition of the lanes and decide the appropriate actions to take. Hence, it is possible that a LCS symbol may be interpreted very differently if the overall display configurations are dramatically different.

STUDY METHOD

Objectives and Method

Two objectives were identified for this study:

1. Determine current motorist interpretations of the standard MUTCD LCS displays in a simulated freeway driving scene, and
2. Determine whether interpretations of the various LCS symbols are dependent on the other LCS symbols displayed in an overall freeway LCS configuration.

To address these objectives, a laboratory experiment was constructed to evaluate motorist interpretations of LCSs. Motorists were shown color drawings of a hypothetical freeway scene that included a sign structure with freeway LCSs attached over each of four travel lanes. In each drawing, some combination of red X's, yellow X's, and green arrows was shown in the LCS signal heads over each lane. A subject was asked to view one of the drawings and imagine themselves driving in a specific travel lane. Subjects were then asked what the symbol meant about the condition of the lane and what would be the proper action for a driver in that lane. Subjects were then asked to consider themselves in a different driving lane (one with a different LCS symbol overhead) and again assess the lane condition and proper action. This was repeated until the subjects had evaluated all the symbols in that display configuration (i.e., freeway drawing).

Subject responses to these questions were recorded as stated (i.e., an open response format) for subsequent categorization and analysis. The survey took approximately 5 min to perform. Subjects were recruited from licensed drivers attending an automobile show at the Astrodome complex in Houston. The study was performed over 10 days in January 1992.

Survey Stimuli

Figures 1 through 5 illustrate the visual stimuli presented to motorists. In each scene, the identical four-lane freeway section was displayed. Lanes were numbered 1 through 4 beginning with the median lane. Five LCS configurations were created, in which the symbols presented and the lanes over which the symbols were positioned were varied. The illustrations presented in this paper were modified to black-and-white copy for reproduction purposes. The actual drawings viewed by motorists were in color.

Figure 1 illustrates Display Configuration A. In this scene, all three symbols were presented to the subjects. A red X was displayed over Lane 1, yellow X's were displayed over Lanes 2 and 3, and a green arrow was displayed over Lane 4. This might indicate a situation in which the median lane has already been closed and an incident in the two middle lanes requires that they be closed a short distance downstream.

Only two symbols were used to create Display Configuration B (Figure 2). Yellow X's were placed over Lanes 1 and 2 and green arrows over Lanes 3 and 4. In comparison, Display Configuration C is shown in Figure 3. Again, only two symbols were presented: red X's over Lanes 1 and 2 and yellow X's over Lanes 3 and 4. This latter scene would indicate a situation in which two lanes are already closed and an incident in the right two lanes is forcing the transportation agency to close the freeway entirely.

Figure 4 presents Display Configuration D, consisting of red X's over Lanes 1 and 2, a yellow X over Lane 3, and a green arrow over Lane 4. Note that this scene is similar to the first scene (Figure 1) in that all three symbols are visible in the same display configuration. Finally, Display Configuration E is shown in Figure 5. In this display, a red X is presented over Lane 1, and green arrows are placed over the three remaining lanes.

Experimental Plan

Each subject recruited was allowed to view and respond to only one particular LCS configuration. In this way, an elaborate experimental design to counterbalance learning effects was not required. As stated earlier, motorists were asked to envision themselves driving in each lane where a different LCS symbol was displayed. In Figure 1, for example, subjects were asked to first envision themselves driving in Lane 1 to evaluate the red X, then in Lane 2 to evaluate the yellow X, and then in Lane 4 to evaluate the green arrow. However, subjects viewing Figure 2 were asked to envision themselves first in Lane 1 to evaluate the yellow X and then in Lane 3 to evaluate the green arrow.

The experiment was designed to evaluate each LCS symbol in conjunction with one or both of the other symbols present in the configuration—that is, the yellow X was evaluated in

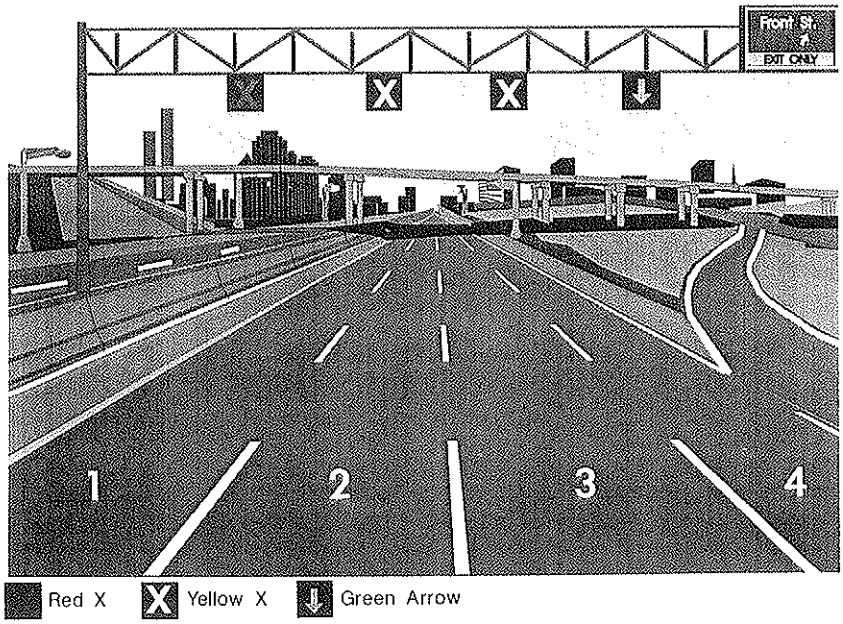

FIGURE 1 Display Configuration A.

one configuration with only green arrows present, in another with only red X's present, and in another with both green arrows and red X's present. The green arrow and red X were likewise examined. To summarize, Table 1 documents the overall experimental design of the study, indicating which symbols were present in which display configuration. As the table indicates, each symbol was included in four of the five configurations. Configurations A and D contain all three symbols, whereas the other configurations contain a combination of two symbols.

It should be noted that the longitudinal dimension of a freeway LCS system was not simulated in this experiment. Motorists traveling on a freeway outfitted with LCSs are likely to pass several LCS display configurations as they approach a lane blockage, and the upstream configurations already encountered would probably also have some influence on motorist interpretations of the symbols in the configuration being viewed. However, the data from this experiment are useful in assessing the effect of an entire display configuration on the interpretations of individual symbols. And situations may

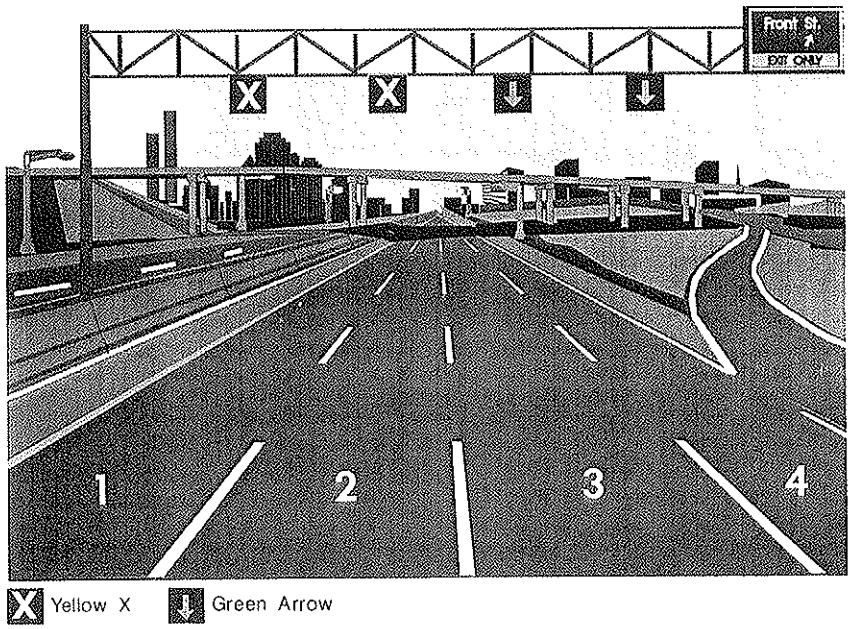

FIGURE 2 Display Configuration B.

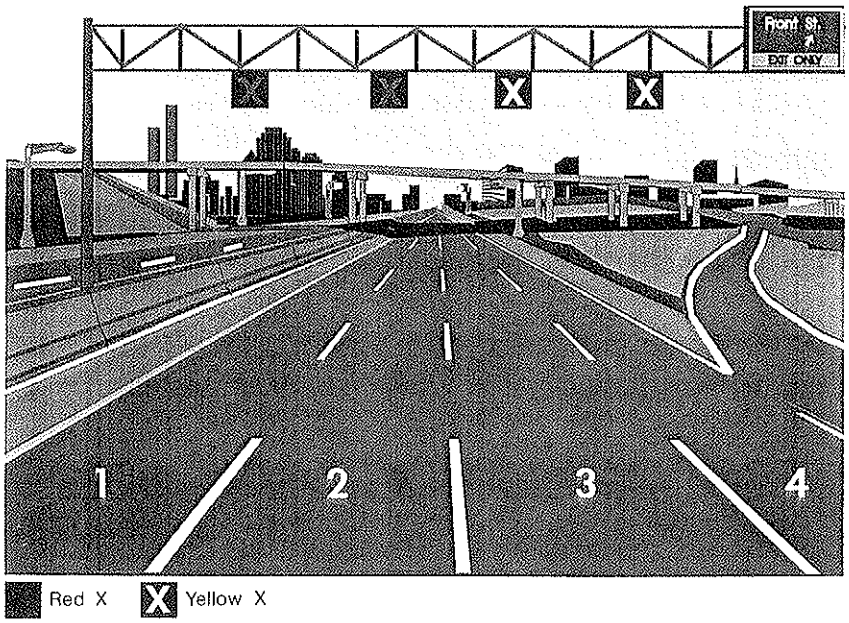

FIGURE 3 Display Configuration C.

arise in which such configurations could be encountered by motorists who had not encountered upstream LCS displays (if an incident occurred at the beginning of a freeway section equipped with LCSs, for example, or if a motorist entered the freeway immediately upstream of a lane blockage and sees only one set of LCSs before reaching the blockage).

Data Reduction

Table 2 summarizes the basic demographic distribution of subjects recruited during this study. Each display configuration was viewed by 73 to 75 subjects, for a total of 371 responses. Overall, the study group was overrepresented by

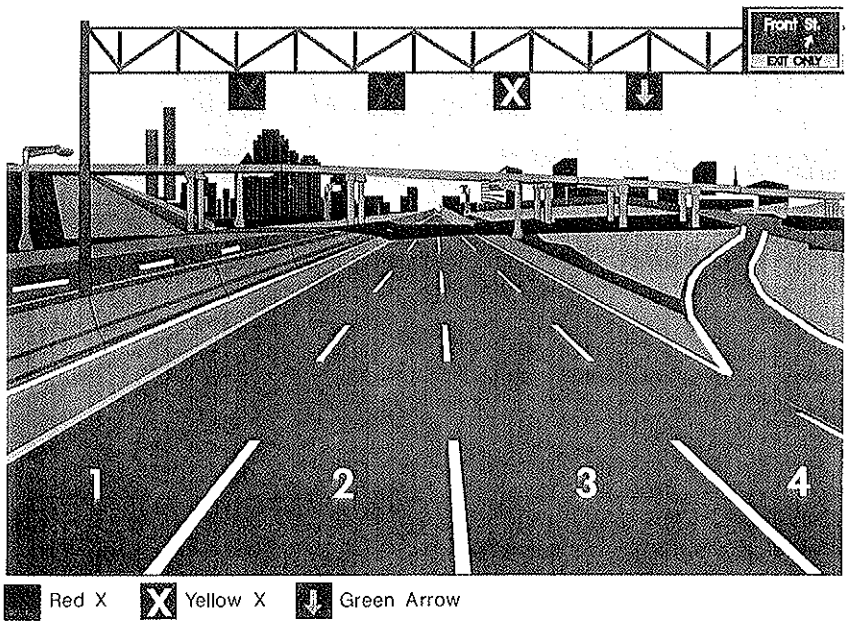

FIGURE 4 Display Configuration D.

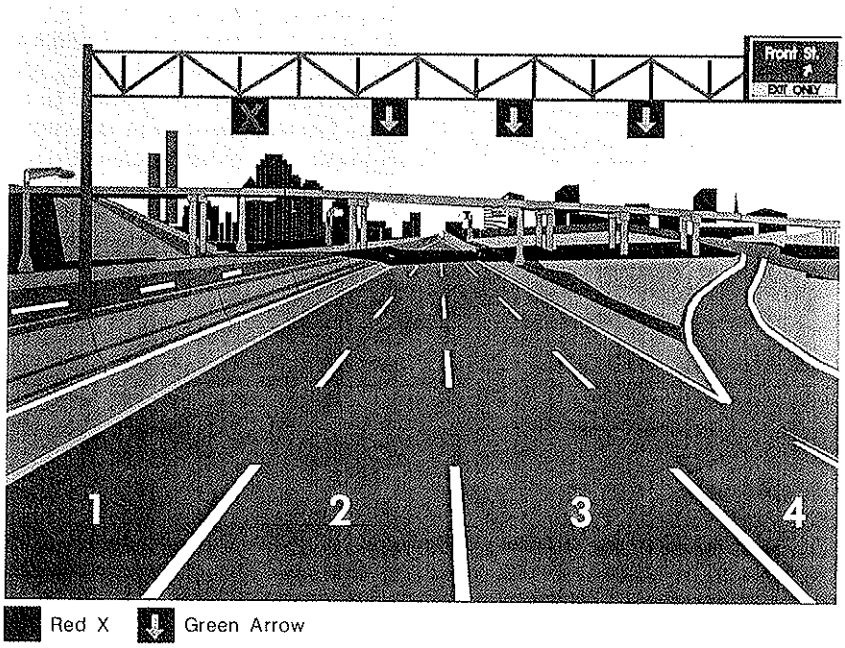

FIGURE 5 Display Configuration E.

men (73 percent men versus 27 percent women) and by the younger age categories (more drivers younger than 25 and fewer drivers older than 55) when compared with national driver licensing statistics (*5*,p.2). This was expected, given the type of event that the subjects were attending (an automobile show), and suggests that survey subjects may not have had as much previous driving experience on which to base their interpretations as would have been desired in this study. However, the major emphasis was on keeping the demographic distributions as consistent as possible from configuration to configuration (which was done successfully by survey administrators).

RESULTS

Interpretation of Downward Green Arrow

Previous research has shown the green arrow to have an implicit meaning among most motorists that the lane under a green arrow is open and that it is allowable to drive in that lane. Data from this study support that contention. Table 3 gives the percentage of subjects viewing each display configuration who believed that the green arrow meant that the corresponding lane was open. Overall, the percentage of subjects responding to the green arrow in this manner was very high, exceeding 85 percent for all display configurations. Averaging all configurations, it was found that 91 percent of the subjects believed the lane to be open.

Slight differences were detected, however, in responses to the green arrow from configuration to configuration. The responses to Configurations A and D were slightly more consistent with each other, as were those to Configurations B and E. Subjects viewing Configurations B and E were asked to envision themselves in Lane 3 when answering questions about the green arrows. Conversely, subjects viewing Configurations A and D envisioned themselves in Lane 4 (the only lane under a green arrow in those figures). A small number of subjects viewing Configurations A and D perceived the green arrow to mean that the lane was for exiting traffic, possibly confusing the LCS indication with a lane drop or exit sign indication.

When subjects were asked what they would do if driving in the lane over which a green arrow was displayed, most indicated that they would remain in that lane and proceed as normal. The configuration-by-configuration percentages of this

TABLE 1 Experimental Design

	Display Configuration				
Symbol	A	B	C	D	E
Green Arrow	*	*		*	*
Yellow X	*	*	*	*	
Red X	*		*	*	*

* denotes symbol was present in that particular display configuration

TABLE 2 Comparison of National and Study Driver Demographics

	Percent of Drivers	
Age	National Statistics (5)	Study Statistics
less than 25	17	34
25 to 39	35	38
40 to 54	23	23
greater than 55	25	7
Gender		
Males	52	73
Females	48	27

response are also presented in Table 3. Again, though, the percentage of "proceed normal" responses for Configurations A and D were slightly lower than for Configurations B and E. A few subjects viewing Configurations A and D stated that they would slow down and be watchful of downstream hazards and merging traffic, whereas none of the subjects viewing Configurations B and E responded this way.

Interpretation of Red X

Table 4 presents the three most common interpretations of the meaning of the red X with respect to the condition of the lane over which it is positioned. Most subjects perceived the red X to mean that the lane is closed or blocked. A small proportion (less than 5 percent) believed that the red X indicated that there was oncoming traffic in that lane. There was a small proportion (also less than 5 percent) who had no idea what the red X meant (none of the subjects were confused by the green arrow). In general, the responses were consistent from configuration to configuration (no statistically significant differences were found based on a χ^2-test of independence between response categories and display configuration), and the responses were similar to those obtained in past studies of LCSs.

Summaries of subject interpretations as to the proper action for a driver in a lane under a red X are also given in Table 4. Most subjects stated that they would exit that lane (on average, 81 percent responded this way), but a few indicated that they would stop in the lane. Whether these few subjects were thinking that there would be traffic stopped in front of them that would require them to stop also was not ascertained. However, the initial reaction of these individuals would not be to exit (or attempt to exit) the travel lane over which a red X was displayed (at least in the absence of other visual cues such as traffic in front of them exiting the lane). The responses were also found to be very consistent from configuration to configuration, indicating that the interpretation of the red X was not dependent on what other symbols were present in the overall LCS display configuration.

Interpretation of Yellow X

Table 5 gives subject responses for each of the display configurations regarding the meaning of the yellow X with respect to the condition of the lane. Unlike responses to the green arrow and red X, responses to the yellow X differed dramatically depending on the display configuration viewed by the subject. As can be seen, most subjects (between 67 and 76 percent) viewing Configurations A, C, and D perceived the yellow X to mean that there were dangerous conditions ahead in the travel lane. Meanwhile, a few subjects believed that the indication meant that the lane was closed ahead or about to be closed. However, these trends were reversed for Configuration B. Only 21 percent of the subjects viewing Configuration B perceived the yellow X as indicative of dangerous conditions in the lane, whereas 45 percent believed that the yellow X meant that the lane was closed ahead or about to be closed.

The yellow X also caused more confusion for the subjects than either the red X or green arrow. About twice as many subjects had no idea what the yellow X meant as those who did not understand the red X (8 percent versus 4 percent, respectively), further suggesting interpretation problems with that indication. Overall, a χ^2-test of independence between lane condition responses for the yellow X and display configuration was found to be statistically significant at a 5 percent level ($\chi^2 = 49.8$, $\chi^2_{critical} = 16.9$). Also, given the intended meaning of the yellow X to indicate an upcoming closure of

TABLE 3 Subject Interpretations of Green Arrow

	Percent of Subjects Responding				
	Configuration				
Interpretation of Lane Condition	A	B	D	E	Ave
"Lane is open"	85	93	87	97	91
"Lane is for exiting"	7	-	7	-	3
Other	8	7	6	3	6
Interpretation of Proper Driving Action					
"Stay in lane/proceed as normal"	87	90	87	99	92
"Slow down and be watchful"	5	4	3	1	3
Other	8	6	10	-	5

- responses total less than 1 percent

TABLE 4 Subject Interpretations of Red X

	Percent of Subjects Responding				
	Configuration				
Interpretation of Lane Condition	A	C	D	E	Ave
"Lane is closed"	81	84	80	81	81
"Lane is for oncoming traffic"	4	7	6	3	5
"I don't know"	4	1	4	4	3
Other	11	8	10	12	11
Interpretation of Proper Driving Action					
"Exit the lane"	77	79	80	89	81
"Exit the freeway"	7	3	5	7	5
"Stop in lane"	12	10	8	3	8
Other	4	8	7	1	6

a travel lane as defined in the MUTCD, it is apparent that most motorists do not inherently associate the signal with an impending lane closure under most of the display configurations tested in this study.

Table 5 presents the most common responses given by subjects as to the proper action when the yellow X is displayed over a travel lane. Again, substantial differences were apparent between configurations and verified through statistical testing ($\chi^2 = 93.7$, $\chi^2_{critical} = 16.9$). For Configurations A and D, subjects as a group were split between those who interpreted the yellow X as requiring them to exit the lane and those who interpreted it to mean that they should stay in the lane but proceed cautiously at a slower speed. For Configuration B, most subjects (72 percent) indicated that the proper action would be to exit the lane, with only 15 percent stating that they should stay in the lane but proceed cautiously. For Configuration C, very few subjects indicated that they should change lanes, whereas 70 percent stated they would proceed in that lane slowly and cautiously.

The responses obtained for Configuration C are not unexpected, given that the display contained only red and yellow X's. This display did not present any clear alternatives to subjects of other lanes that they could move to, so apparently they assumed that the lanes under the yellow X's were preferable to those under the red X's. This explanation of subject responses is further supported by the fact that a significant proportion of the subjects (15 percent) who viewed Configuration C indicated that the proper response would be to proceed normally in the lane under a yellow X. It should be noted that a few subjects (7 percent) did indicate that they would exit the freeway if the yellow X in Configuration C was encountered. Very few subjects viewing the other configurations gave this response.

Finally, it is interesting to note the similarity of responses of the proper actions to the yellow X in Configuration B and the red X in the other configurations. Configuration B contains only yellow X's and green arrows. When presented with this display, most (72 percent) of the subjects believed that the correct action from that lane would be to exit that lane. This percentage is only slightly less than those for the same response to a red X. In the absence of a red X, subjects appear to focus on the type of symbol being displayed (an X) and assume that the proper response would be to exit that lane. Apparently, if a red X is not present in the display, subject interpretations of a yellow X are more consistent with those intended by the MUTCD.

TABLE 5 Subject Interpretations of Yellow X

	Percent of Subjects Responding				
	Configuration				
Interpretation of Lane Condition	A	B	C	D	Ave
"Hazard or danger in lane"	76	21	67	68	58
"Lane is closed or will be closing"	5	45	3	11	16
"I don't know"	11	9	6	6	8
Other	8	25	24	15	18
Interpretation of Proper Driving Action					
"Exit the lane"	35	72	1	57	41
"Exit the freeway"	-	-	7	1	2
"Slow down/proceed cautiously in lane"	45	15	70	35	41
"Stay in lane/proceed normally"	7	3	15	4	7
Other	13	10	7	3	9

- responses total less than 1 percent

SUMMARY

This study has explored the current interpretations of LCSs in a freeway driving situation. In general, the results are similar to those of past studies. The study does suggest, however, that motorist interpretations of the various LCS symbols currently in the MUTCD depend to some degree on the other symbols present in an overall LCS display. This dependency is most noticeable for the yellow X. When displayed with green arrows only, this symbol is most likely to be interpreted as indicating a lane blockage or closure ahead and requiring an exit maneuver out of the lane over which the yellow X is displayed. This interpretation is most consistent with that intended by the MUTCD. However, when displayed with a red X, subjects are more likely to interpret the yellow X as a cautionary symbol and not to associate its display over a lane as indicating a need to exit that lane.

Whether these differences in interpretation result in different behavior by motorists when encountering these symbols on actual freeway sections has yet to be determined. Nevertheless, this research serves as an important starting point to illustrate the complexity of operating freeway LCSs in real time and the need to consider operating strategies from the perspective of the freeway motorist who must try and understand what message is trying to be conveyed.

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Reflector Posts—Signs of Danger?

VELI-PEKKA KALLBERG

Reflector posts are meant to increase optical guidance and help drivers see the road alignment ahead so that they can prepare for the driving task to come. It is often assumed that the additional visual cues provided by reflector posts also promote traffic safety. An experimental study on the effects of reflector posts was carried out on two-lane rural highways in Finland. On roads with 80-km/hr speed limits and relatively low geometric standards, the reflector posts increased driving speeds in darkness. The largest detected increases were 5 to 10 km/hr. The number of injury accidents in darkness increased by 40 to 60 percent. On roads with better geometric standards and 100-km/hr speed limits, the effects on driving behavior and accidents were small. The results indicate that reflector posts on narrow, curvy, and hilly roads can significantly increase driving speeds and accidents in darkness.

Roadside reflector posts are meant to help drivers predict the road alignment ahead and thus prepare for the driving task in advance. They can also affect the lateral position of vehicles on the roadway. They are expected to change driving behavior and increase driving comfort, especially in darkness and in bad weather. These changes often lead to changes in safety.

The risk of having an accident is considerably higher risk in nighttime driving than in daytime driving. There are several reasons for this, including fatigue and alcohol consumption. One of the main reasons is probably visual degradation. Physiological and behavioral research have studied this phenomenon. The results show that visual functions work in two modes—focal and ambient—and that decreasing illumination affects these modes very differently. The focal mode is concerned with object discrimination and identification, or the question "what?" The ambient mode is concerned with spatial orientation, or the question "where?" (*1*). Reducing illumination rapidly degrades focal vision but has much smaller effects on ambient vision. Drivers are not normally aware of these selective visual losses in nighttime, because performance in routine driving tasks is not affected: guidance (or ambient) vision still works relatively well. But focal vision and the ability to recognize low-contrast objects are seriously degraded (*2*). This leads to a situation in nighttime driving in which driving behavior is much the same as in daytime but the driver's ability to detect potential hazards is seriously impaired. The consequences on traffic accidents are obvious.

What could be predicted about the effects of reflector posts on nighttime driving behavior and accidents in the presence of this theory about selective visual degradation? The posts are meant to assist orientation, which is based on ambient vision that functions relatively well even in poor illumination. If reflector posts help drivers in orientation tasks, they have the potential to prevent single-vehicle, run-off-the-road accidents. Reflector posts do not, however, improve a driver's ability to recognize potential hazards, which is relevant to pedestrian accidents and accidents involving moose or deer, for instance. A driver's success in braking and steering maneuvers to avoid an accident after detecting the hazard is strongly speed-dependent. Braking distance, for instance, is proportional to the square of speed. If reflector posts change driving speeds, they can be expected to affect all kinds of accidents.

It was hypothesized in the study that if reflector posts affect traffic accidents, the effect is due to changes in driving behavior. The study was designed to discover the influence of reflector posts on driving behavior and on accidents. Driving speed and the lateral position of vehicles were used as measures of behavior. Accident analysis was based on standard police accident reports.

METHODS

Study Design and Selection of Sites

A before and after study with control roads was designed. Twenty pairs of road sections similar to one another were selected from the trunk road network in Finland. [Similarity here means the same speed limit and close resemblance in respect to road width, curvature, hilliness, and annual average daily traffic volume (AADT).] From each pair, one road was randomly assigned as the experimental road; the other was the control road. On each experimental road reflector posts were installed at 60-m intervals 0.5 m from the edge of the pavement in fall 1987. The reflectors in the posts were about 1 m above the level of pavement, and the configuration of reflectors was different on different sides of the road (Figure 1). Control roads remained unchanged. The total length of roads in the experimental group was 548 km and in the control group 586 km. The length of individual sections varied from 7 to 56 km, and roads in each pair were typically about the same length.

The roads were categorized into two groups: those with a speed limit of 80 km/hr and those with a speed limit of 100 km/hr. This was done so that the effects on different kinds of roads could be found, and speed limit strongly correlates with other features of the road. The 100-km/hr roads have much higher standards (fewer hills and curves, longer sight distances, wider pavement) than 80-km/hr roads. On seven road pairs, the speed limit was 80 km/hr, and on 13 road pairs it was 100 km/hr. A short description of the roads is given in Table 1.

In the after period about a quarter of the roads in the 100-km/hr group had their speed limit lowered to 80-km/hr for

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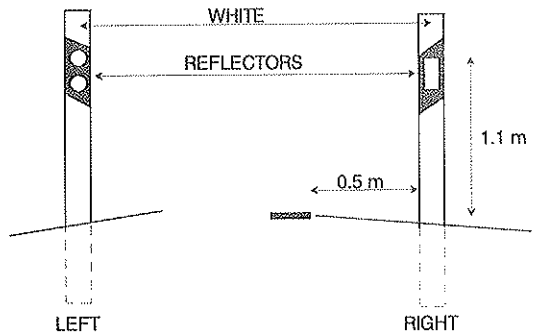

FIGURE 1 Dimensions and lateral position of reflector posts.

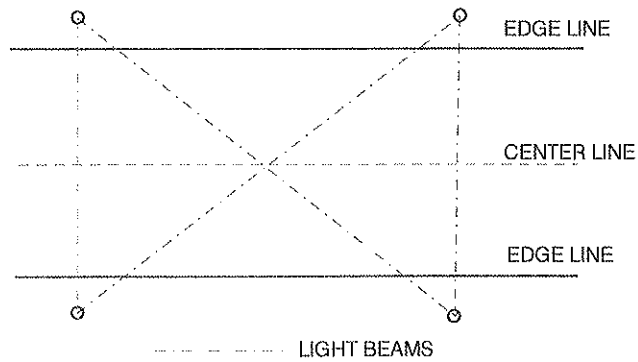

FIGURE 2 Design used in measurement of lateral position of vehicles.

winter (from October to March). These sections, however, remained in the 100-km/hr group in most analyses.

Driving speed and lateral position of vehicles were first measured before the reflector posts were installed in the late summer and early fall of 1987. Measurements were repeated three times during the following year after the reflector posts were installed. The last measurements were made about 1 year after the first measurements.

Police-reported accidents during 1982–1986 were used as a baseline, and accidents during 1988–1990 were used as a measure of change.

Behavioral Measures

The lateral position of vehicles on the road was measured with photoelectric equipment. Transmitters and reflectors were attached to four poles, two on each side of the road (Figure 2). The distance between the right front wheel of the vehicle and the edge line was calculated from the time differences between the wheels crossing different beams. The estimated accuracy of the measurements was ±5 cm. Lateral positions were measured on six experimental and six control roads, in one location on each road.

Speed was measured by radar from fixed positions by the side of the road. Speeds were measured in 26 locations on both experimental and control roads.

Road, Traffic, and Accident Data

The road, traffic, and accident data were retrieved from the data files of the Finnish National Road Administration (FinnRA). The road data included road and shoulder widths, curvature, hilliness, sight conditions, speed limits, and traffic volumes of cars, heavy vehicles, and the like.

The accident data consisted of police-reported accidents. The years 1982–1986 were used as the before period, and the years 1988–1990 as the after period. Accidents in daylight and in darkness were analyzed separately. Different analyses were also made for all accidents and for injury accidents. Accidents were also classified by

- Type: overtaking and meeting, single, pedestrian and bicycle, moose and deer, other;
- Season: summer, winter;
- Road surface condition: dry, other; and
- Weather: dry, other.

Data Analysis

Speed and Lateral Position

Regression models of the following form were used to analyze the effects on driving speed and lateral position:

$$y = \sum(b_i x_i) + r \tag{1}$$

where

y = dependent variable (speed or lateral position),
x_i = independent variables,
b_i = parameters to be estimated by least-squares regression, and
r = residual (normally distributed).

TABLE 1 Description of Roads

	80 km/h		100 km/h	
	Experim.	Control	Experim.	Control
Length (km)	183	196	349	369
AADT (vehicles/day)	2 760	2 380	3 140	3 420
Road width (m)	7.5	7.6	8.5	8.8
Curvature (gon/km)	32	36	15	14
Hilliness (m/km)	17	14	11	11

The independent variables in the model included road geometry, traffic condition, speed limit, time of year, time of day, and, of course, presence of reflector posts.

The main purpose of the models was to discover whether the effects of the reflector posts were similar in different surroundings and to separate the effects from the influence of varying environmental conditions.

Accidents

The effect on accidents was calculated from accident frequencies using the formula

$$E = 100 \times \{N_{EA}/[(N_{CA}/N_{CB}) \times N_{EB}] - 1\} \quad (2)$$

where

E = effect of reflector posts (%),
N_{EB} = number of accidents on experimental roads before intervention,
N_{EA} = number of accidents on experimental roads after intervention,
N_{CB} = number of accidents on control roads before intervention, and
N_{CA} = number of accidents on control roads after intervention.

The expression in brackets is the expected number of accidents on the experimental roads in the after period if there had been no reflector posts. Data were adjusted for changes in exposure to account for the slightly different growth in traffic volumes between the experimental and control roads during the study period.

Accidents numbers in the before period (N_{EB} and N_{CB} in Equation 2) were further adjusted, because injury accident rates in darkness on the 80-km/hr control roads were more than twice as high as on experimental roads (0.32 versus 0.14). A difference of this magnitude was unexpected, because the selection procedure of roads was designed to prevent such bias. It is assumed that much of this observed difference is due to chance. The actual observed accident numbers were 30 on experimental and 54 on control roads. There may, however, also be real differences in the safety between experimental and control roads. By using adjusted instead of observed numbers of accidents, the influence of chance and differences on the estimated safety between experimental and control roads in the before period are reduced. A description of the adjustment procedure follows.

An estimate for the expected number of accidents can be produced in two ways. The first estimate uses the accident history of a particular site. The second uses information about the "average safety" of that particular road type. The best estimate is probably achieved by combining the information from these two sources.

In this case the average accident rate for each road and accident category was calculated from the observed number of accidents and vehicle kilometers in the before period using data in which experimental and control roads were pooled. The accident rate (R) for each accident category was estimated from a linear model that was created with the GLIM (Generalized Linear Interactive Modeling) software (*3*). The models were of the form

$$E(N_{Oi}) = R \times S_i \quad (3)$$

where

$E(N_{Oi})$ = expected number of accidents during 1982–1986 at site i,
R = accident rate (coefficient of model), and
S_i = number of vehicle kilometers during 1982–1986 at site i.

No independent variables describing road geometry were used in the models because roads in each pair were similar. It was assumed in the models that the observed number of accidents varies around the expected number of accidents according to the negative binomial distribution (*4*). Each model produced the maximum likelihood estimate of the accident rate for the accident category (accident categories are given in Table 2).

Next, the estimated number of accidents for each site according to the model N_{Mi} was calculated by multiplying the accident rate by the number of vehicle kilometers:

$$N_{Mi} = R \times S_i \quad (4)$$

The expected number of accidents in the before period for each site N_i was calculated by combining the estimates N_{Mi} and N_{Oi} (*4*):

$$N_i = N_{Oi} + (N_{Mi} - N_{Oi})/[1 + (N_{Mi}/K)] \quad (5)$$

where

N_i = combined estimate,
N_{Oi} = observed number of accidents,
N_{Mi} = number of accidents predicted by average accident rate, and
K = shape parameter of negative binomial distribution that was calculated from model data.

By using this procedure the estimate of the expected number of injury accidents in darkness on 80-km/hr experimental roads during the before period was changed from 30 (observed) to 39 (adjusted). On control roads the change was from 54 (observed) to 44 (adjusted). In other accident categories the effects of the procedure were considerably smaller.

Altogether, the adjustment procedure considerably reduced the bias in the computation of the safety effects of reflector posts that was caused by the differences in accident rates between experimental and control roads in the before period, especially on 80-km/hr roads in darkness. These differences were assumed to be caused by chance. As a result, the effects of reflector posts on accidents were reduced from what they would have been without the adjustment procedure.

RESULTS

Driving Behavior

Effect on Lateral Position of Vehicles

There was a considerable amount of variation in the mean distance of vehicles from the edge of the road between dif-

TABLE 2 Total Number of Accidents

Accident category	Speed limit km/h	Injury accidents Experim. B	Injury accidents Experim. A	Injury accidents Control B	Injury accidents Control A	All accidents Experim. B	All accidents Experim. A	All accidents Control B	All accidents Control A
DAYLIGHT:									
Total	80	112	76	89	49	332	226	315	187
	100	114	70	140	118	372	234	414	322
Overtaking & meeting	80	13	8	8	4	34	21	25	15
	100	23	12	24	21	38	32	155	47
Single	80	38	20	26	16	86	50	93	54
	100	32	26	38	23	84	59	92	79
Pedestrian & bicycle	80	24	12	24	6	27	13	29	7
	100	20	8	21	20	21	9	23	21
Moose, deer etc.	80	1	1	1	1	42	28	36	28
	100	8	5	12	4	107	52	108	51
Other	80	36	35	30	22	143	114	132	83
	100	31	19	45	50	122	82	136	124
Winter (1.10.-31.3.)	80	40	23	28	14	121	75	112	70
	100	43	25	42	36	138	91	146	109
Summer (1.4.-30.9.)	80	72	53	61	35	211	151	203	117
	100	71	45	98	82	234	143	268	213
Bare & dry road	80	67	51	60	30	203	137	189	110
	100	64	42	90	78	217	140	257	202
Wet, snowy, icy road	80	45	25	29	17	129	87	126	73
	100	50	28	50	40	155	94	157	119
Dry weather	80	89	69	80	43	274	190	267	163
	100	97	59	116	100	313	197	346	267
Rain, snow, fog	80	23	7	9	6	58	36	48	24
	100	17	11	24	18	59	37	68	55
DARKNESS:									
Total	80	30	38	54	27	177	132	196	95
	100	66	49	77	40	306	218	349	248
Overtaking & meeting	80	1	12	6	7	13	23	18	18
	100	17	13	10	11	37	32	27	30
Single	80	15	24	29	10	71	47	88	29
	100	17	13	24	7	58	53	86	62
Pedestrian & bicycle	80	3	4	6	6	3	5	6	7
	100	7	1	9	6	8	1	9	7
Moose, deer etc	80	5	4	4	1	61	41	46	29
	100	17	15	19	12	168	102	191	132
Other	80	6	3	9	3	29	16	38	12
	100	8	7	15	4	35	30	36	17
Winter (1.10.-31.3.)	80	25	26	43	24	131	97	154	76
	100	49	36	55	26	217	161	265	192
Summer (1.4.-30.9.)	80	5	12	11	3	46	35	42	19
	100	17	13	22	14	89	57	84	56
Bare & dry road	80	7	13	17	8	60	48	59	22
	100	15	11	22	15	116	77	127	89
Wet, icy, snowy road	80	23	25	37	19	117	83	137	72
	100	51	38	55	25	190	140	222	158
Dry weather	80	19	27	37	18	125	93	133	64
	100	46	33	49	26	229	159	250	177
Rain, snow, fog	80	11	11	17	9	52	39	63	31
	100	20	16	28	14	77	59	99	71

NOTE: B = 1982–1986, A = 1988–1990.

ferent measurements even on the control roads. Some effects of reflector posts could, however, be detected by the models. When the effects of the relevant variables describing the traffic and the environment were accounted for, reflector posts appeared to move the lateral position of vehicles toward the edge of the road. The shift was about 60 cm in winter on roads with 80-km/hr speed limits, both day and night. Smaller shifts were observed on 100-km/hr roads. A summary of the changes in the lateral position of vehicles is presented in Table 3.

There is some question as to whether all the observed shifts in lateral positions were due to reflector posts. In winter, for example, the posts can affect snow plowing. The roads with reflector posts might have been plowed wider than control roads, and the observed effects were the result of the plowing practice instead of the reflector posts directly.

The direction of the lateral shift in summer was somewhat unexpected. It was first thought that the reflector posts would give the impression of narrowness and move the driving lines toward the center of the road, but the effect was quite the

TABLE 3 Effects of Reflector Posts on Lateral Distance of Cars from Edge of Road According to Regression Models

The effect in different conditions			Effect[a] (cm)	Standard dev. (cm)	Number of measurements[b] posts/no posts
Winter	80 kmph		**-61 ***	**13**	7/4
	100 kmph		could not be calculated		4/0
Summer	80 kmph		-11	8	12/10
	100 kmph		-27	16	4/5
Winter	80 kmph	daylight	**-62 ***	**16**	4/2
		darkness	**-64 ***	**17**	3/2
Summer	80 kmph	daylight	-11	9	8/7
		darkness	-10	12	4/3
	100 kmph	daylight	-20	18	3/3
		darkness	-41	25	1/2
Winter	80 kmph	straight road	could not be calculated		4/0
		curve	**-57 ***	**14**	3/4
Summer	80 kmph	straight road	-14	9	6/6
		curve	-4	13	6/4
	100 kmph	straight road	**-32 ***	**11**	3/3
		curve	**-36 ***	**16**	1/2
Winter	80 kmph	open scenery	-27	16	5/2
		other (forest etc.)	**-70 ***	**18**	2/2
Summer	80 kmph	open scenery	**-14 ***	**7**	9/9
		other	-5	19	3/1
	100 kmph	open scenery	**-32 ***	**10**	3/3
		other	**-35 ***	**14**	1/2

[a]*Negative sign means shifting towards the edge of the road.*
[b]*Each Measurement consists of several observations.*

NOTE: Effects statistically significant at 95% level are marked with asterisk and printed in bold.

opposite. The reflector posts may have given drivers a cue to the location of the edge of the pavement and they therefore used the whole width of the road with greater confidence.

Altogether, the effects of reflector posts on the lateral position remain unclear. The largest detected effects may be indirect, caused by changes in snow plowing practice. There was also great variation between different measurements in the same location, and the number of measurements was insufficient to draw final conclusions. It appears clear, however, that the shift in lateral position (if there is a significant shift) is toward the edge of the road.

Effect on Speed

The variation between speed measurements was large. The regression models, however, indicated that reflector posts increase driving speeds in darkness. When the effects of the road and traffic environment were accounted for, they appeared to increase driving speeds in darkness on roads with 80-km/hr speed limits. These roads were relatively narrow and had generally lower geometric standards than the roads with 100-km/hr speed limits. The increase in speeds in summer (when there is no snow) was about 5 km/hr, a value that was even greater in open scenery. On roads with 100-km/hr speed limits and relatively high geometric standards, the reflector posts had no significant effect on speeds (Table 4).

It appears that the reflector posts helped the drivers to outline the direction of the road in darkness. It also seems clear that drivers often used reflector post cues to alignment to increase their speed on roads with 80-km/hr speed limits. Speeds on roads with 100-km/hr speed limits and better geometric standards were not affected.

Results from other studies indicate that a 5- to 10-km/hr increase in the mean speed of traffic can be expected to increase the number of injury accidents by 25 to 40 percent (*5*).

Accidents

Accident Frequencies and Rates

The numbers of accidents in different categories are given in Table 2. The total number of all accidents in the data was 4,123, and the number of injury accidents was 1,149. About 60 percent of the accidents occurred in the before period (5 years) and 40 percent in the after period (3 years).

The total number of vehicle kilometers driven on both experimental and control roads was more than 2 billion before and more than 1.7 billion after the intervention. About one-quarter of the kilometers were driven in darkness. About 60 percent of the kilometers were driven on roads with a 100-km/hr speed limit (Table 5).

The accident rates in different categories are presented in Table 6. The accident rates in the before period were computed using the expected numbers of accidents instead of the observed numbers, as described earlier. The accident rates in the before period were about equal on experimental and control roads with one exception. The accident rate of injury accidents in darkness on control roads with 80-km/hr speed limits (0.263) was 36 percent higher than the corresponding rate on experimental roads (0.182).

TABLE 4 Effects of Reflector Posts on Speeds of Cars According to Regression Models

The effect in different conditions				Effect (km/h)	Standard error (km/h)	Number of measurements° posts/no posts
Winter	80 km/h			+0.2	1.1	23/16
	100 km/h			-1.3	1.2	16/14
Summer	80 km/h			**+2.2 ***	**0.9**	41/37
	100 km/h			-0.9	1.0	23/26
Winter	80 km/h	daylight		-0.2	1.2	17/12
		darkness		+1.1	1.8	6/4
	100 km/h	daylight		-1.1	1.3	12/12
		darkness		-2.1	2.4	4/2
Summer	80 km/h	daylight		+1.5	0.9	33/31
		darkness		**+5.1 ***	**1.6**	8/6
	100 km/h	daylight		-0.8	1.0	21/22
		darkness		-2.6	2.6	2/4
Summer	80 km/h	darkness	open scenery	**+9.4 ***	**2.1**	3/4
		darkness	other	+2.8	2.3	5/2
Summer	80 km/h	darkness	straight road	**+5.7 ***	**2.1**	4/3
		darkness	curve	**+4.7 ***	**2.1**	4/3

°Each Measurement consists of several observations.

NOTE: Effects statistically significant at 95% level are marked with asterisk and printed in bold.

TABLE 5 Vehicle Kilometers Driven During Study Periods

Speed limit (km/h)	Experim. roads (10^8)		Control roads (10^8)	
	Before	After	Before	After
DAYLIGHT				
80	648	462	509	353
100	1 045	811	1 259	931
DARKNESS				
80	203	172	160	132
100	328	291	395	338
Total	2 224	1 736	2,322	1 754

TABLE 6 Accidents per Vehicle Kilometer Driven

Light conditions & speed limit (km/h)		Experim. roads (10^6)		Control roads (10^6)	
		Before	After	Before	After
INJURY ACCIDENTS:					
Daylight	80	0.165	0.165	0.167	0.139
	100	0.110	0.086	0.105	0.127
Darkness	80	0.182	0.221	0.263	0.205
	100	0.198	0.169	0.185	0.118
ALL ACCIDENTS:					
Daylight	80	0.485	0.489	0.552	0.530
	100	0.348	0.289	0.316	0.346
Darkness	80	0.936	0.767	1.050	0.727
	100	0.939	0.749	0.873	0.734

In general, accident rates on Finnish trunk roads decreased by about 10 percent from the before to the after period. In Table 6, there is one case where the accident rate on control roads was higher in the after period than in the before period. This unexpected development affected analysis on 100-km/hr roads in daylight and may have led to an overestimation of the (positive) effect of reflector posts. On control roads in darkness the accident rate decreased more than was expected; the decrease on 80-km/hr roads was 22 percent and on 100-km/hr roads, 36 percent. This may have caused an overestimation of the (negative) effect of reflector posts.

Accident Effects

The effects of reflector posts on accidents and their 95 percent confidence intervals were computed using the maximum likelihood method (*6*). The effects on injury accidents are shown in Figure 3. Reflector posts increased injury accidents in darkness, an effect that is stronger on roads with 80-km/hr speed limits than on roads with 100-km/hr speed limits. The difference reflects the effects of different road geometries in these categories. In daylight the most likely effect on 80-km/hr roads is a nonsignificant increase that can be caused by chance. On roads with 100-km/hr speed limits the effect in daylight is a significant decrease in injury accidents. This result, however, is influenced by an exceptional accident increase on control roads rather than a decrease on experimental roads (Table 6). If the result is adjusted for this increase, the most likely effect would be a nonsignificant decrease of about 10 percent. It is concluded that there is no reason to reject the hypothesis that reflector posts do not significantly affect daytime accidents, especially when there is no rational explanation for any significant effect in daylight.

The effects of reflector posts on injury accidents in darkness by accident type are given in Table 7 and on all reported accidents in Table 8. Sections on 100-km/hr roads that have an 80-km/hr speed limit in winter are included in the data of the 100-km/hr roads. The effect differs from zero at a 95 percent confidence level if the confidence interval does not include zero. The sum of the expected numbers of accidents over different categories in the before period is not always the same as the total number of accidents because of the adjustment procedure.

The effect on injury accidents in darkness on roads with 80-km/hr speed limits was a 59 percent increase that was significant almost at the 95 percent level. The increase on 80-km/hr roads in bad road surface or weather conditions, however, was much smaller than in dry weather and on bare roads.

The effect on injury accidents on 100-km/hr roads was a 39 percent increase. If road sections and periods with a lowered seasonal speed limit (80 km/hr) were excluded from the data of 100-km/hr roads, the accident increasing effect on 100-km/hr roads was only 19 percent and not significant. The effect of reflector posts during the lowered speed limit was an increase of accidents that was about equal to the effect on roads with permanent 80-km/hr speed limits.

It is also worth noting that the accident rate of injury accidents on control roads in darkness decreased from the before to the after period by 22 percent on roads with 80-km/hr speed limits and by 36 percent on roads with 100-km/hr speed limits, when the general trend in Finland was a decrease of about 10 percent. This means that the effects on accidents may have been overestimated. If the results are adjusted for this, the effect on injury accidents in darkness on roads with 80-km/hr speed limits would have been an increase of 38 percent (−14 to 124 percent) and on 100-km/hr roads a decrease of 1 percent (−32 to 36 percent).

The effects on all reported accidents in darkness were considerably smaller than the effects on injury accidents. On 80-km/hr roads the effect was a 23 percent increase and on roads with 100 km/hr it was practically zero. On roads with 80-km/

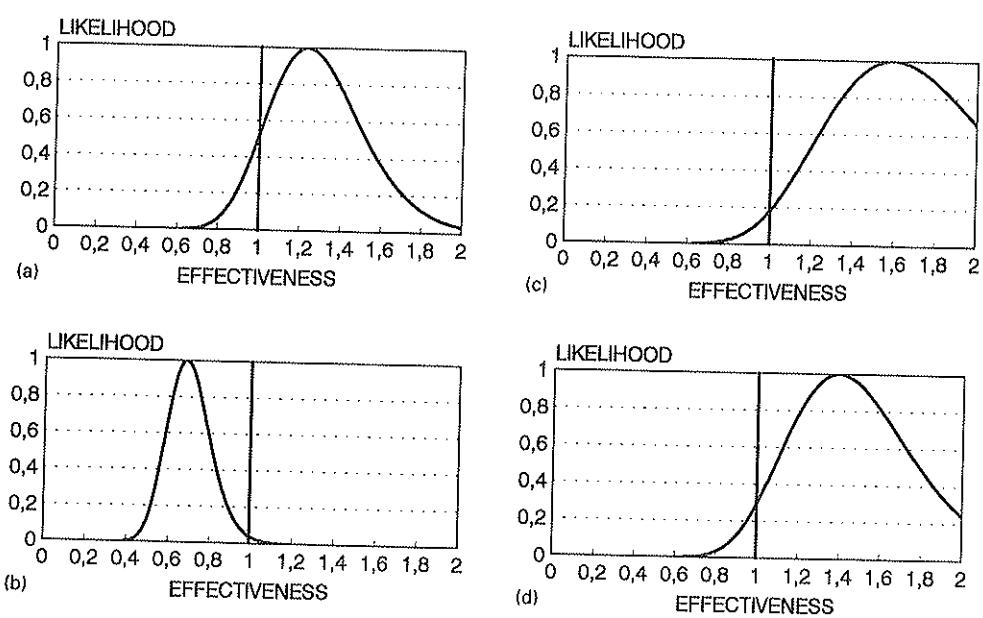

FIGURE 3 Effects of reflector posts on injury accidents in different light and road conditions: *a*, daylight, 80-km/hr roads; *b*, daylight, 100-km/hr roads; *c*, darkness, 80-km/hr roads; *d*, darkness, 100-km/hr roads.

TABLE 7 Effects of Reflector Posts on Injury Accidents in Darkness, Adjusted Number of Accidents in Before Period, and Observed Number of Accidents in After Period on Experimental and Control Roads

Accident category	Speed limit km/h	The effect on injury accidents in darkness		Number of accidents Experim. B	Experim. A	Control B	Control A
Vehicle kilometers (millions)	80			203	172	160	132
All injury accidents	80	+59 %	-3...+163 %	39	38	44	27
Overtaking & meeting	80	* +32 %	-47...+254 %	4	12	3	7
Single	80	+17 %	-48...+171 %	24	14	20	10
Pedestrian & bicycle	80	* -49 %	-87...+79 %	5	4	4	6
Moose, deer etc.	80	* +284 %	-38...>999 %	5	5	4	1
Other	80	* -23 %	-86...+313 %	7	3	8	3
Winter (1.10.-31.3.)	80	+26 %	-28...+120 %	31	26	36	24
Summer (1.4.-30.9.)	80	* +207 %	-3...>999 %	9	12	7	3
Bare & dry road	80	+49 %	-33...+263 %	12	13	11	8
Wet, snowy or icy road	80	+19 %	-34...+119 %	31	25	28	19
Dry weather	80	+67 %	-7...+209 %	26	27	29	18
Rain, snow or fog	80	+6 %	-56...+163 %	15	11	13	9
Vehicle kilometers (millions)	100			328	290	395	338
All injury accidents	100	+39 %	-8...+112 %	66	49	75	40
Overtaking & meeting	100	+27 %	-43...+190 %	13	13	14	11
Single	100	+115 %	-12...+471 %	19	13	22	7
Pedestrian & bicycle	100	* -81 %	-99...+14%	7	1	9	6
Moose, deer etc.	100	+40 %	-34...+205 %	17	15	19	12
Other	100	+110 %	-37...+700 %	10	7	12	4
Winter (1.10.-31.3.)	100	+59 %	-6...+165 %	48	36	55	26
Summer (1.4.-30.9.)	100	+8 %	-50...+131 %	18	13	21	14
Bare & dry road	100	-14 %	-61...+87 %	17	11	20	15
Wet, snowy or icy road	100	**+71 %**	**+4...+186 %**	49	38	55	25
Dry weather	100	+44 %	-14...+143 %	44	33	50	26
Rain, snow or fog	100	+30 %	-37...+170 %	22	16	25	14

*NOTE: *Means that instead of the numbers of accidents in the before period, the number of vehicle kilometers in the after period has been used as control data in the calculations in formula (2). This procedure was adopted in cases where the number of accidents in the before-period on the experimental or control road was less than 10.*

hr speed limit the effects were worse in good road surface and weather conditions than in bad conditions. If adjustment is made for the exceptional trend on control roads, the effect on all reported accidents in darkness on 80-km/hr roads would be a 6 percent increase (−18 to 37 percent) and on 100 km/hr a significant decrease of 30 percent (−41 to −17 percent).

The effects on different accident types on 80-km/hr roads are not significant, and there are no clear indications that some accident types are affected more than others. On 100-km/hr roads two effects are significant: a decrease in pedestrian and bicycle accidents and an increase in the category of "other" accidents. In the first case the number of accidents is small and the exposure of pedestrians and bicycles is uncontrolled. In the other case accidents are intersection accidents and other such accidents that should not be directly affected by the reflector posts, or the effects would be more likely to appear on roads with 80-km/hr speed limits where the overall effect was greater.

SUMMARY AND CONCLUSIONS

The purpose of reflector posts is to increase optical guidance and help drivers foresee the road alignment so that they can prepare themselves for the driving tasks ahead. It is often assumed that the additional visual cues provided by reflector

TABLE 8 Effects of Reflector Posts on All Reported Accidents in Darkness, Adjusted Number of Accidents in Before Period, and Observed Number of Accidents in After Period on Experimental and Control Roads

Accident category	Speed limit km/h	The effect on all reported accidents in darkness	Number of accidents Experim. B	Experim. A	Control B	Control A
Vehicle kilometers (millions)	80		203	172	160	132
All reported accidents	80	+23 % -6...+60 %	179	132	158	95
Overtaking & meeting	80	+20 % -35...+125 %	16	23	15	18
Single	80	+34 % -15...+115 %	86	47	71	29
Pedestrian & bicycle	80	* -45 % -84...+72 %	5	5	4	7
Moose, deer etc.	80	+4 % -35...+69 %	61	41	45	29
Other	80	+42 % -33...+206 %	32	16	34	12
Winter (1.10.-31.3.)	80	+17 % -13...+59 %	147	97	135	76
Summer (1.4.-30.9.)	80	+43 % -17...+155 %	49	35	38	19
Bare & dry road	80	**+72 % +5...+190 %**	66	48	52	22
Wet, snowy or icy road	80	+3 % -25...+42 %	133	83	119	72
Dry weather	80	+18 % -14...+64 %	141	93	115	64
Rain, snow or fog	80	-2 % -39...+58 %	59	39	46	31
Vehicle kilometers (millions)	100		328	291	395	338
All reported accidents	100	-1 % -18...+18 %	303	218	340	248
Overtaking & meeting	100	+3 % -37...+71 %	32	32	31	30
Single	100	+6 % -27...+53 %	63	53	78	62
Pedestrian & bicycle	100	* **-83 % -99...-7 %**	8	1	9	7
Moose, deer etc.	100	-12 % -32...+13 %	165	102	187	132
Other	100	**+104 % +14...+278 %**	32	30	37	17
Winter (1.10.-31.3.)	100	-1 % -20...+22 %	217	161	256	192
Summer (1.4.-30.9.)	100	+11 % -24...+60 %	81	57	88	56
Bare & dry road	100	-1 % -27...+34 %	111	77	127	89
Wet, snowy or icy road	100	±0 % -20...+25 %	190	140	214	158
Dry weather	100	-1 % -20...+23 %	224	159	247	177
Rain, snow or fog	100	-1 % -30...+40 %	74	59	88	71

*NOTE: *Means that instead of the numbers of accidents in the before period, the number of vehicle kilometers in the after period has been used as control data in the calculations in formula (2). This procedure was adopted in cases where the number of accidents in the before-period on the experimental or control road was less than 10.*

posts would also promote traffic safety. The theory of selective visual degradation, however, gives a more pessimistic view of expectations: reflector posts do not improve a driver's ability to detect potential hazards, such as pedestrians, on the road in low illumination. They can only assist drivers in orientation tasks, which has the potential to decrease single-vehicle run-off-the-road accidents. Improved visual guidance can also increase speeds, which could offset the potential safety benefit or even lead to decreased safety.

This research was designed to study the effects of reflector posts on driving behavior and accidents on two-lane rural trunk roads in Finland. Differences in driving culture and habits limit the generalization of the findings to road environments in other countries. The findings of this study, however, could be helpful when the use of reflector posts as a traffic safety measure is considered.

The study design included 20 similar pairs of road sections. One road in each pair was randomly assigned as the experimental road on which reflector posts were installed in fall 1987. The other road in the pair remained as a control road. Measurements of speeds and lateral positions of vehicles were made both on the experimental and control roads before and after the installation of posts. The accident analysis was based on police-reported accidents during 1982–1986 and 1988–1990.

On roads with 80-km/hr speed limits and relatively low geometric standards, the reflector posts increased driving speeds

in darkness. The largest detected increases were 5 to 10 km/hr. On roads with 100-km/hr speed limits and higher geometric standards, no significant effects on speed could be detected. The lateral position of vehicles shifted toward the edge of the road.

On roads with 80-km/hr speed limits, the most likely effect of reflector posts on injury accidents in darkness was a 59 percent increase. The 95 percent confidence interval of the effect was −3 to 163 percent. Even after adjusting for the exceptionally strong decrease in the accidents on control roads from the before to after periods, the most likely increase in accidents was 38 percent (−14 to 124 percent). On roads with a 100-km/hr speed limit the most likely increase in the number of injury accidents in darkness was 19 percent (−21 to 78 percent). After this result was adjusted for the exceptional trend on control roads, the most likely effect would be a 1 percent decrease in the number of injury accidents (−32 to 46 percent).

Some unexpected features in the data caused problems in the analysis. The most disturbing of these features was the big difference in accident rates in darkness between control and experimental roads in the 80-km/hr road group in the before period. Unfortunately, this difference was detected only after the experiment had begun and the posts had been installed. The other problem was the exceptional development of accident rates from before to after periods on some control roads. These things may have biased some of the results. But even after the estimation and correction for this bias the main conclusion remains: that reflector posts increased accidents on roads with relatively low geometric standards and 80-km/hr speed limits.

It is concluded that on roads with comparatively low geometric standards, which generally have 80-km/hr speed limits in Finland, reflector posts have a negative effect on driving behavior that significantly increases accident risk. On wider roads with higher geometric standards, which usually have 100-km/hr speed limits, such negative effects are rare and reflector posts do not necessarily reduce safety. Yet road authorities often want to install reflector posts on roads with poor geometry. Even though the speed limit on most of Finland's 100-km/hr roads is lowered to 80 km/hr in winter, the effects of reflector posts on accidents in darkness are about as bad as on roads with lower geometric standards and permanent 80-km/hr speed limits.

A possible explanation for the different effects on road categories could be that drivers in Finland generally consider 100 km/hr as an ideal or target speed. On roads with lower speed limits they want to drive faster, and improved visual guidance easily leads to faster driving. This increase in speed is not necessarily intentional, and drivers need not be aware of it. It is also probable that drivers in general do not percieve that their accident risk is affected by small increases in speed.

Evans defines three levels of knowledge (7):

1. Not based on observational data,
2. Hinted at by observational data, and
3. Quantified by observational data.

After considering the mentioned shortcomings, the results of this study should be rated somewhere between Categories 2 and 3. The results may not be desirable—to those road authorities who like to use reflector posts on their roads, for instance—but they are logical and based on observational data.

Car drivers in general have been very satisfied with the reflector posts and would like to see more of them. When considering the installation of reflector posts, road authorities often must choose between pleasing the driving population and promoting road safety.

ACKNOWLEDGMENTS

The study was a joint effort between FinnRA, several road districts, and the Technical Research Center of Finland (VTT). The road districts installed and maintained the reflector posts and carried out a part of the speed measurements. FinnRA commissioned VTT to carry out the research about the effects on driving behavior and safety. FinnRA's personnel also provided road and accident statistics and gave valuable comments in the reporting phase. Several people at VTT carried out measurements on the road, assisted in data preparation and analysis, and helped in preparation of the report. The author is grateful to all these people for their contributions.

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Driver Comprehension of Regulatory Signs, Warning Signs, and Pavement Markings

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A survey of 1,745 Texas drivers was conducted to assess their comprehension of selected traffic control devices. The survey consisted of a 17-min videotape presentation of 46 devices, of which 38 were regulatory signs, warning signs, or pavement markings. For each question, the survey participant was exposed to an in-context and close-up view of the device. The questions were asked verbally, and the participants selected their answers from a list of four multiple choice responses, of which one was always "not sure." The survey results for questions on regulatory signs, warning signs, and pavement markings are presented. There are 13 regulatory signs in the survey, 18 questions on warning signs, and 7 questions on pavement markings. Desirable response rates ranged from 15.5 to 93.2 percent. The survey results should be interpreted carefully, because some of the questions tested understanding of specific aspects of the sign message, such as the speed message implied by the Curve sign. Response rates for other devices are influenced by the possible response choices. The survey results for individual questions are not directly comparable and must be interpreted in isolation.

Traffic control devices are a vital element of the highway environment. They provide a means of communicating important information about the highway to the driver. Since the beginning of the 20th century, traffic control devices have grown continually in number and complexity. The *Manual on Uniform Traffic Control Devices* (MUTCD) contains the principles that govern the design and application of traffic control devices (*1*). The signs and markings in the MUTCD use shape, color, symbols, words, or a combination thereof to convey the information needed by a driver. However, these devices serve little purpose if they are not understood. Therefore, this research was initiated to determine how well motorists understand some of the most critical traffic control devices.

The question of how well drivers understand traffic control devices has been a concern for many years. A number of studies evaluating driver comprehension of traffic control devices have been conducted during the last 15 years (*2–7*). But even though these studies provide much useful information about motorist understanding of traffic control devices, several devices that are widely used in Texas have not been tested in the past. Furthermore, specific aspects of other signs have not been tested. For these reasons and others, the Texas Department of Transportation (TxDOT) sponsored a research study to measure driver comprehension of selected traffic control devices. Driver comprehension was measured through the use of a survey given to 1,745 Texas drivers; the survey addressed 46 traffic control devices. This paper describes the results of 38 survey questions related to regulatory signs, warning signs, and pavement markings. It also describes the survey methodology behind the development and administration of the survey.

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SURVEY METHODOLOGY

A survey instrument was developed that would

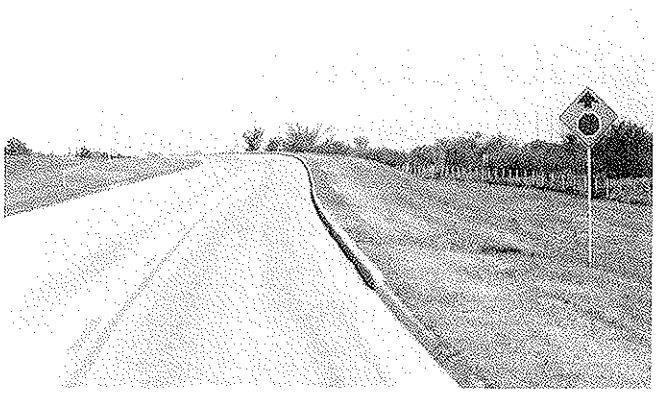
- Administer the survey in a convenient, quick, and consistent manner;
- Include many traffic control devices in the survey (at least 30); and
- Test a large sample of drivers (approximately 2,000) representative of the Texas population.

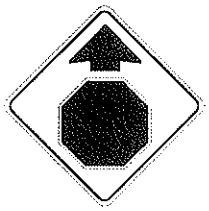
The process used to develop the survey instrument involved selecting the survey format, choosing the traffic control devices to include in the survey, evaluating the effectiveness of the survey instrument, and developing a plan for administering the survey.

Survey Format

The research team set several requirements for the format of the survey instrument. It had to address a number of traffic control devices, present in-context and close-up views of each device, and provide the question and response choices verbally. Exposure to a traffic control device had to be consistent for each test subject, and the instrument had to be portable enough to allow for easy travel and setup. These requirements led to a decision to use a videotape as the survey instrument. The videotape was prepared from 35-mm slides.

The videotape began with an introduction to the survey. Each of the devices was then addressed with two photographs. The first was an in-context photograph of a traffic control device in its typical environment. While the in-context photo was being displayed, the narrator in the videotape asked a question about the device. This was followed by a close-up view of the device with the response choices. While the close-up view was displayed, the narrator repeated each of the response choices. Figure 1 illustrates the in-context and close-up views for the question on the Stop Ahead sign.





1. Stop when you see this sign.
2. Be prepared for a STOP sign ahead.
3. At the next STOP sign, you should go straight after you stop.
4. Not sure.

FIGURE 1 Example of survey question for Stop Ahead sign: *top*, in-context view; *bottom*, close-up view with responses.

Sixteen questions at the end of the survey provided information on the demographics and driving experience of the survey participants.

The survey questions were designed to serve as a tool by which to identify problems and not to explain why misunderstandings exist or provide solutions to problematic traffic control devices. Some of the questions were developed to test specific aspects of the intended message of the sign. Multiple-choice responses were selected to reduce the answering time. There were four multiple choice responses for each traffic control device: one "correct" or "desirable" response, two responses within the realm of possible misunderstanding (referred to herein as "incorrect" or "undesirable" responses), and a "not sure" response. In some cases, the incorrect or undesirable responses contained some degree of truth. The survey was administered in English to all of the participants.

Selection of Traffic Control Devices

A survey that addressed every device in the MUTCD would be cumbersome and time-consuming. Therefore, a ranking procedure was developed to determine which devices were the most appropriate to include. The ranking procedure was necessary because comprehension alone is not sufficient to determine whether a device performs adequately or not, in part because there are no standards that establish a minimum comprehension level for traffic control devices. The ranking procedure evaluated each traffic control device with regard to three major and three minor factors. The major factors were (a) the findings of previous research, (b) the results of a poll of transportation professionals, and (c) the results of an assessment of the consequences of misunderstanding a device. The minor factors were (a) whether the meaning of a traffic control device was described in the *Texas Drivers' Handbook* (*8*), (b) the frequency that a traffic control device is used, and (c) any special interest that the research team had about a specific traffic control device.

The major factors were weighted at 25 percent each, and the minor factors were weighted at 8 percent each. A total score for each traffic control device was determined by adding the individual weighted scores for the six factors. Devices with the highest total scores were identified as candidates for the survey.

The results of the ranking process identified 60 traffic control devices for possible inclusion in the survey. These 60 devices were later reduced to 46, as will be described. The 60 devices were neither the least understood nor the highest ranked. Several traffic control devices were not included in the survey for a variety of reasons, including an abundance of prior research indicating that a traffic control device is not adequately understood, the inability to include a traffic control device in the survey format, or the inclusion of a closely related traffic control device in the survey. Once these 60 devices had been agreed upon, questions, responses, and graphics were developed for each device and a 30-min pretest survey instrument was produced.

Survey Evaluation

The evaluation of the survey instrument was a three-step process involving evaluation of a pretest survey, a pilot survey, and the final survey instrument. All three surveys used the same videotape format. The purpose of the pretest survey was to evaluate the survey questions and answers, identify problems in the survey administration, determine the proper pace of the survey, and identify the traffic control devices that could be deleted. The pretest survey was given to 38 individuals at a local shopping mall and driver licensing station. The results and observations from the pretest survey were used to delete 14 devices with high comprehension levels from the survey and to modify several questions and responses to reduce confusion. The pace of the survey instrument was also increased. The result of these changes was a 17-min pilot survey covering 46 traffic control devices.

The pilot survey was then administered at an automobile show in Houston, Texas. The 17-min videotape presentation was given to 165 walk-up volunteers from those touring the show. The results of the pilot test survey indicated that the survey instrument was effective and no changes were necessary. As a result, the final survey instrument was the same as the pilot survey instrument.

Survey Administration

The survey was administered at driver licensing stations throughout Texas. Driver licensing stations were chosen as logical places to recruit drivers because the individuals that enter the stations represent a good cross section of demographic and socioeconomic subgroups. The final survey was

administered at stations in 12 Texas cities throughout the state that were selected to represent six regions of the state. In each region the survey was conducted in a large and a small city (with populations of more and less than 50,000, respectively).

A quota sampling plan was selected for the final survey. Quotas were developed for each of the six regions in which the survey was administered. A representative quota sample of 2,000 was targeted. This sample size was determined to provide enough data for meaningful analysis for the various population subgroups—that is, men, women, and different age and ethnic groups—with varying levels of driving experience. Demographic and background information about the survey respondents was obtained from 16 questions at the end of the survey. The quota sample was selected such that it was representative of the driving population of Texas with respect to gender, age, and ethnicity. Other characteristics of interest included language, education, and driving-related variables.

Surveyors were instructed to approach potential respondents without regard to individual characteristics, in order to avoid introducing bias into the sample. The clientele of the licensing station was presumed to match regional demographics. The only screening question was to ascertain that the potential respondent was a driver.

TABLE 1 Sociodemographic Characteristics of Survey Sample

Characteristic	Number	Percent
Gender		
Male	894	51.2
Female	851	48.8
Family Background		
Anglo	1,057	60.6
Black	207	11.9
Hispanic	391	22.4
Other	90	5.2
English Language		
Primary	1,529	87.6
Secondary	216	12.4
Age		
16 - 24	455	26.1
25 - 64	1,202	68.9
65 +	88	5.0
Years of Education		
Less than High School	282	16.2
High School Graduate	480	27.5
Tech/Business School	96	5.5
Some College	433	24.8
College Graduate	303	17.4
Graduate School	151	8.7
Total	1,745	100.0

SURVEY SAMPLE

The survey was administered in the 12 cities over 6 months. The actual sample size obtained in the survey was 1,745. This sample size was determined to be large enough to allow analysis of each of the variables of interest with an acceptable level of precision. The four response choices for each question were classified into two variables: the desired response, and all other responses. Desired responses and other responses were cross-tabulated with subsets of the data representing the sociodemographic and driving-related variables. The relationships between these variables are mentioned in this paper only when statistical significance was found. χ^2-tests of significance were used to identify significant relationships among the variables with the level of significance set at $\rho \leq .01$. Table 1 gives the sociodemographic characteristics of the survey sample, and Table 2 presents the driving-related characteristics of the survey sample. The sample size generated frequencies for each of these variables that permitted analysis of the effect of these experience and exposure characteristics.

It is important to note that the sociodemographic variables were covariant—specifically, there were significantly more college-educated respondents in the 25- to 64-year-old group than in other age groups. Additionally, minority ethnic groups were overrepresented in the youngest category. Anglos and the ethnic groups classified as "other" were significantly more likely to be college-educated than Hispanics and African-Americans. As expected, ethnicity and language were highly correlated. Education was associated with language: more non-English-speaking respondents than English-speaking respondents had less than a high school education.

As with the sociodemographic variables, many of the driving-related variables were covariant. Specifically, men were more likely than women to drive on the job, be professional drivers, drive a different type of vehicle than a passenger car, drive more miles, and make more long-distance trips.

Several obvious relationships were noted with regard to age and driving experience. For example, the number of years of driving experience was positively associated with age. As in the general driving population, the sample reported fewer miles driven and long-distance trips per year among both the younger and older respondents. Commercial driver licenses were held primarily by middle-aged drivers.

There were significant differences between those who had and those who had not taken driver education on the basis of age, ethnicity, education, language, miles driven, type of miles driven, number of trips per year, and length of time that they had been licensed. Respondents who had taken driver education were more likely to be younger, Anglo, highly educated, and English speaking, as well as to drive more miles on average, take more trips on average, and be newly licensed or licensed within the past 10 years. There were no significant differences between those who had and had not taken driver education on the basis of gender or license type.

STUDY LIMITATIONS

The survey method used in this research has several limitations that must be kept in mind when evaluating the results. Although the driver licensing stations are ideal venues for finding and questioning drivers, at least some of these drivers may have been more prepared for driving-related questions, depending on their purpose for being in the station on the day of the survey. Most of the respondents were not newly licensed or recently tested; they were more often accompanying someone else doing business at the office or renewing their licenses. The survey stimulus material was auditory and

TABLE 2 Driving Characteristics of Survey Sample

Characteristic	Number	Percent
Drive for Job		
Yes	435	24.9
No	1,310	75.1
Type of License		
Operator	1,586	90.9
Commercial	188	6.8
Motorcycle	40	2.3
Trips/Year		
None		
> 300 mi	300	17.2
1-10	1,262	72.3
> 10	183	10.5
Years Licensed		
No License	99	5.7
< 1	88	5.0
1-10	475	27.2
> 10	1,083	62.1
Type of Vehicle Driven		
Passenger Car	1,508	86.4
Pickup	205	11.7
Diesel	18	1.0
Motorcycle	2	0.1
Other	12	0.7
Driver Education		
Yes	1,002	57.4
No	743	42.6
Years Since Driver Education		
None	738	42.3
< 1	116	6.6
1-10	386	22.1
> 10	505	28.9
Type of Driving		
Within City	930	53.3
Outside City	188	10.8
Both	627	35.9
Miles Driven per Year		
< 10,000	554	31.7
10,000 - 30,000	1,074	61.6
> 30,000	117	6.7
Total	1,745	100.0

the responses were verbal. This technique was used to compensate for variations in reading ability. However, the videotape was timed such that most responses were required within 3 or 4 sec of hearing the question. It is acknowledged that processing time varies within the population as well. A survey with unlimited response time would probably show higher comprehension levels than a survey with time limitations, as was used in this study. And, although each traffic control device was presented in two formats (in and out of context), neither truly represented the driving environment in which the traffic control devices would be encountered and interpreted.

The use of a multiple-choice format places some restrictions on the interpretation of the survey results. Because multiple-choice questions eliminate drivers' freedom to develop their own explanations of a device, their responses to questions are influenced by the possible choices. The use of multiple-choice questions may also eliminate potential areas of confusion. For example, all of the response choices for the Narrow Bridge sign were related in some manner to a bridge. Because the possible responses for each question are not always comparable, the response rates cannot be used to provide a relative measure of the effectiveness of any warning sign. The response rates for each question must be interpreted in isolation from other questions.

Some of the questions in the survey test specific aspects of comprehension of warning signs. Therefore, is it inappropriate to assume that the correct response rate for any sign represents the proportion of drivers who understand the sign. As an example, the correct response rate for the Curve sign question was 32.4 percent. However, this does not mean that only 32.4 percent of drivers recognize that the Curve sign indicates a change in horizontal alignment. Instead, it means that only 32.4 percent recognize the speed-related message implied by the Curve sign.

REGULATORY SIGN RESULTS

The MUTCD states that "regulatory signs shall clearly indicate the requirements imposed by the regulation" (*1*). The regulatory signs in the survey can be categorized as a word or symbol legend, and some of the signs can also be classified as a particular type, such as signal regulatory signs. Figure 2 indicates the 13 regulatory signs included in the survey. Table 3 gives a summary of the response percentages for each regulatory sign question. However, as previously emphasized, the specific aspect of a regulatory sign studied and the possible choices to a designated question affect the manner in which the results are interpreted.

In the following, the results for each regulatory sign studied in the survey are presented. The regulatory sign name and label are given for each question. The survey questions and responses are shown in the order in which they were given in the survey along with the response percentages for each question. An asterisk is used to indicate the desirable response for each question.

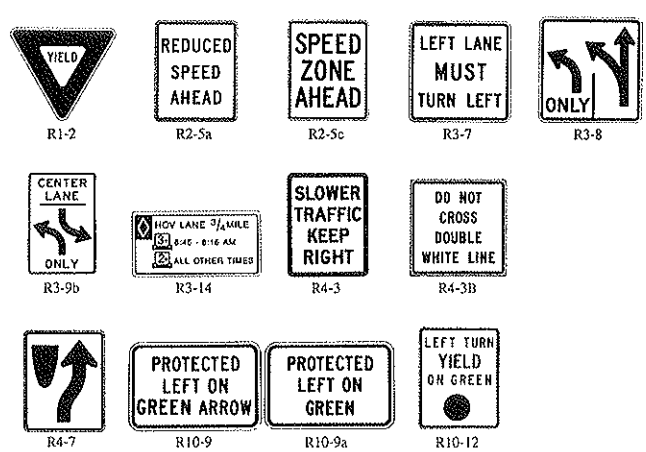


FIGURE 2 Regulatory signs included in survey.

TABLE 3 Survey Results for Regulatory Signs

Sign	Sign Label	Percent		
		Correct	Incorrect	Not Sure
YIELD	R1-2	79.4	19.8	0.8
REDUCED SPEED AHEAD	R2-5a	93.2	5.6	1.1
SPEED ZONE AHEAD	R2-5c	55.0	37.3	7.7
Mandatory Movement	R3-7	79.5	18.9	1.6
Double Turn	R3-8	65.0	31.3	3.7
Two-Way Left Turn Lane	R3-9b	58.6	50.4	5.0
HOV Restriction	R3-14	45.7	21.1	33.2
SLOWER TRAFFIC KEEP RIGHT	R4-3	70.8	27.7	1.5
DO NOT CROSS DOUBLE WHITE LINE[a]	R4-3B	72.6	21.3	6.1
Keep Right	R4-7	69.9	25.1	5.0
PROTECTED LEFT ON GREEN ARROW[a]	R10-9	53.0	43.7	3.3
PROTECTED LEFT ON GREEN[a]	R10-9a	15.5	82.2	2.3
LEFT TURN YIELD ON GREEN Ball	R10-12	74.5	17.9	7.6

[a]This sign is contained in the Texas MUTCD but does not appear in the National MUTCD.

Yield Sign

When participants were shown a Yield sign (R1-2), they were asked, "What does the Yield sign tell you?"

Answer Choice	*Percentage*
You must slow down before entering the intersection.	15.1
You may enter the intersection if it is safe to do so; otherwise, you must stop or slow down until it is safe.	*79.4
You must stop at the intersection before you enter it.	4.6
Not sure.	0.8

Although most drivers know that this sign means to yield, it is of greater importance to determine if they know how the term "yield" applies to them as they approach it. There is some concern that although the legal definition of yielding has not changed, the actual practice of yielding in daily driving has become more "permissive," that is, that slowing is all that is required. For 15.1 percent of drivers, this may well be the case. However, 79.4 percent are knowledgeable about the correct response to a Yield sign.

Previous research (*9*) has shown an overinvolvement of older drivers (over 65 years) in accidents due to failure to yield right of way at intersections. However, the survey results did not show a significant relationship between age and misunderstanding the Yield sign. Hispanics and those who reported that they did not take any long-distance trips were most apt to indicate that slowing down is the appropriate response to the Yield sign.

Reduced Speed Ahead Sign

Signs indicating a reduced speed are used when advance notice is needed to enable the motorist to comply with a posted speed a short distance ahead. Two of the three versions of the signs for reduced speed were tested in this survey. Participants were first shown a Reduced Speed Ahead sign (R2-5a) and asked, "What does this sign mean?"

Answer Choice	*Percentage*
The speed limit will be higher ahead.	1.9
The speed limit ahead will be strictly enforced by the police.	3.7
The speed limit will be lower ahead.	*93.2
Not sure.	1.1

The Reduced Speed Ahead sign had the highest desirable response rate (93.2 percent). The dramatically higher percentage of desirable responses for the Reduced Speed Ahead sign than the Speed Zone Ahead sign suggests that the Reduced Speed Ahead signs conveys a clearer meaning of the situation.

Speed Zone Ahead Sign

Signs indicating a reduced speed zone are typically used in rural areas when advanced notice is needed to enable the motorist to comply with a posted speed a short distance ahead. The Speed Zone Ahead sign appears to be understood by a lower percentage than the Reduced Speed Ahead sign (R2-5c).

Answer Choice	*Percentage*
The speed limit will be higher ahead.	6.2
The speed limit ahead will be strictly enforced by the police.	31.1
The speed limit will be lower ahead.	*55.0
Not sure.	7.7

A common association with the message of Speed Zone Ahead was there is enforcement ahead (selected by 31.1 percent of the respondents). This misunderstanding was held by a significantly larger proportion of non-Anglo drivers, drivers with less than high school education, drivers who do not make

long-distance trips, and drivers with few years of driving experience. As respondents increased in age, so did understanding of this sign. The Speed Zone Ahead sign had a higher percentage of "not sure" responses than any other regulatory sign except the HOV [high-occupancy vehicle] Restriction sign.

Mandatory Movement Sign

Upon being shown a Mandatory Movement sign (R3–7), participants were asked, "What does this sign mean?"

Answer Choice	*Percentage*
Turn right at the next driveway if you are in this lane.	14.0
Turn right at the next intersection if you are in this lane.	*79.5
You are not allowed to change lanes after you see this sign.	4.9
Not sure.	1.6

The response choices provided for this question were designed to determine how literally this sign is interpreted. Do drivers think that they must turn immediately or that they have no other immediate option but to turn? Approximately 19 percent did. By and large, these were drivers whose primary language was something other than English.

Double Turn Sign

Participants were shown a Double Turn sign (R3–8) and asked, "Which is the most correct statement about this sign?"

Answer Choice	*Percentage*
To go straight, you must be in the lane on the right.	*65.0
You may go straight or turn left in the left lane.	18.4
You must go straight if you are in the lane on the right.	13.0
Not sure.	3.7

The Double Turn sign was not clearly understood by 35 percent of those surveyed. This sign is complicated by the several options presented with the arrows. Likewise, the responses required more thought than most of the other questions because options were presented contingent on lane position. Undesirable responses were given by significantly more Hispanic drivers, drivers with less than high school education, respondents whose primary language was not English, drivers who had not taken driver education, and drivers with little driving experience.

Two-Way Left-Turn Lane Sign

The Two-Way Left-Turn Lane sign (R3-9b) has three components: the words "center lane," two arrows pointing in opposite directions, and the word "only." The survey attempted to determine how well drivers assemble these components into meaning an exclusive lane for left-turning vehicles: "Which one of the following statements is true when you see this sign?"

Answer Choice	*Percentage*
The center lane is to be used only for making left turns.	*44.6
You will be able to make only left turns at the next intersection.	6.7
The center lane is to be used only for making left and right turns.	43.7
Not sure.	5.0

Only 45 percent of the survey respondents gave the desirable response for the sign. The presentation of the two arrows prompted 44 percent of the respondents to say the center lane is usable for making left and right turns. These respondents were more likely to be non-Anglo drivers with little driving experience. In postsurvey interviews, several respondents immediately recognized the error in their thinking. It is not known what the effect of this misinterpretation is in the driving environment.

HOV Restriction Sign

The HOV Restriction sign (R3-14) was presented to the survey respondents along with the question "It is 7:30 a.m.; what vehicles are allowed to enter the HOV lane?"

Answer Choice	*Percentage*
Carpools with 2 or more people.	9.9
Carpools with 3 or more people.	*45.7
Carpools with more than 3 people.	11.2
Not sure.	33.2

The number of people in an allowed carpool was the source of confusion for 21 percent of the respondents—that is, 10 percent said vehicles with carpools of two or more people were allowed, and 11 percent said vehicles with carpools of more than three people were allowed. One-third of the drivers surveyed were not sure which vehicles would be allowed in the HOV lane. The drivers that were knowledgeable about this sign tended to be younger, Anglo, higher-educated, English-speaking respondents who had also taken driver education.

Slower Traffic Keep Right Sign

Survey participants were asked the meaning of a Slower Traffic Keep Right sign (R4-3):

Answer Choice	*Percentage*
If you are driving slower than the speed limit, you should be in the lane on the right.	26.6
If you are driving slower than the other traffic, you should be in the lane on the right.	*70.8
If you have car trouble you should pull off on the right side of the road.	1.1
Not sure.	1.5

The *Texas Drivers Handbook* (*8*) states that those driving slower than the normal stream of traffic are to keep in the right-hand lane. The study hypothesis was that some drivers think that if they are going the speed limit, they should not be considered "slower traffic." Thus, the weaving that this sign is supposed to eliminate would not be eliminated. This proved to be the case for more than a quarter of the drivers surveyed. Undesirable responses were given significantly more

often by those who did not speak English as their primary language. Contrary to expectation, the notion that the right-hand lane is for vehicles traveling slower than the speed limit was not associated with age.

Do Not Cross Double White Line Sign

The Do Not Cross Double White Line sign (R4-3b) appears in the Texas MUTCD (*10*) but is not described in the national MUTCD. It is intended to inform motorists of the regulation against changing lanes or turning across double white lines. When asked the meaning of the sign, participants responded as follows:

Answer Choice	*Percentage*
Do not change lanes or turn across the double white lines.	*72.6
Do not pass. Two-way traffic.	9.6
Do not change lanes.	11.7
Not sure.	6.1

The prohibition against crossing the double white lines was understood by 73 percent of the motorists surveyed. Twelve percent interpreted the sign simply as a prohibition against changing lanes, and 10 percent interpreted this sign as a prohibition against passing. Drivers over 75 years old and Spanish-speaking Hispanics were more likely to misinterpret this sign.

Keep Right Sign

The Keep Right symbol sign (R4-7) is intended for use at the ends of medians, traffic islands, parkways, and so forth. Survey participants were asked, "What is the appropriate response to this sign?"

Answer Choice	*Percentage*
Turn right.	1.2
Go to the right side of this sign.	*69.9
Stay in the far right lane.	23.9
Not sure.	5.0

The Keep Right sign is not intended as a lane assignment regulation. However, 24 percent of those surveyed interpreted this sign as a directive to stay in the far right lane. Seventy percent gave the appropriate response choice. This sign was more clearly understood by those who reported they traveled more than 30,000 mi/year and by drivers with commercial licenses.

Protected Left on Green Arrow Sign

The Protected Left on Green Arrow sign (R10–9) is in the Texas MUTCD (*10*) but not in the national MUTCD. Participants were asked, "Which one of the following statements is true with regard to a left turn at this intersection?"

Answer Choice	*Percentage*
You are allowed to turn only when the green arrow is on.	27.0
You are allowed to turn when the green ball is on if it is safe to do so.	*53.0
You are protected from oncoming traffic if you turn from the turn lane when either the green arrow or the green ball is on.	16.6
Not sure.	3.3

Fifty-three percent recognized the ability to make a left turn when facing a green ball as well as the ability to make a protected left turn when facing a green arrow. However, 27 percent believed that turns are permitted only when facing a green arrow if this supplemental plate accompanies the signal. A more serious error was committed by the 16.6 percent who believed that their turns are protected when they are facing either the green arrow or the green ball if this supplemental plate accompanies the signal. Language was the most significant variable associated with correctly identifying the meaning of this sign.

Protected Left on Green Sign

The Protected Left on Green sign (R10-9a) is another sign that is in the Texas but not the national MUTCD. When participants were shown this sign, they were asked, "If you want to turn left at this intersection and the green light is on, what should you do?"

Answer Choice	*Percentage*
Yield to oncoming traffic. They will have a green light also.	34.7
Wait for a green arrow. Then turn left.	47.5
Turn left. Oncoming traffic will have a red light.	*15.5
Not sure.	2.3

The survey results indicate that this sign does not effectively communicate right-of-way assignment to a large majority of drivers. Only 15.5 percent recognized that a left turn would be protected, whereas 47.5 percent would wait for a green arrow to provide a protected left turn. Thirty-five percent thought oncoming traffic would have a green light also. These undesirable responses were fairly uniformly distributed across the survey population. However, respondents who had taken driver education within the past year performed significantly better on this question.

Left Turn Yield on Green Ball Sign

Participants were shown a Left Turn Yield on Green Ball sign (R10-12) and asked, "If you have a green signal, what should you do to turn left?"

Answer Choice	*Percentage*
Stop and wait for a gap in traffic. Then turn left.	*74.5
Wait for green arrow. Then turn left.	13.6
Turn left. Oncoming traffic will have a red light.	4.3
Not sure.	7.6

The Left Turn Yield on Green Ball sign does the best job of those signs in this survey of informing the driver of a permissive left turn condition: 74.5 percent chose the desirable response for this question. A certain percentage of respondents (13.6) would wait for a green arrow. Only 4.3 percent of the respondents made the more dangerous interpretation (interpreting a protected left turn). Those least apt to provide the correct interpretation were drivers over 65 years old, respondents with less than high school education, non-English-speaking respondents, unlicensed drivers, and drivers who had not taken driver education.

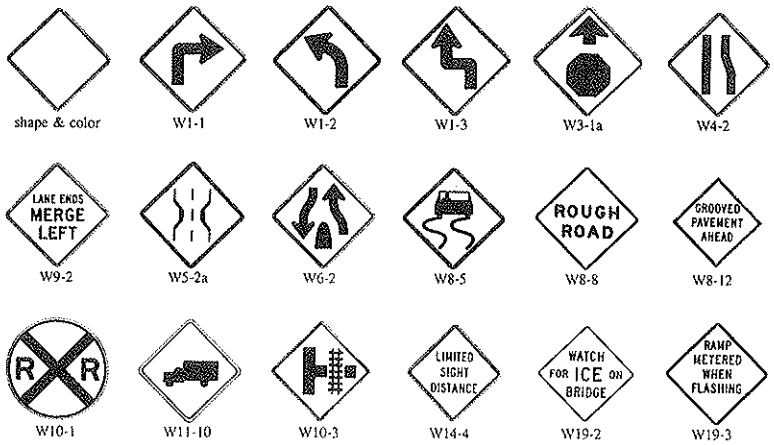


FIGURE 3 Warning signs included in survey.

WARNING SIGN RESULTS

Approximately one-third of the survey (18 questions) dealt with the warning signs shown in Figure 3. A summary of the response rates for each of the warning signs is presented in Table 4. The survey results should be interpreted for each sign, giving consideration to the subject matter of the question and possible response choices. This section of the paper analyzes the results for each warning sign and includes the survey question for each sign and the possible response choices with the percentages that selected each response. For each question, the correct response is indicated by an asterisk.

Warning Sign Shape and Color

One of the basic premises of a uniform signing system is that shape and color are standardized for a given category of signs. Therefore, the survey included one question that addressed the standard shape and color of a warning sign. In the next

TABLE 4 Survey Results for Warning Signs

Warning Sign	Sign Label	Percent		
		Correct	Incorrect	Not Sure
Warning Sign Shape & Color	None	58.1	32.6	9.4
Turn	W1-1	31.9	55.9	12.2
Curve	W1-2	32.4	66.7	0.9
Reverse Turn	W1-3	66.5	30.8	2.7
Stop Ahead	W3-1a	87.4	9.7	2.9
Lane Reduction Transition	W4-2	61.2	34.2	4.6
LANE ENDS MERGE LEFT	W9-2	64.0	28.4	7.6
Narrow Bridge	W5-2a	81.7	14.6	3.7
Divided Highway Ends	W6-2	50.7	43.7	5.6
Slow Down on Wet Road[a]	W8-5	62.3	36.5	1.1
ROUGH ROAD[b]	W8-8	88.7	9.7	1.7
GROOVED PAVEMENT AHEAD[b]	W8-12	29.2	56.0	14.7
Railroad Advance Warning	W10-1	77.8	20.9	1.3
Parallel Railroad Advance Warning	W10-3	69.3	22.6	8.1
Truck Crossing	W11-10	66.1	30.7	3.2
LIMITED SIGHT DISTANCE[c]	W14-4	44.9	40.3	14.8
WATCH FOR ICE ON BRIDGE[b]	W19-2	84.0	13.9	2.1
RAMP METERED WHEN FLASHING	W19-3	45.7	27.5	26.8

[a]This sign is known as the Slippery When Wet sign in the National MUTCD.
[b]This sign is contained in the Texas MUTCD but does not appear in the National MUTCD.
[c]This sign was dropped from the National MUTCD, but is still contained in the Texas MUTCD.

to last question in the survey, a yellow diamond shape with a border but no legend was shown and the respondent was asked, "What does a sign this shape and color mean?"

Answer Choice	*Percentage*
Warning	*58.1
Directions or guidance	19.7
Construction area	12.9
Not sure	9.4

Despite the fact that this question came after 16 other questions about a yellow diamond-shaped warning sign, only 58 percent were able to select the correct response. These responses indicate that drivers are not fully aware of the basic design premises of warning signs.

Turn Sign

The Turn sign (W1-1) is used where the recommended speed on a turn is 30 mph or less and the recommended speed is equal to or less than the speed limit. This was the point emphasized in the correct response to the question. When asked to select the meaning of a Turn sign without an Advisory Speed plate (W13-1), survey participants gave the following responses:

Answer Choice	*Percentage*
There is an intersecting road to the right ahead.	10.7
You should drive 30 mph or less to make the next turn.	*31.9
You should turn right at the next intersection.	45.2
Not sure.	12.2

This question was a confusing one to many of the respondents, as indicated by the large percentage of "not sure" responses and by the number of comments made during the survey to the effect that there is more than one correct answer or that there is no correct answer. Those who did have a thorough understanding of the Turn sign were more often men and more often professional drivers. Misunderstanding was not significantly related to age, ethnicity, language, education, or driver education.

Curve Sign

The Curve sign (W1-2) is used where the recommended speed is greater than 30 mph and equal to or less than the speed limit. This survey question presented the Curve sign without an Advisory Speed plate (W13-1) to see if drivers recognized the speed message of the sign. When drivers were asked what the sign meant, the following responses were selected:

Answer Choice	*Percentage*
The road will curve to the left a short distance ahead and you should slow down before reaching the curve.	65.0
The road will curve to the left a short distance ahead, but you may drive the curve at the speed limit.	*32.4
The next mile of highway has several curves and you should slow down.	1.7
Not sure.	0.9

The responses to this question indicate that drivers tend to believe that a Curve sign without an Advisory Speed plate implies the need for a speed reduction, as two-thirds of the drivers selected the "slow down" response. Although this is a safe response, it is nonetheless incorrect. The one-third of the drivers who knew the correct answer tended to be Anglos who had taken driver education.

Reverse Turn Sign

The directional aspect of the Reverse Turn sign (W1-3) was the focus of this survey question. Drivers were asked what the sign meant and selected the following responses:

Answer Choice	*Percentage*
Winding road ahead.	25.6
You will make a turn to the right, then turn to the left ahead.	5.3
You will make a turn to the left, then turn to the right ahead.	*66.5
Not sure.	2.7

The responses to this question indicate that there may be some confusion between the Reverse Turn sign and the Winding Road sign, as one-fourth selected the "winding road" response. The "winding road" response was more often a source of confusion for women and African-American respondents.

Stop Ahead Sign

Comprehension of the Stop Ahead symbol sign (W3-1a) was a concern because of two potentially confusing symbols in the sign. The red octagon has the potential for being confused with a Stop sign and the upward pointing arrow might be misinterpreted as a directional indication. Drivers were asked what the sign told them to do, and the following responses were selected:

Answer Choice	*Percentage*
Stop when you see this sign.	2.1
Be prepared for a stop sign ahead.	*87.4
At the next stop sign you should go straight after you stop.	7.6
Not sure.	2.9

This sign turned out to be the second best understood warning sign in the survey. Only 13 percent of the survey participants selected incorrect or not sure responses. The survey results indicate that the comprehension concerns about the octagon and arrow symbols were unfounded.

Lane Reduction Transition Sign

The Lane Reduction Transition sign (W4-2) uses a symbol to indicate that there is a reduction in the number of traffic lanes. This sign was introduced in the 1961 edition of the MUTCD (*11*). Since then, there have been concerns about comprehension of the sign. Previous research studies have found that there are several common misinterpretations of this sign (*5,7*). Among the most common misinterpretations are that there

is a single lane ahead, the road changes from two-way to one-way, there are narrow lanes, and a there is shift in lane position. For this survey, drivers were placed in the left-hand lane and asked what the sign meant. The following responses were selected:

Answer Choice	*Percentage*
There are fewer lanes ahead, and traffic on your right will move into your lane.	*61.2
There is a one-lane road ahead.	22.8
There are narrow lanes ahead.	11.3
Not sure.	4.6

The response choices for this question require the driver to be knowledgeable of this warning sign because the symbol could conceivably describe any of the three choices. The difference between fewer lanes, one lane, and narrow lanes ahead was not apparent to 39 percent of the respondents. Language was a major factor in choosing the incorrect response, and driver education was a major factor in choosing the desirable response.

Narrow Bridge Sign

The Narrow Bridge sign (W5-2a) is used to warn the driver of a bridge or culvert with a two-way width of 16 to 18 ft or a width that is less than the approach pavement. Drivers were asked the meaning of the sign and the following responses were selected:

Answer Choice	*Percentage*
Passing is not allowed on the bridge ahead.	4.2
A one-lane bridge is ahead.	10.4
A narrow bridge is ahead.	*81.7
Not sure.	3.7

Given these options, respondents had little difficulty determining the intended message. However, since the word "bridge" was included in each response, the level of correct interpretation of the plan drawing of a bridge was not directly measured.

Divided Highway Ends Sign

The Divided Highway Ends sign (W6-2) is used to indicate a change from a divided to an undivided cross section. This sign uses the same symbol as the Divided Highway sign (W6-1) except that it is rotated 180 degrees. Therefore, one of the reasons for including the Divided Highway Ends sign was to determine its interchangeability with the Divided Highway sign. Drivers were asked what the sign told them, and the following responses were selected:

Answer Choice	*Percentage*
There is two-way traffic ahead.	*50.7
There is one-way traffic ahead.	6.0
There is a divided highway ahead.	37.8
Not sure.	5.6

Divided Highway Ends and Divided Highway signs are both commonly used, but the problem hypothesized was the interchangeability of these two signs in the minds of motorists. The 37.8 percent who thought that this sign meant there is a divided highway ahead may have been responding to the "divided highway" phrase in the multiple-choice response and overlooking the implication for traffic directions. Men correctly answered this question significantly more often than women. Furthermore, the largest difference in correct responses between men and women was evidenced for this question.

Slow Down on Wet Road Sign

Texas has renamed the Slippery When Wet sign to Slow Down on Wet Road (W8-5). The sign is used to warn drivers that the pavement surface may present a potentially hazardous condition when it is wet. The symbolic version of this sign was shown to drivers and they were asked what it meant.

Answer Choice	*Percentage*
Be prepared for a winding road.	33.9
Slow down when the pavement is wet.	*62.3
Watch for out of control vehicles.	2.6
Not sure.	1.1

Almost two-thirds of the respondents were able to select the correct meaning of this sign, but the other third confused this sign with the Winding Road sign, an interpretation that has also been found in previous research on this sign (*2,5*).

Ethnic minorities were most inclined to give incorrect and "not sure" responses. However, correct answers were not associated with the language variable. Commercial drivers were significantly more knowledgeable of the meaning of this sign. Driver education was not significant for comprehension of this sign.

Rough Road Sign

The Rough Road sign (W8-8) is included in the Texas MUTCD but not in the national MUTCD. The sign is used to warn of an extraordinarily rough pavement condition. Survey participants were shown the sign and asked what its purpose is. The responses to this question are as follows:

Answer Choice	*Percentage*
To let motorcyclists know they should use caution.	7.2
To let motorists know the road will be noisier ahead.	2.5
To let motorists know the pavement is in poor condition.	*88.7
Not sure.	1.7

The Rough Road sign had the highest desirable response rate of all the warning signs in the survey. It is worth noting that the first two incorrect responses contain some degree of truth. Almost everyone selected the correct response except respondents who classified themselves in the "other" ethnic group and who did not speak English as their primary language.

Grooved Pavement Ahead Sign

The Grooved Pavement Ahead sign (W8-12) is primarily intended to warn motorcyclists that the pavement has been

grooved to improve its wet weather performance. Drivers were shown the sign and asked its purpose.

Answer Choice	*Percentage*
To let motorists know the road will be slippery when wet.	16.5
To let motorists know the road will be noisier ahead.	39.5
To let motorcyclists know they should use caution.	*29.2
Not sure.	14.7

Although the first and second responses may be true conditions, they do not accurately define the purpose of this sign. Drivers most frequently associated increased noise with grooved pavement. The 29 percent who did know the purpose of the Grooved Pavement Ahead sign more often were under 25 years old, classified in the ethnic group "other," spoke a language other than English as their primary language, had no operator license, but had a motorcycle license.

Lane Ends Merge Left Sign

The Lane Ends Merge Left sign (W9-2) is intended to be used as a supplement to the Lane Reduction Transition sign. Drivers in the left lane were asked how they would respond to the sign, and the following responses were selected:

Answer Choice	*Percentage*
Be aware that traffic will be coming into your lane from the right.	*64.0
Move to the right lane.	11.6
Prepare to exit on the left.	16.8
Not sure.	7.6

Although 64 percent selected the correct meaning of the sign, 12 percent of the drivers selected the meaning that is exactly the opposite of the desired maneuver. Another 17 percent thought the sign was related to an exit condition, which is completely different than the correct meaning. Drivers over 75 years of age and non-English-speaking drivers were particularly prone to select incorrect answers.

Railroad Advance Warning Sign

The circular Railroad Advance Warning sign (W10-1) is placed upstream of a grade crossing to warn drivers that they are about to cross railroad tracks. This sign is one of only two signs that use the circular shape (the other is the civil defense evacuation route marker sign). Drivers taking the survey were asked to describe the purpose of this sign.

Answer Choice	*Percentage*
To let you know you are at a railroad crossing.	17.4
To let you know you will cross railroad tracks ahead.	*77.8
To let you know there are two railroad tracks ahead.	3.5
Not sure.	1.3

The responses to this question indicate that one of the problems associated with the Railroad Advance Warning sign is the failure to recognize the advance nature of the circular sign as compared with the railroad crossbuck, which is located at the grade crossing. The advance nature of the Railroad Advance Warning sign was recognized by 78 percent of the respondents, although 17 percent thought that the Railroad Advance Warning sign is located at the grade crossing itself. Understanding of this sign was positively associated with driver education and negatively associated with age.

Parallel Railroad Advance Warning Sign

Another type of advance railroad crossing sign is the Parallel Railroad Advance Warning sign (W10-3), which is used to warn drivers on a parallel highway that they will cross the railroad tracks if they turn. Although this sign provides an advance warning of a railroad-highway grade crossing in a manner similar to the circular sign, the Parallel Railroad Advance Warning sign is diamond-shaped. The survey question asked drivers what this sign means:

Answer Choice	*Percentage*
If you turn onto the side road, you will cross a gravel road.	0.9
You will cross a railroad track, then come to an intersection ahead.	21.7
If you turn onto the side road, you will cross a railroad track.	*69.3
Not sure.	8.1

Driver orientation was the confusing aspect of the Parallel Railroad Advance Warning sign for the 22 percent of the drivers who selected the second response. These individuals assumed that the driver facing this sign would be on the intersecting roadway. A relatively large number of drivers were not sure of the desirable response. Language and driver education were key variables associated with interpreting this symbol sign.

Truck Crossing Sign

The symbolic Truck Crossing sign (W11-10) is used to warn drivers of locations where trucks may be entering, leaving, or crossing the highway. This sign was included in the survey to determine whether drivers associated the truck symbol with a crossing location or with truck use of the highway. Drivers were asked what the sign means:

Answer Choice	*Percentage*
Be prepared for fire trucks entering or crossing the roadway in this area.	2.0
This is a warning that this road is heavily used by large trucks.	28.7
Be prepared for trucks entering or crossing the roadway in this area.	*66.1
Not sure.	3.2

This warning sign was correctly understood by two-thirds of the survey respondents. However, 29 percent thought the sign indicated that the highway was heavily used by large trucks. Not surprisingly, a driver characteristic that was significantly associated with knowledge of this traffic control device was possession of a commercial driver license.

Limited Sight Distance Sign

The Limited Sight Distance sign (W14-4) is used with an Advisory Speed plate to indicate the recommended speed on vertical curves where the sight distance is restricted. This sign was dropped from the national MUTCD in the 1988 edition (*1*), although it remains in the Texas MUTCD (*10*). Drivers were asked to identify the purpose of this sign.

Answer Choice	*Percentage*
To warn drivers that shadows make it difficult to see cars coming from the other direction.	31.7
To let drivers know they should be prepared to stop with little warning.	*44.9
To let drivers with eyesight problems know they should use caution in this area.	8.6
Not sure.	14.8

Fewer than half of the respondents correctly interpreted this warning. Almost one-third perceived the message as one of a temporary condition (i.e., the presence of shadows), and a relatively large percentage of the respondents (15 percent) were not sure of its meaning.

Watch for Ice on Bridge Sign

Several signs are used in the United States to warn drivers that the road surface may be icy. In Texas the warning is provided with a fold-down sign with the legend Watch for Ice on Bridge (W19-2), which is displayed in advance of bridges during cold weather periods. In the survey, drivers were asked how they would respond to this sign and the following responses were selected:

Answer Choice	*Percentage*
Don't drive on the bridge if there is ice on it.	2.5
Slow down and gently apply the brakes while you are on the bridge.	11.5
Slow down, don't brake or make sudden turning movements on the bridge.	*84.0
Not sure.	2.1

The message conveyed by the words on this sign appears obvious. However, other than watch for ice, what would motorists think is an appropriate driving response? Most (84 percent) did know the appropriate response, but 11.5 percent thought that brakes should be applied. The most significant effect on understanding this sign was language. Those that did not speak English as their primary language were most apt to misinterpret the sign.

Ramp Metered When Flashing Sign

Although the Ramp Metered When Flashing sign (W19-3) is not in the national MUTCD, it does appear in the Texas MUTCD (*10*). When used, it is accompanied with one or two flashing beacons. Drivers were asked the meaning of this sign:

Answer Choice	*Percentage*
When the yellow lights are flashing, a traffic signal at the entrance to the freeway is in use.	*45.7
Only a certain number of cars are allowed on the ramp when the yellow lights are flashing.	19.9
You must pay a toll to use the freeway entrance ramp.	7.6
Not sure.	26.8

A metered ramp is a relatively rare encounter for most drivers, particularly in the smaller cities where the survey was given. Therefore, many of the survey respondents based their responses solely on the sign comprehensibility instead of on previous driving experiences. Fewer than half of the respondents selected the correct meaning of this sign, although another 20 percent recognized the fact that ramp metering limits the use of the entrance ramp. The novelty of the sign as a traffic control device no doubt accounts for a portion of the 27 percent who selected the "not sure" response. This sign has a higher "not sure" response than any other warning sign in the survey. Drivers who knew the meaning of the sign tended to be from urban areas and had commercial or motorcycle driver licenses.

PAVEMENT MARKING RESULTS

Seven of the survey questions addressed pavement markings. The response rates for each of the pavement marking questions are given in Table 5. These results should be interpreted carefully, as differences in questions and response choices may not allow for comparisons between question results. This section describes the results of the survey questions on pavement markings. Similar questions were asked in a study performed by the Texas Transportation Institute (TTI) in 1981 (*5*). The results of the two surveys that span 10 years are compared for many of the questions.

Single Broken Yellow Center Line

Two questions were asked in the 1981 survey (*5*) about a broken yellow center line separating two lanes. The first question asked if the road was one way or two way, and the second question asked if passing was permitted. Both questions had a correct response rate of 87 percent in the statewide survey. When shown the film of a broken yellow center line, 53 percent gave the correct open-ended response for both issues. Another 20 percent had one or the other issue correct, but not both. A total of 28 percent did not understand the meaning of the marking at all.

In the current survey, participants were asked, "Which one of the following statements is true about the dashed yellow center line?"

Answer Choice	*Percentage*
This is a two-way road where you are allowed to pass.	*76.8
This is a two-way road where you are not allowed to pass.	12.2
This is a one-way road where you are allowed to change lanes.	8.2
Not sure.	2.8

Approximately 77 percent of the respondents correctly identified the broken center line as a two-way road where passing is allowed. However, more 12 percent of the respondents thought that passing was not allowed. Although the passing distinction was not made by 12 percent of the drivers surveyed, 89 percent of the respondents recognized the two-way characteristic of the broken yellow line. A relatively small percentage was not sure of the correct response. The most

TABLE 5 Survey Results for Pavement Markings

Pavement Marking	Percent		
	Correct	Incorrect	Not Sure
Single Broken Yellow Center Line	76.8	20.4	2.8
Single Broken White Lane Line	50.3	46.4	3.3
No-Passing Zone	88.0	9.0	3.0
Double Solid White Lane Line	61.0	29.0	10.0
Solid White Edge Line	74.7	20.0	5.3
Two-Way Left Turn Lane Marking	58.6	33.8	7.6
Preferential Lane Marking	65.3	6.8	27.9

erroneous response choice was selected by more than 8 percent of the drivers surveyed. Respondents who had taken a driver education course were far more likely to answer this question correctly than respondents who had not taken a driver education course.

Single Broken White Lane Line

Two questions were also asked in the 1981 survey (*5*) about a broken white lane line separating two lanes. The first question asked if the road was one or two way, and the second asked if passing was permitted. Only 47 percent selected the correct response of a one-way road. However, 93 percent chose the response that passing was permitted.

In this study drivers were to select one of three statements as being true about the dashed white line:

Answer Choice	*Percentage*
This is a one-way road where you are allowed to change lanes.	*50.3
This is a one-way road where you are not allowed to change lanes.	4.2
This is a two-way road where you are allowed to pass.	42.2
Not sure.	3.3

Just more than half of the respondents recognized the one-way designation of the white lane line. However, a large percentage (42 percent) responded that the white lane line indicated a two-way road. In this case the broken lane line effectively communicates the ability to change lanes or pass but does not effectively communicate directional information. An important variable associated with a correct response was driver education. Additionally, a linear relationship between age and correct responses was observed. Respondents under 25 answered this question correctly 65 percent of the time, and respondents over 75 answered correctly 10 percent of the time.

No-Passing Zone Markings

No-passing zone markings were the most understood pavement markings surveyed. The 1981 survey found that 93 percent of drivers recognized that these markings would be found on a two-way road. Almost all of the interviewees (99 percent) knew that a no-passing situation was indicated. However, when asked which direction of traffic was permitted to pass, only 69 percent identified the appropriate lane.

The current survey asked, "If you are traveling in the right lane, which of the following statements is true about the center line?"

Answer Choice	*Percentage*
This is a two-way road where you are allowed to pass.	5.8
This is a two-way road where you are not allowed to pass.	*88.0
This is a one-way road where you are allowed to change lanes.	3.2
Not sure.	3.0

Very few respondents (3.2 percent) confused the roadway with a one-way road, and very few (3.0 percent) were not sure of the meaning of this marking. These few were more likely to be older drivers, drivers with lower levels of education, non-Anglos, and drivers who had no driver education training.

Double Solid White Lane Line

When asked about the double white lines on the pavement, participants chose the following responses:

Answer Choice	*Percentage*
It is illegal to change lanes across these lines.	*61.0
You may change lanes across these lines with caution, if necessary.	22.1
You may change lanes across these lines from left to right, but not from right to left.	6.9
Not sure.	10.0

Thirty-nine percent of the drivers surveyed either considered it permissible, conditionally, to change lanes across double solid white lane lines (29 percent), or were not sure if changing lanes is permitted (10 percent). The fact that 61 percent of the respondents answered this question correctly is actually somewhat positive, given that the *Texas Drivers Handbook* (*8*) does not specifically address double solid white lines. The handbook illustrates the solid white line and describes its purpose to include channelizing, transitions, and lane use control. The handbook specifies that "crossing a solid white line should be avoided if possible." The in-context presentation used in the video survey portrayed a channelizing use of the double solid white lane lines. Therefore, some confusion may be explained by the similarity of use to the single solid white line and the lack of information available regarding double solid white lane lines. Respondents with college degrees were far more likely to choose the correct response. Driver education was not a significant variable for this pavement marking. With respect to age, the youngest drivers were most likely to select incorrect responses, and older drivers were more inclined to select the "not sure" response.

Solid White Edge Line

Drivers selected the following responses when asked the purpose of the solid white line on the right side of the roadway:

Answer Choice	*Percentage*
To let you know there is no curb on this road.	9.6
To let you know that you should not cross this line for any reason.	10.4
To let you know where the edge of your driving path is.	*74.7
Not sure.	5.3

The purpose of the question concerning the solid white edge line was to determine the number of drivers who mistakenly believe that it represents something other than the edge of the driving path—a belief held by 20 percent of those surveyed. The survey indicated that approximately 10 percent interpreted the edgeline as notice of the absence of a curb, which may be true in some cases, but not all. Another 10 percent viewed the solid white line as a prohibitive marking against crossing in all cases. A significantly correlated sociodemographic variable was language. To a driver whose primary language is not English the responses provided may seem similar or at least in some ways redundant. Age was not a significant factor in response to this question. The solid white edge line was not included in the 1981 survey (5).

Two-Way Left-Turn Markings

The Texas MUTCD states that the two-way left-turn center lane is "for exclusive use of left turn vehicles and shall not be used for passing and overtaking or travel by a driver except to make a left turn." The *Texas Driver Handbook* specifies that the center lane should not be used as a travel or passing lane but also says "the only time a vehicle should enter the center lane is at a point where the vehicle will have time to slow down or stop in order to make a safe left turn." When asked how they would use the center lane, participants responded as follows:

Answer Choice	*Percentage*
Get into this lane at the point where you are ready to turn left.	26.2
Get into this lane when you need to slow down in order to turn left.	*58.6
Get into this lane when you need to speed up in order to move into the traffic lane.	7.6
Not sure.	7.6

Technically, the first two responses could be considered appropriate, because of the slight difference between the statements of the Texas MUTCD and the driver handbook. For survey tabulation purposes, the second response (given by 58.6 percent of the respondents) was considered the preferred response, and the first response (given by 26.2 percent of the respondents) was considered second best. Since the question asked was "How do you use the center lane?" the respondents were told (if they asked) that there was no incorrect response, but that the second response was a desirable response.

Of interest was the percentage of drivers who use the center turn lane as an acceleration lane. This response, the least desirable driving response, was given by 7.6 percent of the survey respondents. Another 7.6 percent were not sure how the lane should be used. None of the driving or demographic characteristics were found to have a significant relationship to responses for this question.

The 1981 TTI survey included a multiple-choice question regarding two-way left-turn markings with the following choices and corresponding percentage of responses: (a) left turn lane, 59 percent; (b) passing lane, 5 percent; (c) emergency stopping area, 21 percent; and (d) don't know, 13 percent. Although the two questions are not comparable, the responses to each illustrate that 5 to 8 percent of drivers interpret these markings as acceleration or passing lanes and that a sizable percentage of drivers are not sure of the meaning of the markings.

The ambiguity surrounding this question (and the fact that 59 percent of drivers would use this lane to decelerate) points to a need for clarification. According to state trooper representatives on the current TTI study advisory panel, driving violations with respect to two-way left turn lane markings are apt to be enforced according to varying interpretations.

Preferential Lane Marking (Diamond)

The diamond preferential lane marking was included in the survey to determine the familiarity and comprehension level of Texas motorists statewide with a marking used only on select freeways in the state. When asked why the white diamond is painted on the pavement, respondents selected these responses:

Answer Choice	*Percentage*
This is a symbol used for aircraft speed control.	4.3
This lane is to be used only by certain vehicles.	*65.3
This is a two-way road.	2.5
Not sure.	27.9

A large percentage (28 percent) of respondents were not sure of the meaning of this marker. Incorrect and "not sure" responses were given more often by respondents living in the smaller cities of the sample. Many commented that they had never seen this marking. Correct responses were given more often by drivers in Houston, Dallas, and San Antonio. Other driver characteristics that were associated with knowledge of the diamond preferential lane marking were those with high levels of education, men, and those who had taken driver education. Unfamiliarity with this traffic control device was more prevalent among drivers over age 55 and those with lower levels of driving exposure: those who drove fewer miles per year, made fewer long distance trips per year, and had no license. This pavement marking was not in use in Texas in 1981.

SUMMARY

This paper has described the results of a survey assessing driver comprehension of traffic control devices. The survey, which included 13 questions on regulatory signs, 18 questions on warning signs, and 7 questions on pavement markings, was given to 1,745 drivers in Texas. These summary results should be used with caution, as the correct response rate by itself

does not provide a true indication of the effectiveness of a regulatory sign. Instead, the survey results should be interpreted for each individual sign, giving consideration to the subject matter of the question and possible response choices. The correct response rate for a given question should not be equated with the effectiveness of the traffic control device.

Regulatory Signs

Comprehension levels for the regulatory signs ranged between 15 and 93 percent. The survey results for the regulatory signs revealed that the Reduced Speed Ahead sign more effectively conveys the upcoming lower speed limit than Speed Zone Ahead. Almost 80 percent of the respondents selected desirable driving responses to the Yield and Mandatory Movement word message signs. The Slower Traffic Keep Right, Do Not Cross Double White Line, and Keep Right signs were each indicated to be understood on the basis of correct responses by 70 percent of the drivers surveyed. Messages that involve a decision using choices of left and right or choices of contingency appear to be more complicated to drivers. The desirable response rate was only 65 percent for the Double Turn sign and 45 percent for the Two-Way Left Turn Only sign. These lower percentages may be a function of the measurement format, as evidenced by correlations between education, language, and desirable responses. The HOV Restriction sign was not interpreted correctly on the basis of responses from the majority of the drivers surveyed.

Warning Signs

Comprehension levels for the 18 warning signs ranged between 29 and 89 percent. However, the specific aspect of the warning sign being tested and the possible response choices to a specific question have an impact on the correct response rate. These results indicate that there are several warning signs that the driving public does not fully understand. Some of the more significant areas of misunderstanding include the following: many drivers are not aware of the basic color and shape premises associated with warning signs, drivers do not associate a speed with the Turn and Curve signs, drivers are not familiar with the concept behind the Ramp Metered When Flashing sign, the Divided Highway Ends and the Divided Highway signs are sometimes confused with each other, drivers confuse the Slow Down on Wet Road sign with the Winding Road sign, drivers do not recognize that the Grooved Pavement Ahead sign is intended for motorcyclists, and drivers associate Railroad Advance Warning signs with the crossing location itself and not an advance notice of the crossing.

Pavement Markings

In the 1981 TTI survey, the findings showed that those drivers with the highest level of knowledge of pavement markings were those who had taken a driver education course. This characteristic was the most important to overall understanding of the road marking code system. Drivers in the 1981 sample who took driver education tended to be young men who drove fewer miles per year than older drivers and had taken the driver education course within the previous 2 years.

Examination of comparable questions in the 1981 and 1991 surveys does not indicate much improvement in pavement marking comprehension. In 1981 two-way traffic and permissive passing was associated with the broken yellow center line by 87 percent of drivers. In 1991 the corresponding percentage was 77. Although 88 percent of the 1991 survey respondents correctly responded to a single question concerning no-passing zone markings, 93 and 99 percent of the 1981 respondents knew the two-way and no-passing indications, respectively. Forty-seven percent in 1981 recognized white pavement markings as applicable to one-way roads, compared with 50 percent in 1991. The two-way left-turn marking question was answered correctly by 59 percent of Texas drivers in both surveys.

These results suggest that, in general, the comprehension level of pavement markings has not improved in 10 years. A key avenue for improvement among younger drivers is driver education. Among drivers over 55, other methods such as public information efforts and message reinforcement through signing would probably be more effective. As the driving population ages in conjunction with the current pavement marking system, continuity may bring about greater understanding of traffic control devices.

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Presenting Descriptive Information in Variable Message Signing

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In a study of driving simulators the effects on route choice and driving behavior of presenting descriptive types of information on variable message (route guidance) signs were evaluated. Subjects had to choose between a normal route to a fixed destination, which could suffer from congestion of varying severity, and an alternative route. Three modes of variable information presentation were compared: (a) length of congestion, in kilometers; (b) delays relative to normal travel times, in minutes; and (c) travel times, in minutes. The reliability of the information was also varied and could be high, intermediate, or low. Thirty-six men participated in the experiment, and every subject made 123 runs in the simulator. By presenting descriptive information, divergence levels were found that varied widely over the range from 0 to 100 percent, as a function of the actual information given. This is to be compared with the inflexibility of conventional (prescriptive) signing. User optimum was most often reached by presenting travel time information. Such information also proved to be most resistant against degradations in reliability. There was an overall increase in driving speed when descriptive information was given, and this may be interpreted as anticipatory behavior from the side of the driver to compensate for the expected delay upon finding the normal route to be congested.

Certain parts of a road network may suffer from congestion while other sections still have spare capacity. In those cases variable message signing (VMS) may be a means for diverging traffic from an originally intended, or normal, route toward a reasonable alternative.

A driver's inclination to diverge and the driver's capability to find a user-optimal decision strategy will depend on what information is presented and how it is presented. An important choice for the signing authority in this respect is whether to present prescriptive messages that indicate the alternative that one would want the driver to follow or to present descriptive messages that inform the driver of relevant conditions on the alternatives without providing an explicit recommendation.

The potential gain of descriptive VMS messages is that driver acceptance could be high because drivers would appreciate the freedom to make their own choices. And because information could be given in a fine-grained form, so that it could reflect prevailing conditions on the alternatives with high accuracy, descriptive messages could achieve a level of fine-tuning of traffic streams to capacities that would be unattainable with prescriptive messages.

It is in this latter respect, however, that descriptive modes of information provision may be vulnerable—that is, the presented information had better be sufficiently reliable, or drivers might start disregarding it to such a degree that the road-signing authority wishes it had stuck to a purely prescriptive mode of signing. Empirical evidence on some aspects of descriptive information modes was gathered in questionnaire studies by Heathington et al. (*1*) and Dudek et al. (*2*). These studies were directed at discovering motorists' preferred forms of descriptive information when encountering congestion. The pattern of the results in both studies appeared to be that information on congestion length and travel speed was clearly preferred to descriptions of travel time or delays in travel time. For several reasons, however, this pattern may not be directly applicable to the present issue. First, both studies asked only about preferred information on a single (habitual) route, without actually posing a choice problem. Second, situations displayed were hypothetical and did not involve actual behavior. Third, the issue of reliability was not raised, that is, it was not investigated whether preferences would have been maintained after experiencing possible fluctuations in the degree of reliability of the information.

Heathington et al. subsequently did put their subjects in a (hypothetical) choice situation in which they could indicate whether they would diverge to avoid some specified delay at a certain monetary cost (*3*). Results showed that probability of diversion was a function of the magnitude of the delay (or saved travel time) as well as of the implicated cost. Like the earlier authors, however, Heathington et al. did not consider how the inherent unreliability of the displayed information could affect behavior.

The recent literature on VMS, motivated by the increasing congestion levels on the world's roads, contains modeling efforts of diversion behavior in which a central role is assigned to motorists' apprehension of the state of affairs on the alternative routes (*4,5*). However, these models appear to lack realism because they must pose levels of user knowledge—and conditionalize model outputs on these—that are arbitrary because it is not known what these depend on (e.g., the type of information and the way it is displayed and the inherent unreliability that this information might possess).

The present study sought to determine the effects on drivers' inclinations to diverge from their normal routes when descriptive VMS messages of different reliability are encountered. Reliability here is defined in terms of the degree of correlation between the information provided on the VMS sign and the driver's subsequent experience on the chosen alternative, that is, the actual arrival time.

DESIGN OF STUDY

Subjects were presented with route-choice decisions while driving in the TNO Institute for Perception's driving simu-

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lator. Driver behavior was measured at the decision locations so that the experiment would yield results not only in terms of route choices but also on the relation between route choice and actual driving behavior (*6*).

General

Subjects were first shown a stylized layout of the configuration of highways around Amsterdam (Figure 1). They were asked to imagine themselves as having to arrive in Zaanstad each day at 9:00 a.m. at the latest, finding themselves at Diemen at 8:30 a.m. and having to choose to circumvent Amsterdam clockwise or counterclockwise from the entrance of the beltway. An experimental run consisted of the subjects driving from Diemen to the decision point at the entrance of the beltway and then farther, for a total of about 4 km. The simulator then stopped and subjects were told of their arrival times. No other simulated traffic was present.

VMS Implementations

VMS signs were positioned 300 m from the entrance of the beltway. VMS descriptive information was presented in three ways:

1. Length of congestion on the alternatives, in kilometers (Figure 2);
2. Expected delays relative to normal travel times on the alternatives, in minutes (Figure 3).
3. Expected travel times on the alternatives, in minutes (Figure 4).

A standard (prescriptive) decision sign was, moreover, positioned exactly at the entrance of the beltway, that is, at the end of the sequence of signs that subjects encountered. Under normal conditions (no congestion on either of the alternatives) the expected travel time was taken to be 7 min in the clockwise direction (A10-W) and 12 min in the counterclockwise direction (A10-O). These were based on an average travel speed of 100 km/hr. Under critical conditions congestion was assumed on the clockwise route (A10-W), and it could vary in length between 1 and 6 km. Corresponding travel speed under congestion was taken to be 23 km/hr, with resulting expected travel times on the normal (clockwise) routes varying between 9 and 19 min, and with consequent expected delays ranging from 2 to 12 min. The alternative (counterclockwise) direction

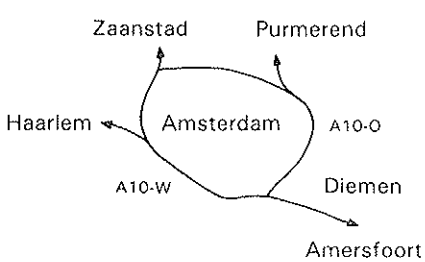

FIGURE 1 Configuration of Amsterdam Beltway as used in experiment.

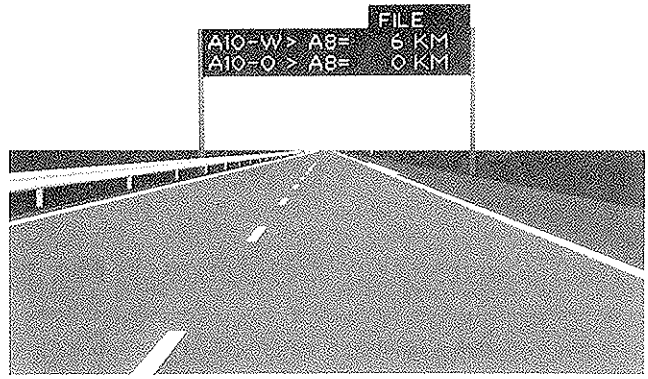

FIGURE 2 Indication of congestion lengths; sign says there is 6 km congestion (FILE) on normal route (A10-West), and none on alternative (A10-East) to A8 interchange (for Zaanstad destination).

was always assumed to be congestion-free, so the expected travel time on this route was always 12 min.

Reliability of Information and Arrival Times

The reliability of the information presented to subjects was experimentally manipulated by varying the degree to which actual travel times fluctuated about their expected values, which are the values given in the previous section. For example, if there was an assumed 3-km-long congestion on the normal route, resulting in a 6-min expected delay on that route, the real delay as experienced by subjects would always be close—on either side—to 6 min in the most reliable condition, whereas it would fluctuate considerably about that value in the least reliable condition.

Reliability conditions were thus defined in terms of the standard deviation of travel times (or, equivalently, delays) about their expected values. In the most reliable condition the standard deviation was 1.4 min; in the moderately reliable condition, 2.5 min; and in the least reliable condition, 3.0 min.

The manipulation of reliability levels was done only for the normal (clockwise) route. In the counterclockwise direction,

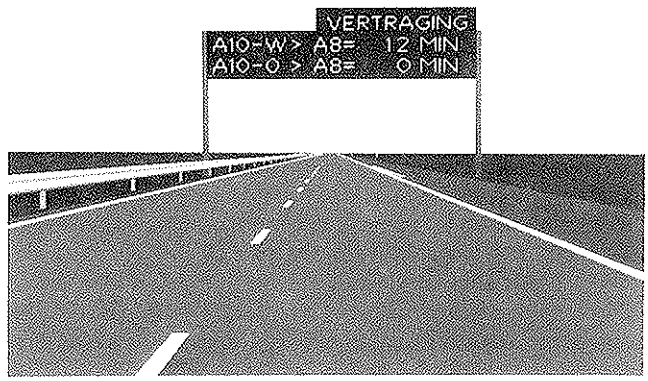

FIGURE 3 Indication of delays (VERTRAGING) relative to normal travel times.

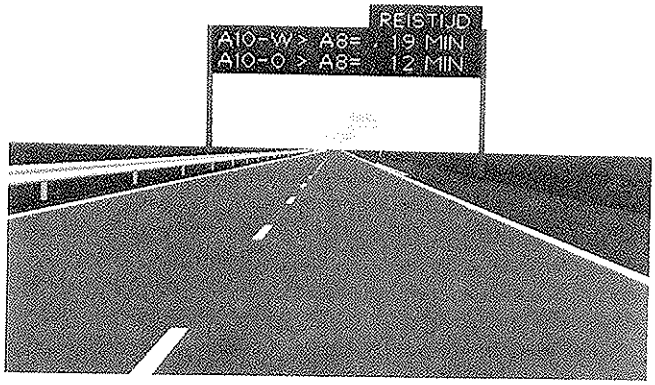

FIGURE 4 Indication of absolute travel times (REISTIJD).

travel times always had a standard deviation of 1.4 min about their expected values.

Arrival times were predetermined and did not depend on the subjects' actual speeds on the 4-km stretch that they drove. Thus, arrival times were only a function of the information shown on the VMS, of the prevailing (and predetermined) level of reliability of the messages, and of a subject's route choice.

The distributions of arrival times were composed in such a way that there was always a user optimum to diverge at a congestion length above 2 km (i.e., an expected travel time on the normal route above 12 min or a delay above 4 min), irrespective of reliability conditions.

The deadline for arrival at the Zaanstad destination was 9:00 a.m. A penalty applied of Fl 2.00 per minute late (Fl 1.81 = $1.00 U.S.). The total penalty earned was subtracted from an initial sum, which left most subjects with a reasonable award for taking part in the experiment.

Measurements

The TNO Institute for Perception's simulator has a MEGATEK 944 CGI-system that generates real-time images displayed by means of a high-resolution projector (BARCOGRAPHICS 800) (7).

Each subject conducted 123 runs in the simulator, 33 of which contained congestion on the normal route. In the first part of the series subjects were familiarized with the routes so that they could recognize the normal route. Besides the route choice decisions, the following measures of driving performance were taken at the decision point:

1. Vehicle speed on the last 200 m of the approach to the decision sign.
2. The position of the vehicle, measured in the longitudinal direction, on the off-ramp when the subjects diverged from the normal route.

Experimental Design and Subjects

The independent variables of information presentation mode (three levels) and reliability (three levels) were manipulated between subjects, so that there were 3 × 3 = 9 groups of four subjects each. Each subject thus drove for the complete series of 123 simulator trials under a fixed combination of "information presentation mode" and "reliability." The subjects were 36 men between 23 and 51 years old (average 34), with a minimum of 10 000 km/year traveled over the most recent 5-year period.

RESULTS

Diversions from Normal Route

Figure 5 shows the percentage of runs in which subjects diverged from the normal route. The reliability of the presented information appears to have a considerable effect on the inclination to diverge when information is in terms of congestion length. In this information mode it may happen, with less reliable information, that divergence does not even approach 100 percent under the most extreme conditions of congestion on the normal route.

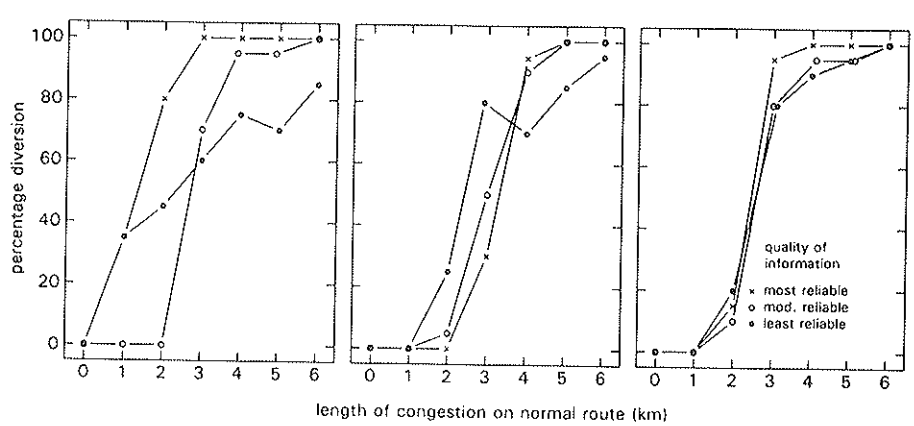

FIGURE 5 Rate of diversion as a function of informative mode, reliability of information, and extent of congestion (and associated travel time or delay: 1 km congestion is equivalent to 2 min delay): *left*, length of congestion; *middle*, delay; *right*, travel time.

When information is in terms of travel times or delays, divergence is much less affected by the reliability of the information, although there is the tendency that diversion levels only slowly approach 100 percent under the less reliable conditions.

Application of User-Optimal Strategy

The diversion data as shown in Figure 5 may also be analyzed in terms of whether subjects applied the user-optimal strategy—to diverge at congestion lengths (or their time equivalents) of more than 2 km. The following table gives the results:

	Reliability		
Information Mode	*High*	*Medium*	*Low*
Congestion length	81	93	68
Delay	81	89	84
Travel time	97	93	91

A χ^2-test on the data in this table yielded 4.68, which is significant at level $p < .05$ for 4 degrees of freedom. The pattern in the interaction is as follows. When information is given in the form of expected travel times, the user-optimal choice is made in most cases; this is not affected by the reliability of the information itself. Information on delays, relative to normal travel times, shows a lower overall percentage user-optimal choice, which also does not appear to be affected by the information's reliability. However, presenting the information in the form of an expected length of congestion is a mode that breaks down, in terms of user-optimal choice, at the least reliable condition.

Driving Behavior at Decision Point

An average increase in driving speed of 1.05 m/sec was observed on the last 200 m of approach to the decision sign when the preceding VMS sign contained information indicating a deviation from the normal (i.e., congestion-free) situation. As Figure 6 shows the exact magnitude of the increase depended on the indicated length of congestion (or its equivalent travel time or delay); the effect was statistically significant at $p = .002$ as tested by analysis of variance [$F(5.135) = 4.17$].

No relation was found between the off-ramp longitudinal position at which the vehicle left the normal route in case of divergence and either the VMS congestion message or the inclination to diverge itself, as measured by the relevant percentages for all subjects taken together.

DISCUSSION OF RESULTS

Effects of Decision To Diverge When There Is Descriptive Information

The results of this experiment show that the form in which descriptive information is given, the reliability of the information, as well as the content of the information determine whether a driver will diverge from the normal route. Not surprisingly, there is an overall increasing tendency to diverge when signing indicates worsening conditions on the normal route. However, a driver's inclination to diverge is also sensitive to certain conditions in which a particular type of information comes in conjunction with a particular level of reliability. Thus, although inherent reliability is of little effect in the travel time mode, reliability matters a lot when information is given as length of congestion.

The reason for this presumably is that the user optimum is easier to find when information is in the form of expected travel times, or delays relative to normal travel times, than when it is in the form of kilometers of congestion. That is, despite the deviations occurring between expected and actual arrival times, a driver is more capable of discerning the statistical relationship between these variables than when he or she must work on the basis of expected kilometers of congestion (with performance nevertheless being judged in temporal terms, i.e., having to arrive at the destination in time). The latter process thus simply appears to break down when sufficient unreliability is added.

Descriptive Information and Driving Behavior

The analysis of driving speed on the approach section to the decision point showed that the display of information indicating congestion on the normal route caused a slight increase in speed (3.8 km/hr). This may be interpreted as an anticipatory action in the face of an expected time loss, irrespective of the actual choice made at the decision point. The finding that the increase in speed tended to rise with the indicated severity of the congestion (Figure 6) is in line with this interpretation. Thus, there appears to be a link between the displayed descriptive information and the driving behavior on the approach to the decision point.

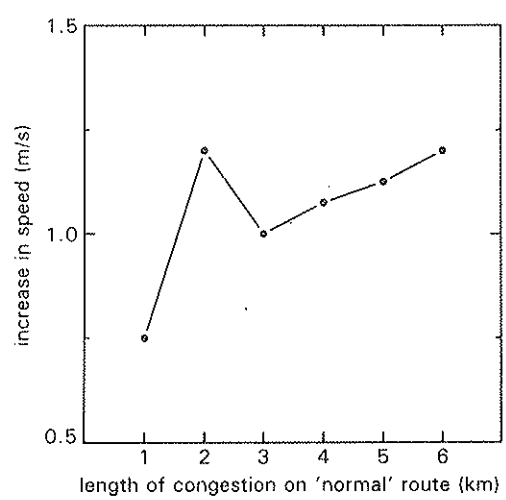

FIGURE 6 Relation between extent of congestion [length in kilometers, or equivalent travel time (delay)] and increase in speed relative to noncongested condition.

CONCLUSIONS

The experiment described in this paper permits the following conclusions:

1. Providing descriptive information on VMSs results in diversion rates that are sharply differentiated according to prevailing conditions, so that they offer a high potential for the fine-tuning of traffic streams to capacities in more or less critical route choice configurations.
2. Supplying descriptive information in the form of expected travel times is relatively insensitive to degradation in the reliability of the information.
3. Offering descriptive information in the form of congestion length in kilometers is relatively sensitive to degradations in reliability.
4. Driving speed toward the decision point increases slightly when VMS indicates congestion on the normal route.

ACKNOWLEDGMENT

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Hierarchy of Symbolic Computer-Generated Real-Time Vehicle Dynamics Models

MICHAEL W. SAYERS AND PAUL S. FANCHER

Symbolic multibody code generation technology enables a new approach for developing vehicle models for driving simulators. Rather than assembling terms in the equations of motion, a modeler can concentrate on modeling issues such as degrees of freedom (df), joint constraints, and kinematical assumptions. An automated code generator makes it practical to test many modeling assumptions to determine their influence on computation time and simulation fidelity, leading to a model that offers the most fidelity while running in real time on available hardware. The new methodology is illustrated by (a) describing seven vehicle handling models, with various levels of complexity, ranging from 4 to 10 df; (b) comparing the computational requirements for their use; and (c) presenting example comparisons of predicted motions. All of the models can be simulated in real time on a fast personal computer. The simplest (4-df) model runs more than 40 times faster than the more complex 10-df one, yet it predicts overall vehicle motions that agree closely. Among the 10-df models, the fastest runs 2.3 times quicker than the slowest. The methodology illustrated can be used to extend the models to include additional mechanical characteristics of interest.

Driving simulators are not in widespread use, even though they are acknowledged as highly useful research tools for human factors and psychology studies. Recent technical developments make the development of driving simulators much simpler than has ever been possible. Computer hardware has improved so much that even desktop computers with graphical capabilities have the speed and software needed to generate simple scenes in response to driver motions. A system consisting of a mock-up dashboard or car interior, computer, and visual display can now be assembled for a fraction of the cost required a few years ago. Complementing the hardware improvements are new software technologies that can be used to develop suitable vehicle dynamics models.

The purpose of this paper is to use these new software technologies to show quantitatively the effects of modeling assumptions used in familiar vehicle dynamics models with different levels of complexity (*1–6*). Comparisons are made on the bases of computational speed and accuracy.

All of the mathematical models described in this paper were developed using AUTOSIM, a software package that automatically derived equations of motion for mechanical systems composed of multiple rigid bodies. The AUTOSIM software has been described previously (*7,8*). The models presented are not new and have also been described before. By combining an automated equation generator with a set of vehicle models, it is possible to compare the models quantitatively. In this paper, the focus is on the kinematics of the various models. The goal is to demonstrate a general method for using new technology involving the dynamics of multibody systems and the automatic generation of symbolic computer codes for simulating vehicle dynamics.

This paper illustrates a new way of thinking about models—not as a set of equations, but as physical connections with degrees of freedom (df), constraints, and their kinematical interpretations.

NEW MULTIBODY SIMULATION TECHNOLOGY (AUTOSIM)

AUTOSIM is a symbolic code generator that reads text input describing the model and produces source code as output in one of the supported computer languages (FORTRAN, C, MATLAB, ACSL, and ADSIM). Parameters are represented by symbols, so that the same equations can be applied many times without changing the equations themselves. Persons wishing to try the ideas presented in this paper can license AUTOSIM commercially in North America from Mitchell and Gauthier Associates in Concord, Massachusetts, and, for other countries, from University of Michigan Software, in Ann Arbor.

The method of developing models with a symbolic multibody program provides several novel advantages:

- Equations are written in terms of parameters chosen by the modeler instead of a fixed set of multibody parameters.
- The multibody program is used only to develop the model. Once the equations are written, the model can be exercised directly to answer questions of interest.
- The time needed to develop a self-contained simulation code is very short (typically, a few hours—a time that might not appear possible to persons with experience in developing models by other methods).
- AUTOSIM usually generates equations that are more efficient than those developed by any other method, including hand derivations made by experts. It uses an advanced form of Kane's equations (*9*) and then applies extensive algebraic and programming optimization methods to achieve high efficiency. [See work by Sayers (*10*) for comparisons of AUTOSIM formulations with those obtained by other methods, including hand-derivation, for several models.]

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- The generated source code is completely accessible for inspection and modification.
- Hand-written subroutines and auxiliary variables can be easily included in models.
- An interactive multibody program lets the modeler rapidly develop and inspect equations to debug the model and evaluate alternative modeling assumptions.

The mathematical basis of for this technology has been described previously (*7,8*), and example uses of the technology in support of a comprehensive vehicle system dynamics model for a driving simulator have been presented (*11,12*).

Communicating with AUTOSIM entails describing the system to be simulated on the computer. In general terms, the software is structured around a geometric description of the system, involving matters such as the connections between bodies and the locations of the joint connections, the centers of mass, and the action of the forces. Developing a model with the new technology clearly involves different tactics than developing a model with pencil and paper. Mathematical matters that otherwise might be given a great deal of attention have been reduced to computer algorithms, freeing the modeler from some past burdens.

The rest of this paper uses the type of thinking that goes into the development of a vehicle model when using a symbolic multibody program. Alternative models are developed for a vehicle system, using a fixed set of basic vehicle parameters. Modeling decisions are described explicitly, and the effects are shown quantitatively in terms of the complexity of the resulting equations and the accuracy of the model predictions.

MODEL DESCRIPTIONS

Vehicle Description

For purposes of comparison, a hierarchy of vehicle models is defined, from complex to simple. The models are formulated to calculate the vehicle response to steer inputs when running on a smooth and level surface at a constant speed. Table 1 gives the complete set of parameters used in the models. The vehicle being considered is a front-wheel-drive compact with a solid rear axle and independent front suspension with unequal upper and lower control arms. To help isolate the significance of assumptions that reduce the kinematical complexity, areas of behavior that are not of primary interest are left out of the models or greatly simplified. The models will be compared under conditions of constant forward speed, therefore longitudinal tire forces are not included. Details of how control inputs from the driver cause the wheels to steer are not considered: the control inputs in the models are simply the steer of the front wheels. Aerodynamic effects are ignored. Suspension and tire matters are treated in the following discussions.

TABLE 1 Vehicle Parameters

Symbol	Value	Description
C_{A1}	880N/deg	front cornering stiffness, one tire
C_{A2}	880N/deg	rear cornering stiffness, one tire
C_{S1}	600 N-s/m	front shock absorber damping (1 wheel)
C_{S2}	600 N-s/m	rear shock absorber damping (1 wheel)
F_{ZA1}	880 kg	front axle load (2 wheels)
F_{ZA2}	550 kg	rear axle load (2 wheels)
H	0.51 m	height of sprung mass c.g. above the ground
H_{RC1}	0.0 m	height of front suspension roll center
H_{RC2}	0.25 m	height of rear suspension roll center
I_{XX}	330 kg-m2	moment of inertia of S
I_{YY}	1300kg-m2	moment of inertia of S
I_{ZZ}	2000 kg-m2	moment of inertia of S
K_G	5 deg/m	change in wheel inclination with vertical position
K_{S1}	26000 N/m	front suspension vertical stiffness (1 wheel)
K_{S2}	26000 N/m	rear suspension vertical stiffness (1 wheel)
K_{SWAY1}	600 m-N/deg	auxiliary anti-roll stiffness for front
K_{SWAY2}	50 m-N/deg	auxiliary anti-roll stiffness for rear
K_{T1}	175000 N/m	front tire vertical stiffness (1 wheel)
K_{T2}	175000 N/m	rear tire vertical stiffness (1 wheel)
L	2.5 m	wheelbase
M_{A1}	120 kg	front unsprung mass (2 wheels)
M_{A2}	90 kg	rear unsprung mass (2 wheels)
R_1	0.3 m	front tire rolling radius
R_2	0.3 m	rear tire rolling radius
S_2	0.6 m	rear spring spacing
T_1	1.4 m	front track
T_2	1.4 m	rear track

Suspension Kinematics

Figure 1 shows a simplified front view of the front suspensions, with the dimensions T_1, R_1, and H_{RC1}. The figure also shows a linkage analysis of the independent suspension on the right-hand wheel that locates an instant center. (For small vertical movements of the wheel, the motions are as if the wheel is attached to a rigid body that rotates about the instant center.) By considering a simple rotation, it is easy to visualize small roll-plane motions of the wheel and determine such properties as how the camber and track (distance between tire centers) change with suspension deflection. The instant center is also a point at which the net moment applied to the car body by the suspension is 0. Thus, any force acting on the wheel whose line of action passes through the instant center does not apply a moment to the car body. The figure shows a line connecting the instant center with the center of the contact patch between the tire and the road. The moment applied to the car body as a result of a tire force vector is determined by the orientation of the vector relative to this line. Because of symmetry, a similar analysis for the other front wheel leads to the identification of a single point that is at the intersection of the lines connecting the tire contact patch centers with the corresponding instant centers. The intersection point is called the roll center. The instant centers and roll center are "paper points" that do not correspond to any physical connections. Their locations depend on the actual position of the unsprung masses. Thus, the instant centers, and the roll center, can change position as the suspensions move.

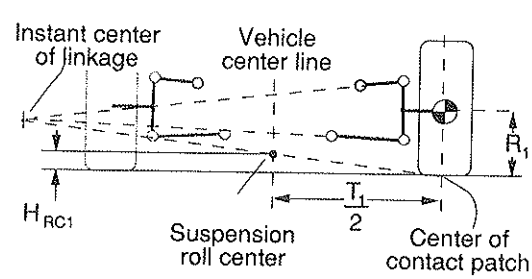

FIGURE 1 Front suspension.

The mass center for the suspension subsystem (wheel, spindle, and suspension links) is shown at the center of the wheel. In general, the mass center is not at this point, although it is close. The approximation is made to reduce the number of parameters.

Figure 2 shows the corresponding view for the rear axle. For simplicity, a leaf-spring suspension is shown. However, the same dimensions (T_2, S_2, and H_{RC2}) could be used for any suspension with a solid axle. Here, the leaf springs react lateral forces such that the net moment applied to the sprung mass is 0 along a line connecting the attachments of the springs to the body. [The role-center analyses illustrated in Figures 1 and 2 are brief and simple. More detailed analyses can be found elsewhere for a variety of suspension types (*13*).]

Fully detailed suspension descriptions are usually inappropriate for low-cost real-time driving simulators. Simplified representations, as will be presented, have been used in models that have been validated through comparison with experimental handling tests. In all of the models that follow, suspension kinematics are simplified. The degree of simplification depends on the model.

Suspension Force Elements

Linkages shown in Figures 1 and 2 control the motions permitted between the sprung and unsprung masses. In addition, springs and dampers connect the bodies. In both the front and rear, each side has a spring with a force deflection relation

$$F_{\text{spring}} = f_{\text{static}} + f_s(\delta) \tag{1}$$

where δ is the spring deflection and f_{static} is the static load carried by the spring. Each suspension may have auxiliary forces applied as functions of relative roll, due to antisway bars and linkage compliances. This effect results in a force acting between the two wheels on the same suspension, and has the general form

$$F_{\text{roll}} = f_r(\delta_L - \delta_R) \tag{2}$$

where, in this case, δ_L and δ_R are movements of the left and right wheels relative to the body. The suspensions also include shock absorbers that produce force as a function of shock absorber displacement rate:

$$F_{\text{damper}} = f_d(\dot{\delta}) \tag{3}$$

The displacements and rates appearing in these equations (δ, δ_L, δ_R, and $\dot{\delta}$) are derived from the kinematics of the moving rigid bodies by AUTOSIM. The force laws, expressed by the functions f_s, f_d, and f_r, can be arbitrarily complex nonlinear relationships. In this paper, simple linear relations are used. The spring forces are computed using linear coefficient K_{S1} and K_{S2} for the front and rear springs, the damping forces are computed using linear coefficients C_{S1} and C_{S2} for front and rear dampers, and the auxiliary roll force is computed with a linear relation

$$F_{\text{roll}} = 57.3\,\frac{K_{\text{SWAY}}}{S}\,(\delta_L - \delta_R) \tag{4}$$

where K_{SWAY} and S are as defined in Table 1.

The baseline set of parameters shows a spring spacing for the front suspension equal to the track. This means that the spring and damper rates are effective at the wheel plane. None of the models represents the relative displacement of a coil spring in a double A-arm suspension, and therefore the forces predicted by the different models do not agree unless the spring spacing is set equal to the track. To apply spring or damper data to any of these models, a separate analysis is needed to convert the true force and deflection to the effective force and deflection at the wheel plane. This is an application of a multibody program that has been described elsewhere (*11*).

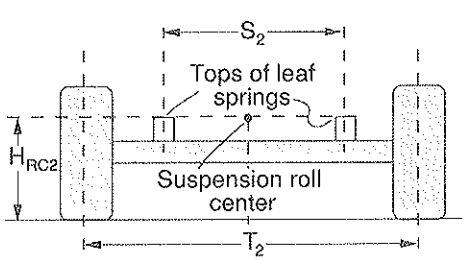

FIGURE 2 Rear axle.

Tire Forces and Moments

The most important actions affecting a vehicle being steered at constant speed are the vertical tire forces and lateral shear forces. Experiments have established that the vertical and lateral tire forces are essentially functions of just a few variables. The vertical force (normal to the ground surface) has the form

$$F_Z = f_{\text{static}} + f_z(\delta, \gamma) \tag{5}$$

where δ is tire deflection (from the static condition) and γ is tire inclination angle. The relation that will be used for all models in this paper is

$$F_Z = -g\,\frac{F_{ZA}}{2} - K_T\delta_T \tag{6}$$

where F_{ZA} and K_T are parameters defined in Table 1 for front and rear wheels and δ_T is the change in the distance from the center of the wheel to the center of the contact patch between the tire and ground. An expression for δ_T is derived by AUTOSIM for each wheel in a model, on the basis of multibody kinematics. (The negative sign is to satisfy the SAE coordinate system, in which the vertical Z-axis points down.)

When running at constant speed with no longitudinal forces from braking or acceleration, lateral tire force is a function of vertical load and a few kinematical variables:

$$F_Y = f_y(F_Z, \alpha, \gamma, V, \mu) \tag{7}$$

where

α = slip angle (angle between direction a rolling tire is pointing and direction of velocity vector of a point in wheel plane where it meets ground),

γ = inclination angle of wheel,
V = forward speed of rolling tire, and
μ = friction coefficient.

The vertical load is determined by Equation 6, α and γ are determined by multibody kinematics, and μ is a parameter. [The slip angle, α, is sometimes given a time delay to account for the need for the tire to roll a certain distance, called the relaxation length, to build up a lateral force (*14*).] For all of the models that will be presented, a very simple relation is used to determine lateral tire force:

$$F_Y = -57.3\ C_A\alpha \tag{8}$$

This model omits significant influences, particularly those of load (F_Z) and inclination angle (γ). The omissions are made to simplify the comparisons between the different models. The F_Z values predicted by the different models are compared to show the form of inputs available to a sophisticated tire model if one were to be used.

Models that are developed and compared in the following will not include aerodynamic effects or longitudinal tire forces that occur when braking. Tire moments will not be considered either.

Summary of Models

There are many ways to model a vehicle to include the elements described and predict vehicle motions in response to control inputs. Four multibody models were developed to describe a vehicle with the characteristics just described. Furthermore, equations were formulated for the first model using four variations. Thus, seven formulations were obtained.

Models 1a Through 1d: 10-df Models with Translational Joints

The first three models (1a, 1b, and 1c) are similar to the Highway-Vehicle Object System Model (HVOSM), developed two decades ago for mainframe and hybrid computers (*5*). They have 10 pertinent df: 6 for the sprung mass (the car body), 2 for the rear axle, and 1 each for the two front independent suspensions. The independent suspensions are modeled by assuming that the wheel unsprung masses move relative to the car body as if they were connected with purely translational joints, as shown in Figure 3. Although the translational joint in the figure is shown at a slant to add generality, in the original HVOSM model and in Models 1a, 1b, and 1c, the direction of the translation is parallel to the vertical axis of the sprung mass. In the AUTOSIM program, this kinematical relationship is described by defining each front wheel/suspension body as being connected to the sprung mass and as having a single allowable translational motion, parallel to the Z-axis of the sprung-mass coordinate system. The simple translational motions, permitted each wheel, approximate the motion of the front suspension.

When the lateral tire forces, applied in the road plane, are reacted completely by the translational joint, they do not apply a roll moment to the car body. However, the simple kinematical analysis shown in Figure 1 indicates that the double-arm suspension applies a net moment of 0 only at the roll center. The two cases are not equivalent unless the suspension roll center is at the ground plane, as is the case for the nominal parameter values given in Table 1. (The original HVOSM model was modified to include additional terms, called jacking forces, to generate the correct reaction forces and moments between the wheel and car bodies).

The multibody representation of the rear axle is shown in Figure 4. A massless intermediate body is connected to the sprung mass at the roll center. The unsprung mass, consisting of a rigid body with the axle, wheels, tires, and the like lumped together, is connected to the intermediate body with a purely translational joint.

The tire deflections and slip angles are defined by considering vectors defined in a coordinate system of a wheel spindle rigid body. Consider the geometry shown in Figure 5. The inertial coordinate system is defined by X-, Y-, and Z-axes whose directions are shown in the figure. The directions are defined mathematically by unit vectors $\mathbf{n}_x$, $\mathbf{n}_y$, and $\mathbf{n}_z$. Three unit vectors are also fixed in the moving reference frame of the spindle: $\mathbf{s}_x$, $\mathbf{s}_y$, and $\mathbf{s}_z$. Point S is at the center of the wheel, Point O is a point fixed in the ground plane, and Point C is defined such that it is in the local Z-direction ($\mathbf{s}_z$) of the spindle, relative to Point S, and it coincides with the ground plane. The position vector going from Point S to Point C is

$$\mathbf{r}^{SC} = r\mathbf{s}_z \tag{9}$$

The fact that Point C lies in the ground plane is expressed mathematically by the condition

$$\mathbf{r}^{OC} \cdot \mathbf{n}_z = 0 \tag{10}$$

where $\mathbf{r}^{OC}$ is the position vector connecting Points O and C. Noting that

$$\mathbf{r}^{OC} = \mathbf{r}^{OS} + \mathbf{r}^{SC}$$

the local Z-coordinate of Point C (r in Equation 9) can be

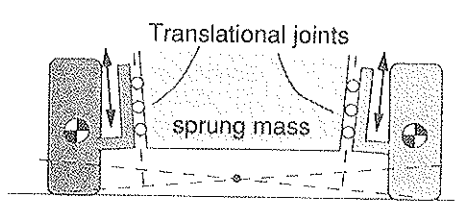

FIGURE 3 Multibody representation of front suspensions for Model 1.

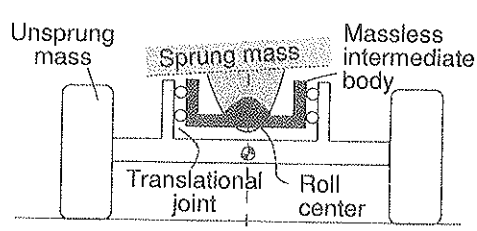

FIGURE 4 Multibody representation of rear axle for Model 1.

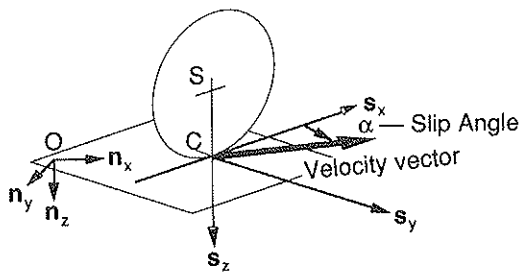

FIGURE 5 Geometry of slip angle.

defined as

$$r = -\frac{\mathbf{r}^{OS} \cdot \mathbf{n}_z}{\mathbf{s}_z \cdot \mathbf{n}_z} \tag{11}$$

The tire deflection δ_T, appearing in Equation 6, is simply

$$\delta_T = r - \bar{r} \tag{12}$$

where $\bar{r}$ is the value of r when the system is in its nominal configuration.

The rigorous geometric definition of slip angle, α, is the angle between the vector projection of $\mathbf{s}_x$ onto the road plane and the absolute velocity vector of Point C, $\mathbf{v}_C$:

$$\alpha = \text{angle}\{[\mathbf{s}_x - (\mathbf{s}_x \cdot \mathbf{n}_z)\mathbf{n}_z], \mathbf{v}^C\} \tag{13}$$

where angle(•) is a function that determines the angle between two vectors and $[\mathbf{s}_x - (\mathbf{s}_x \cdot \mathbf{n}_z)\mathbf{n}_z]$ is the projection of $\mathbf{s}_x$ onto the ground plane. Model 1a uses this definition of slip.

When this definition for the slip angle is used as an input, AUTOSIM derives a lengthy formula that fills several pages. A considerably more simple formulation is obtained by changing the definition slightly to consider the angle in the plane perpendicular to the vector $\mathbf{s}_z$:

$$\alpha' = \text{angle}\{[\mathbf{s}_x, \mathbf{v}^C - (\mathbf{v}^C \cdot \mathbf{s}_z)\mathbf{s}_z]\} \tag{14}$$

Although these two formulations for slip angle appear very similar, it will be seen that the second one improves the simulation performance by about 50 percent. The reason is that the formulation in Equation 13 includes the local velocity of C in the reference frame of the wheel spindle. The local velocity component, in the $\mathbf{s}_z$ direction, is eliminated in the second formulation. Models 1b, 1c, and 1d use Equation 14 to define slip.

When formulating equations for mechanical systems, modelers often use knowledge that some movements are "small" to simplify the equations. AUTOSIM also has this capability (*8*). Model 1c was produced by declaring to AUTOSIM that certain motions are small. (Except for forward speed and yaw angle, the translations and rotations for all df were declared as small in Model 1b, thereby producing Model 1c.)

Models 1a, 1b, and 1c involve all of the parameters in Table 1 except two: the front roll center height, H_{RC1}, and the change in wheel inclination with vertical position, K_G.

A fourth variation, Model 1d, was defined by describing inclined directions for the translational joints as shown in Figure 3. For Models 1a, 1b, and 1c, the direction of the translation was defined as being purely in the Z-direction of the sprung mass, $\mathbf{s}_z$. For Model 1d, the direction $\mathbf{d}_t$ was specified as

$$\mathbf{d}_t = \frac{T_1}{2}\mathbf{s}_z \pm H_{RC1}\mathbf{s}_y \tag{15}$$

When the parameter H_{RC1} is assigned a value of 0, the two formulations are equivalent. However, because the equations for Model 1d include terms for the condition that H_{RC1} is not 0, the full equations are more complex.

Model 2: 10-df Model with Rotational Front Suspension Joints

The second model is identical to the Model 1c, except in the treatment of the front suspensions. Figure 6 shows the multibody representation of the geometry of the front wheel spindles. The instant center of rotation, a "paper point" shown in Figure 1, is used as the physical point of attachment between the unsprung and sprung masses. The model shown in Figure 6 defines the transfer of roll moments between the unsprung and sprung masses that is correct when the suspension is at the nominal (design) position. The model also predicts the first-order change in wheel camber angle with suspension deflection.

This model requires two dimensional parameters to locate the instant center: a lateral coordinate and a vertical one. These two dimensions are not common ones for vehicle dynamics models. However, they can be defined in terms of two commonly used parameters: roll center height, H_{RC1}, and a coefficient for the linear change in inclination angle with respect to vertical movement, K_G (see Table 1). The lateral distance from the wheel plane to the instant center is given by

$$L_{ICY} = \frac{57.3}{K_G} \tag{16}$$

and the height of the instant center above the ground plane is

$$H_{IC} = 2H_{RC1}\frac{L_{ICY}}{T_1} \tag{17}$$

As was done for Model 1c, all motion variables except the forward speed and the yaw angle are declared as small. Slip angles were defined by Equation 14. This model involves every parameter given in Table 1.

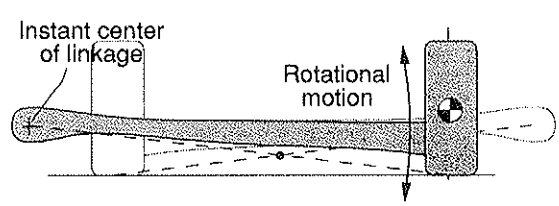

FIGURE 6 Multibody representation of front suspensions for Model 2.

Model 3: 6-df Model

This model has 6 df and is similar in pertinent respects to the VDANL model (*2,4*). Three df involve planar movement of a vehicle reference frame (*X*- and *Y*-translations and yaw rotation). The moving reference frame has front and rear roll centers, about which the front and rear unsprung masses roll. The geometry, shown in Figure 7, is as if the vehicle has two solid axles that rotate independently about a longitudinal axis passing through the respective roll centers. The sprung mass rolls relative to the reference frame as if it were connected by a hinge whose axis passes through both roll centers (see Figure 8). The body and two axles each add a roll df to the system, bringing the total to 6.

The equations derived for this model were made after specifying that the roll angles (and rates) and the lateral velocity are small. All of the parameters in Table 1 are used in this model, except K_G.

To describe the model in terms of the parameters of Table 1, all of the points needed to define the spring, damper, and tire forces are introduced. Because the AUTOSIM descriptions of forces from the tires, springs, and dampers depend on the relative movements of the reference points, the descriptions used for the 10-df models were repeated without modification to describe this model.

Model 4: 4-df Model

This model is similar to the 3-df model developed and validated by Segel in the 1950s (*6*) and embellished since then in many variations (*1*). Kinematically, the model is nearly identical to Model 3, except that the front and rear axles are not permitted to roll. Thus, all suspension motions are lumped into a single rotational df of the sprung mass about the roll axis. To maintain compatibility with the other models, torsional stiffness and damping coefficients are defined in terms of the parameters in Table 1. The torsional stiffness for each suspension $i(i = 1, 2)$, $K_{\text{susp}i}$, and each pair of tires, $K_{\text{tire}i}$ ($N - m$/rad), can be written

$$K_{\text{susp1}} = 57.3\, K_{\text{SWAY1}} + \frac{T_1^2\, K_{S1}}{2} \tag{18}$$

$$K_{\text{susp2}} = 57.3\, K_{\text{SWAY2}} + \frac{S_2^2\, K_{S2}}{2} \tag{19}$$

$$K_{\text{tire}i} = \frac{T_i^2\, K_{Ti}}{2} \qquad \text{for } i = 1, 2 \tag{20}$$

An overall torsional stiffness for each axle, with effects of both suspensions and tires being treated as springs in series, is then defined as

$$K_{\text{tors}i} = \frac{1}{\dfrac{1}{K_{\text{susp}i}} + \dfrac{1}{K_{\text{tire}i}}} \qquad \text{for } i = 1, 2 \tag{21}$$

A torsonal damping coefficient for each axle is defined as

$$C_{\text{tors1}} = \frac{T_1^2\, C_{S1} K_{\text{tors1}}}{2\, K_{\text{susp1}}} \tag{22}$$

$$C_{\text{tors2}} = \frac{S_2^2\, C_{S2} K_{\text{tors2}}}{2\, K_{\text{susp}i}} \tag{23}$$

where the ratio $K_{\text{tors}i}/K_{\text{susp}i}$ is used to scale the torsional damping to be representative of the level of shock absorber motion.

The total roll moment acting on the sprung mass, from both Axles 1 and 2, is

$$M_{\text{roll}} = -(K_{\text{tors1}} + K_{\text{tors2}})\phi - (C_{\text{tors1}} + C_{\text{tors2}})\dot{\phi} \tag{24}$$

Although the tire behavior assumed for all models in this paper does not include the effect of load on lateral shear force, the ability of the models to predict vertical tire load would of interest if a load-sensitive tire model were to be used. With the 4-df model, the vertical tire force can be written

$$F_Z = \frac{F_{ZA}}{2} \pm \frac{M_{\text{roll}}}{T} \tag{25}$$

MODEL PERFORMANCE

Each model was described as an AUTOSIM input. AUTOSIM then generated a ready-to-run FORTRAN simulation program for that model. The simulation programs take nearly identical inputs (the parameters shown in Table 1) and integrate ordinary differential equations to obtain motions of

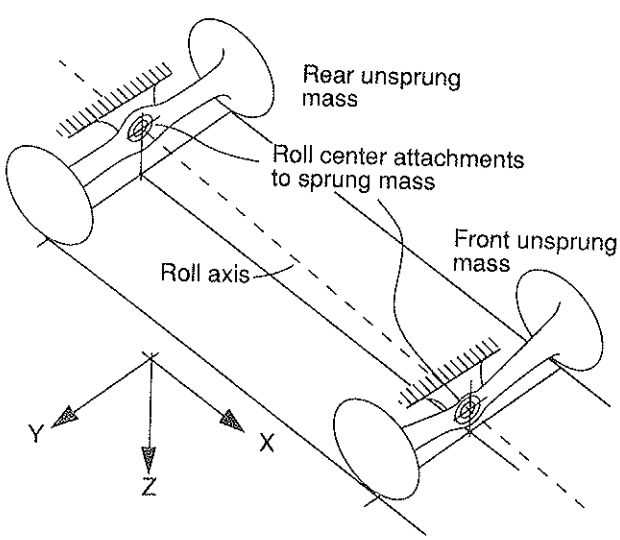

FIGURE 7 Joints used to build the 6-df model.

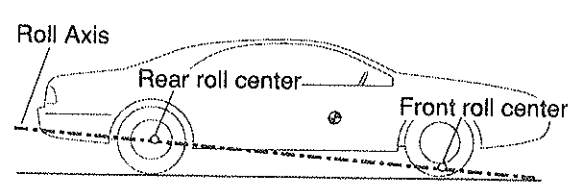

FIGURE 8 Vehicle roll axis.

the vehicle in response to a steer input of the front wheels. The number of equations corresponds to the number of state variables, which is twice the number of df for all of these models. (Each df is associated with one position variable and one speed variable.)

Computational Efficiency

When used in a driving simulator, the first and foremost requirement of the vehicle simulation is that it be capable of running in real time on the available hardware. Table 2 presents a summary of the computational aspects of the models. The main computational effort is spent computing the derivatives of the state variables. The three columns in the table for computation effort show the number of operations needed to compute the derivatives each time step. These computations are performed in a single subroutine that is repeatedly invoked in the loop by the numerical integration algorithm. Table 2 gives the number of multiply, divide, and exponent operations (*, /), the number of add and subtract operations (+, −), and the number of function and subroutine calls (funcs) such as sines, cosines, and absolute values. During their derivation, the equations are manipulated by AUTOSIM to avoid redundant computations and to precompute expressions involving constants. Auxiliary calculations that are not needed to compute derivatives each time step are not included in the table.

A second-order, fixed-step Runge-Kutta algorithm was selected as an integrator for all models. It causes the derivatives be calculated twice each time step, at the start and midpoint of the intervals shown in the table. The time steps shown in the table were selected by first finding the time step at which integration error could be discerned by visual inspection of plotted time histories and then cutting that time step in half. For example, Model 2 and all versions of Model 1 gave no noticeable error for a time step of 0.014, but all were unstable with a time step of 0.016. Therefore, the "safe" time step was set to 0.014/2 = 0.007 sec.

To give an approximate idea of the real running time, each model was timed on a Macintosh II fx. The simulated times were divided by the run times to yield a normalized speed in units of real time. (A factor of 1.3 means that the computer program runs 1.3 times faster than needed for real-time simulation with the time step shown. By increasing the time step, the program can be run up to 2.6 times faster than real time, where it borders on the limit of numerical integration stability.) The standard of what is real time clearly depends on the computer hardware. The results shown are intended not to link absolute simulation speeds with the models, but to show how the models compare relative to each other and to give at least an approximate idea of the types of absolute computational speed that would be expected from a "fast" personal computer made in 1990.

Table 2 shows that all 10-df models require a time step of 0.007 sec. Although only two of the first five models run faster than real time with the conservative time steps shown, all can be run in real-time within limits of stability. Model 3, with 6 df, runs more than three times faster than real time. Although it requires a time step almost as short as the 10-df models, it is described by equations of motion that are much simpler. Model 4, with 4 df, is 24 times faster than real time. The equations of motion are an order of magnitude simpler than the equations for the other models, and the dynamic system includes only low-frequency eigenvalues. Consequently, a much larger integration time step can be used to further reduce the computational requirements.

Numerical Results

All of the simulation programs were used to compute vehicle response to a simple ramp-to-step input for a right turn, shown in Figure 9. The steer angle is applied at the front wheels, eliminating any dynamic effects of the vehicle steering system. The forward speed is 30 m/sec (108 km/hr). The overall vehicle motions predicted by the different models agree closely. Plots of the responses from all five of the 10-df models were in-

TABLE 2 Comparison of Model Formulations

			Computation effort				
Model	DOF[a]	Notes	*,/	+,−	funcs	time step	run speed*
1a	10	Similar to HVOSM, translational joints in Z direction for front suspensions, full nonlinear kinematics, exact slip equations from eq. (13)	831	780	27	0.007	0.56
1b	10	Same as 1a except with slip defined in eq. (14)	540	514	21	0.007	0.85
1c	10	Same as 1b except with some "small" angles and speeds	335	386	5	0.007	1.3
1d	10	Same as 1c except translational joints are angled to fit roll center	416	459	7	0.007	1.05
2	10	Same as 1c except with rotational joints for front suspensions	515	548	5	0.007	0.91
3	6	Similar to STI model	155	162	3	0.008	3.1
4	4	Similar to Segel model	34	22	5	0.020	24

* Note: run speeds are shown as multiples of real time on a Macintosh II fx running under Macintosh System 7.
[a]DOF = df.

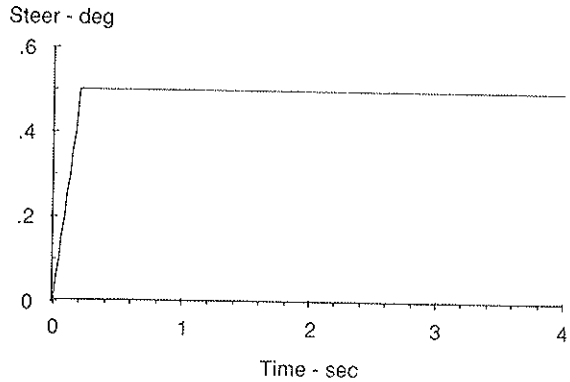

FIGURE 9 Steer input at front wheels.

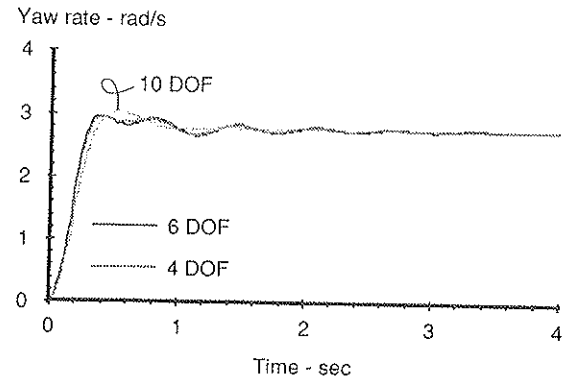

FIGURE 11 Predicted yaw rate responses.

distinguishable. Figure 10 shows that predictions of lateral acceleration were nearly identical for all models. Figure 11 shows that yaw rate predictions for the 4- and 6-df models do not completely match the prediction from the 10-df models. However, the predictions from the two simpler models agree with each other. The greatest difference in predicted vehicle motion was found for roll angle, shown in Figure 12. (However, even these differences are minor.) The main difference is that the 10-df models predict a slightly less oscillatory roll response.

The 4-df model is the simplest and fastest running. Because it does not directly account for roll of the axles, exact agreement in roll is not obtained. However, the results are not far off. Other than roll angle, the other predictions from the 4-df model are very close to those from the 10-df models.

The disagreement between the 10-df and simpler models was found to be mainly due to the different ways in which the models couple roll between the sprung and unsprung masses. The difference exists only when the roll centers at the front and rear differ, such that the vehicle roll axis is tilted. One factor associated with the tilt is that products of inertia are introduced in the simpler models that amplify the transient roll response. A second factor is that due to axle pushing in the 10-df models, shown in Figure 13. When the sprung mass rolls, the rear axle is constrained to move in the direction of the body roll, whereas the front axle moves in the opposite direction. The lateral movements of the axles modify the slip angles, instantly changing the lateral forces generated by the tires. The effect is to add damping to the 10-df model that is not present in the 4- and 6-df models.

The axle-pushing mechanism in the 10-df models may be exaggerated because of the simple tire model of Equations 8 and 13 or 14. In reality, lateral tire forces do not build instantly. A tire model with dynamic lag or lateral compliance might change the significance of the kinematic "pushing."

Recall that most of the 10-df models with translational joints for the front wheels have a front roll center in the ground plane (Models 1a, 1b, and 1c), whereas Models 1d and 2 locate a roll center whose height is defined as the parameter H_{RC1}. When H_{RC1} is set to 0, all of the 10-df models agree so closely that identical time history plots are obtained for any given response variable. However, differences exist for values of H_{RC1} other than 0. In this case, Models 1d and 2 compare closely with the simple models, and Models 1a, 1b, and 1c generate an incorrect roll response.

Although the simulation results in this paper are based on a tire equation that is not sensitive to load, all of the models can be easily extended to include load sensitivity in the lateral tire force calculations. Figure 14 compares the vertical force time histories for the right front tire. The 6-df and 10-df models agree closely, and the 4-df model produces estimates that may be sufficient to capture the rudimentary handling effects of tire load sensitivity.

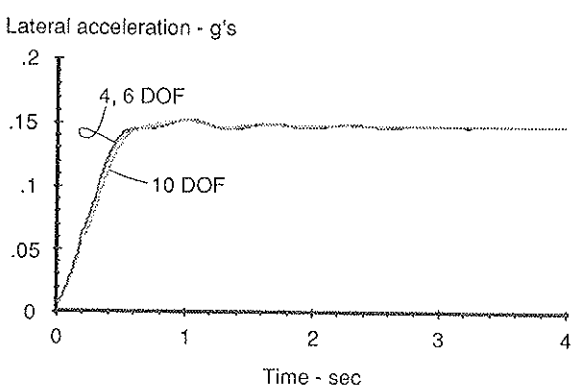

FIGURE 10 Predicted lateral acceleration responses.

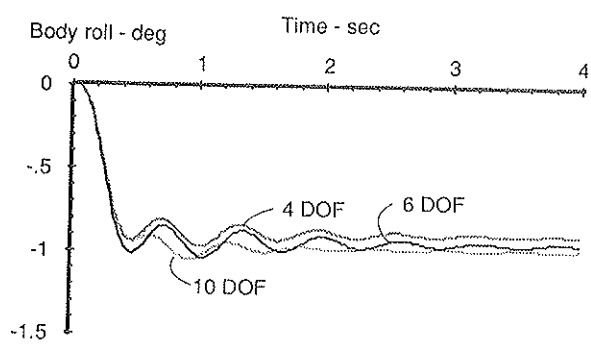

FIGURE 12 Predicted roll angle responses.

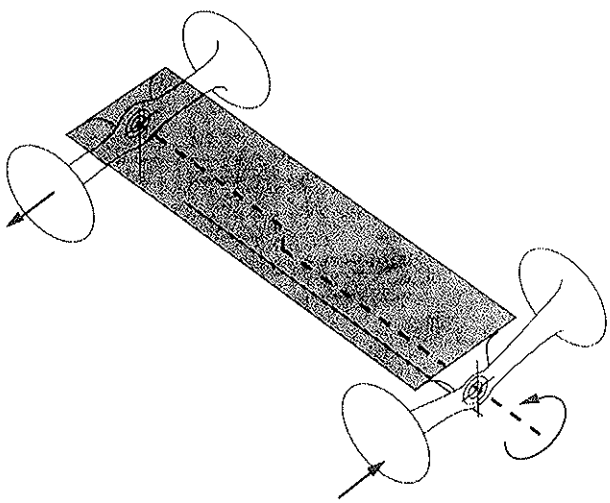

FIGURE 13 Front and rear suspension roll axes that are not collinear.

CONCLUSIONS

This paper shows how a symbolic multibody code generator is used to rapidly develop real-time vehicle dynamics models. Making comparisons between the models was easy, because all of the models were formulated using the same sets of vehicle parameters. The simplest simulation program runs more than 40 times faster than the most complex, yet the predictions of the overall system response were very close. The general approach of building simulation programs with a code generator has several advantages over the use of hand-coded programs:

- The development time is small. The first working 10-df model reported in this paper was developed and debugged in 2 days. The other 10-df models required less time. The initial versions of the 4- and 6-df models were done in several hours.
- The generated code runs fast. For a given model, the automated software for developing simulations usually formulates efficient equations and then generates code that is as fast or faster than that which can be written by experts (*10*).
- Models with different levels of complexity can be formulated and compared, to speed the debugging process and ensure that the modeling assumptions have the intended results.
- A model can be rapidly fine-tuned to run with maximum detail in real time on available hardware. Radical changes can be made in connection between bodies with little effort.

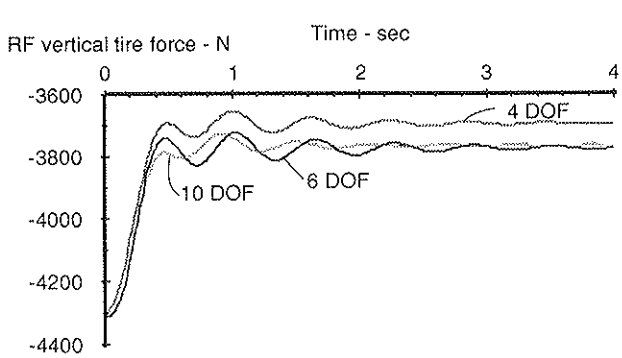

FIGURE 14 Vertical tire forces simulated by models.

The capability of a simulation program to run in real time depends on the computational efficiency in the equations of motion and the minimal integration time step required. The relatively close agreement seen between the simple 4-df model and the others argues that simple multibody models, with no high-frequency eigenvalues, offer a sound basis for building low-cost driving simulators. Complexities can be added such as roll steer, compliance steer, steering system dynamics, aerodynamic effects, nonlinear tire behavior, load-sensitive tires, dynamic tire lags, nonlinear springs and dampers, and so on. The model runs so fast that there is plenty of room for additional computations if they do not affect the required minimal time step.

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Motion Algorithm for Large-Displacement Driving Simulator

L. D. REID AND P. R. GRANT

Renewed interest in developing driving simulators with large motion amplitudes has engendered simulator motion drive algorithms and computer software capable of predicting the performance of such devices for design purposes. One such computer package is described. The hardware is assumed to consist of an unrestricted turntable on top of a hexapod motion platform carried by a large-amplitude *x-y* carriage. Algorithms are included to represent the motion-drive washout algorithms and the physical motion of the simulator. Routines are developed to split the six linear and angular motions among the three principal hardware subsystems. The presence of an unrestricted turntable has resulted in the need to develop a new tilt-coordination algorithm to simulate sustained accelerations. By selecting a Euler angle set specifically suited to the present geometry, a considerable simplification of the washout algorithm has been achieved. Potential problems with algorithm stability and crosstalk are pointed out, and guidelines on how to avoid them are provided. Several typical car maneuvers are employed to demonstrate the features of the motion algorithm and the benefits and limitations of the hardware configuration. These maneuvers include an entry and steady turn, braking, and a single lane change. The effects of including and deleting the turntable and the *x-y* carriage are studied. The results are described in terms of the amounts of hardware travel used and the fidelity of the motion cues provided to the driver.

Recent interest in high-performance driving simulators has led to the production of several facilities capable of large amplitude motion such as the Daimler-Benz system (*1*) and the Swedish VTI system (*2*). In addition, conceptual designs have been proposed with 9 degrees of freedom (*3*), and the National Advanced Driving Simulator (NADS) (*4*) is gaining momentum in the United States.

To assess the problems involved with operating recently proposed large-amplitude simulator motion-drive systems and the cost/benefits associated with the increased size, a software package has been developed that can produce a computer simulation of both the motion of the physical hardware and the performance of the motion-drive algorithms that must be used to interface the vehicle equations of motion and the hardware (*5,6*).

Before the software could be created it was necessary to specify the general characteristics of the lage-amplitude motion-base hardware. The configuration selected was based on a standard flight simulator hexapod motion system (supported by six hydraulic actuators) as is the Daimler-Benz simulator. This was taken to be mounted on a large-amplitude *x-y* carriage producing motions in the horizontal plane. Finally, an unrestricted turntable was mounted on the hexapod's upper payload platform and the vehicle cab affixed to the turntable.

This paper will not deal with the details of the mechanical design or with the dynamic response characteristics of the hardware. It will be assumed that the software and hardware are well matched so that each hardware subsystem has a high bandwidth relative to the motion command signals it receives from the motion-drive software. It will also be assumed that the hexapod and the turntable both have the same high-bandwidth properties due to the modest mass they must support. The *x-y* carriage, on the other hand, is assumed to be a more massive low-frequency device (see Figure 1). All mechanical systems are assumed to have unity transfer functions over the frequency range of their input command signals.

The goal of the classical washout algorithm used herein is to match as closely as possible the angular velocity $\underset{\rightarrow}{\omega}$ and specific force $\underset{\rightarrow}{f}$ at a particular reference point in the actual vehicle (the origin of F_A) and the simulated vehicle (the origin of F_S) (*7,8*). Here, specific force at a point is defined to be

$$\underset{\rightarrow}{f} = \underset{\rightarrow}{a} - \underset{\rightarrow}{g} \tag{1}$$

where $\underset{\rightarrow}{a}$ is the inertial acceleration of the point and $\underset{\rightarrow}{g}$ is the acceleration due to gravity. The algorithm is intended to produce the desired motion cues mentioned while restricting the motion of the hardware to remain within its physical limitations. Without going into the details to be covered later in this paper, Figures 2 and 3 can be used to illustrate the essential features of the classical washout algorithm. The inputs to the algorithm are $\underline{\omega}_{AA}$ and $\underline{f}_{AA}$, the computed angular velocity and specific force at the selected reference point in the vehicle being simulated. The outputs from the algorithm are ℓ_{3i}, $\underline{C}_I$, and ψ_{TT}, the input commands to the motion-base hardware. Consider $\underline{\omega}_{AA}$: it is first scaled and limited to reduce the demands on the motion system. It is then converted to Euler angles, which are fed through high-pass filters to remove low-frequency signals that tend to drive the motion system into its travel limits. These Euler angles are then used to help generate the hardware drive signals and to produce transformation matrices at various points in the algorithm. Now consider $\underline{f}_{AA}$: after being scaled and limited, it is transformed into earth frame components and high-pass-filtered and double-integrated to produce linear displacement commands. As before, the removal of low-frequency signals is the goal of this process. With most of the computed low-frequency motions removed by the high-pass filters, a special effect has been developed to represent sustained accelerations in the *xy* plane

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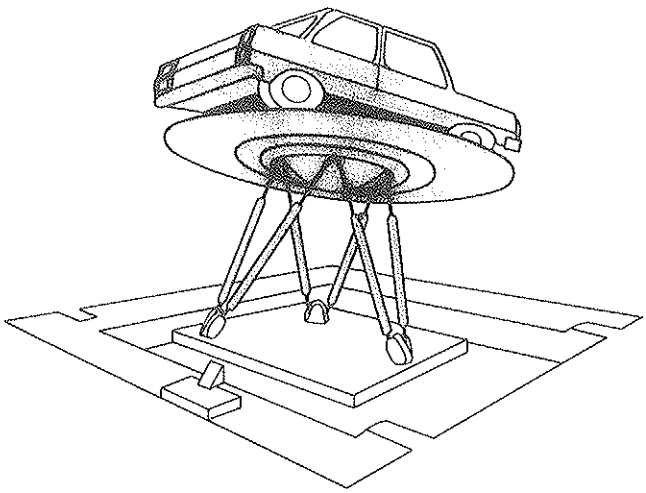

FIGURE 1 Hardware configuration.

of the vehicle axis system. It is called tilt-coordination, and it makes use of Equation 1. When $\underset{\rightarrow}{a}$ is 0, $\underset{\rightarrow}{f}$ can still be simulated by $\underset{\rightarrow}{g}$. For example, the sensation of forward sustained acceleration in the simulator cab can be created by placing the cab in a pitched-up attitude. The driver's vestibular system and the sensation of the seat pressing against his back both register cues that the driver would experience if he or she were indeed accelerating forward. In Figures 2 and 3 the tilt-coordination is created by passing a modified version of $\underline{f}_{AA}$ (namely $\underline{f1}$) first through a low-pass filter to pick up its low-frequency component and then creating an increment to the simulator's Euler angles that approximates the desired tilt.

REFERENCE FRAMES

Frame F_H

The hexapod frame F_H is located with its origin on the payload platform at the point at which the turntable's axis of rotation meets the platform. The x-axis points forward and the z-axis downward. The xy plane is parallel to the payload platform. It is assumed that the axis of rotation of the turntable is coincident with the z-axis and that the floor of the simulator cab is also parallel to the xy plane.

Frame F_S

The simulator frame F_S has its origin in the simulator cab at a point selected to suit the requirements of the simulation. It is attached to the cab with its x-axis pointing forward and its z-axis parallel to the z-axis of F_H.

Frame F_P

Frame F_P is fixed to the simulator driver's head with its origin midway between the driver's left and right vestibular systems. The x-axis points forward and the z-axis downward along the spine. In this study it will be assumed that F_P is parallel to F_S.

Frame F_A

The car reference frame F_A has its origin at the same relative cab location as the simulator reference frame F_S. Frame F_A

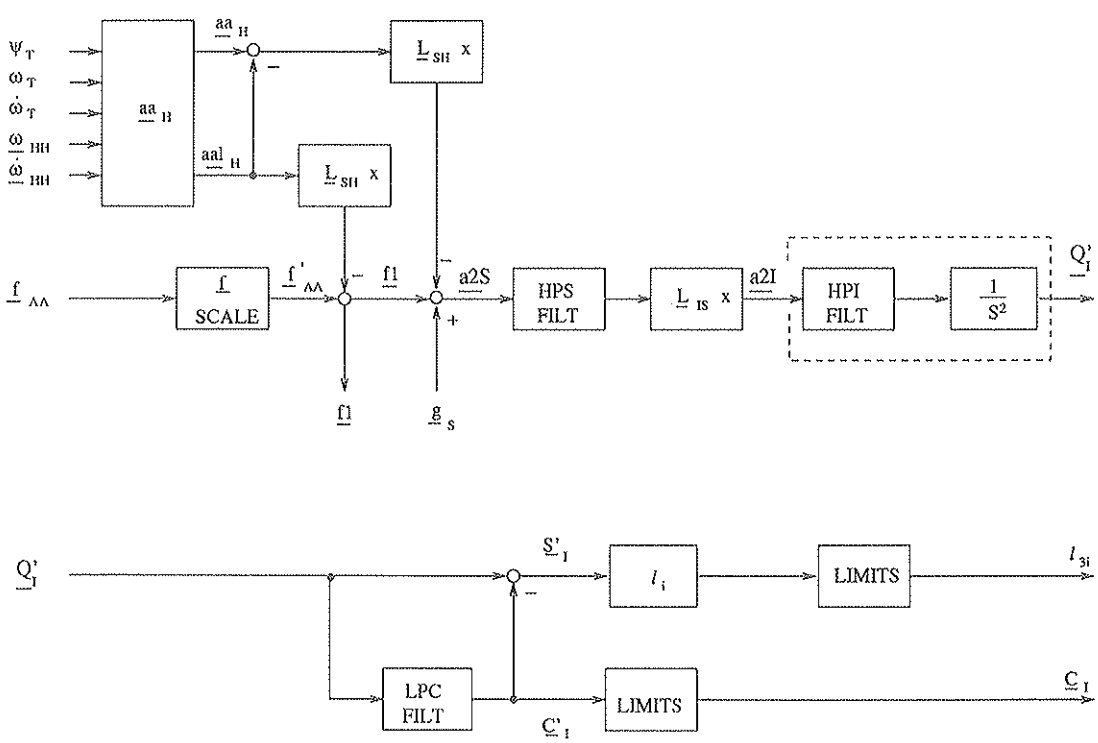

FIGURE 2 Classical algorithm: linear motion.

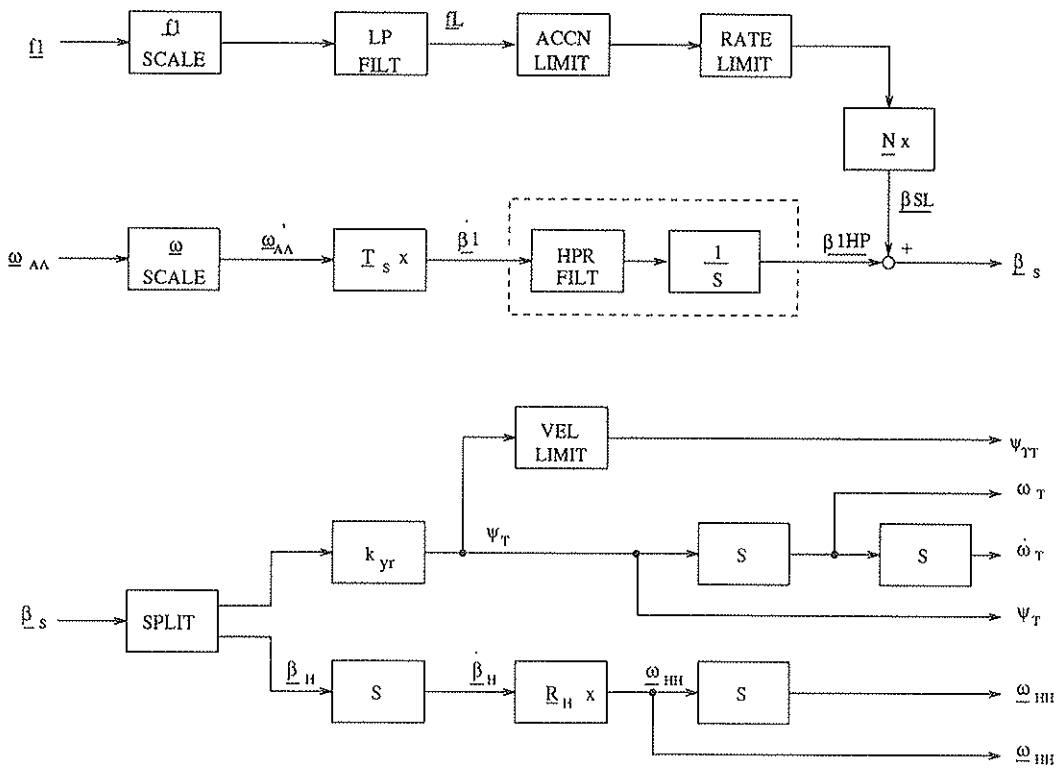

FIGURE 3 Classical algorithm: angular motion.

has the same orientation with respect to the cab as the simulator frame F_S.

Frame F_I

The inertial frame F_I is earth-fixed with its z-axis aligned with the gravity vector $\underset{\rightarrow}{g}$. The location of its origin and the orientation of its x-axis are selected to suit the problem under study.

Frame F_V

The x-y carriage frame has its origin fixed to the centroid of the hexapod's lower platform bearing attachment points. It is parallel to F_I and is translated by the x-y carriage.

EULER ANGLES AND TRANSFORMATION MATRICES

With the F_H and F_S frames related as described, it is found that the formulations involving the calculation of angular rates and Euler angles are simplified if a nonstandard set of Euler angles is employed. In the present development the order of rotation when applying Euler angles will be roll (ϕ), pitch (θ), then yaw (ψ). In general, the three Euler angles will be represented by

$$\underline{\beta} = [\phi\ \theta\ \psi]^T \tag{2}$$

If the turntable angles relative to the hexapod be ψ_T, then it follows that

$$\underline{\beta}_S = \underline{\beta}_H + [0\ 0\ \psi_T]^T \tag{3}$$

The transformation matrices based on the present nonstandard Euler angles are (for a general frame F_B)

$$\underline{L}_{IB} = \begin{bmatrix} \cos\theta\cos\psi & -\cos\theta\sin\psi & \sin\theta \\ \cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \cos\phi\cos\psi - \sin\phi\sin\theta\sin\psi & -\sin\phi\cos\theta \\ \sin\phi\sin\psi - \cos\phi\sin\theta\cos\psi & \sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi & \cos\phi\cos\theta \end{bmatrix}_B$$

$$= \underline{L}_{BI}^T \tag{4}$$

where $[\phi\ \theta\ \psi]_B^T$ are the Euler angles of F_B relative to F_I and where in general for any vector $\underset{\rightarrow}{V}$

$$\underline{V}_I = \underline{L}_{IB}\,\underline{V}_B \tag{5}$$

$$\underline{L}_{SH} = \begin{bmatrix} \cos\psi_T & \sin\psi_T & 0 \\ -\sin\psi_T & \cos\psi_T & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \underline{L}_{HS}^T \tag{6}$$

$$\underline{\omega}_{BB} = \underline{R}_B\,\dot{\underline{\beta}}_B \tag{7}$$

$$\dot{\underline{\beta}}_B = \underline{T}_B\,\underline{\omega}_{BB} \tag{8}$$

$$\underline{R}_B = \begin{bmatrix} \cos\theta\cos\psi & \sin\psi & 0 \\ -\cos\theta\sin\psi & \cos\psi & 0 \\ \sin\theta & 0 & 1 \end{bmatrix}_B \tag{9}$$

$$\underline{T}_B = \begin{bmatrix} \sec\theta\cos\psi & -\sec\theta\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ -\tan\theta\cos\psi & \tan\theta\sin\psi & 1 \end{bmatrix}_B \tag{10}$$

SYSTEM GEOMETRY

The linear displacement geometry including the ith hexapod actuator is shown in Figure 4. $\underset{\rightarrow}{Q}$ gives the location of the origin of F_H relative to the origin of F_I, and $\underset{\rightarrow}{C}$ the location of the origin of F_V relative to the origin of F_I. The displacement $\underset{\rightarrow}{C}$ is generated by motion of the x-y carriage. As shown in the figure, $\underset{\rightarrow}{S}$ gives the location of the origin of F_H relative to the origin of F_V so that

$$\underset{\rightarrow}{Q} = \underset{\rightarrow}{C} + \underset{\rightarrow}{S} \tag{11}$$

In the figure $\underset{\rightarrow}{A}_i$ and $\underset{\rightarrow}{B}_i$ locate the upper and lower attachment points of the hexapod's ith actuator, and $\underset{\rightarrow}{\ell}_i$ represents the ith actuator. Thus, $\underset{\rightarrow}{\ell}_i$ expressed in F_I components becomes

$$\underline{\ell}_{iI} = \underline{L}_{IH}\,\underline{A}_{iH} - \underline{B}_{iI} + \underline{S}_I \tag{12}$$

where $\underline{A}_{iH}$ and $\underline{B}_{iI}$ are constants for given hexapod geometry. The actuator length command signal relative to its neutral position is given by

$$\ell_i = (\underline{\ell}_{iI}^T\,\underline{\ell}_{iI})^{1/2} - L_i \tag{13}$$

where L_i is its neutral length.

The location of the origin of F_S relative to the origin of F_H is given by $\underset{\rightarrow}{D}$. Because F_S is fixed to the turntable, the direction of $\underset{\rightarrow}{D}$ is time varying while its length remains fixed. When $\psi_T = 0$, then

$$\underset{\rightarrow}{D} = \underset{\rightarrow}{D}_o \tag{14}$$

It follows that, in general,

$$\underline{D}_H = [d\cos(\psi_T + \gamma) \quad d\sin(\psi_T + \gamma) \quad D_{oz}]^T \tag{15}$$

where d, D_{oz}, and γ are constants.

TILT-COORDINATION

Consider a situation in which specific force at the origin of F_S is generated by tilt-coordination alone. Thus

$$\underline{f}_{SS} = -\underline{g}_S = -\underline{L}_{SI}\,\underline{g}_I \tag{16}$$

If ϕ_S and θ_S are assumed to be small angles, then Equation 16 can be approximated by

$$\underline{f}_{SS} = g\begin{bmatrix} \theta\cos\psi - \phi\sin\psi \\ -\theta\sin\psi - \phi\cos\psi \\ -1 \end{bmatrix}_S \tag{17}$$

Now, from work by Reid and Nahon (7) and Figure 3, the specific force to be simulated by tilt-coordination is given by the scaled, low-frequency part of the x- and y-components of $\underline{f}_{AA}$, represented by $\underline{fL}$, where

$$\underline{fL} = [fL_x\; fL_y]^T \tag{18}$$

Thus, from Equations 17 and 18 the tilt-coordination is given by

$$[\phi SL \quad \theta SL]^T = \underline{N}\,\underline{fL} \tag{19}$$

where

$$[\phi SL \quad \theta SL \quad 0]^T = \underline{\beta SL} \tag{20}$$

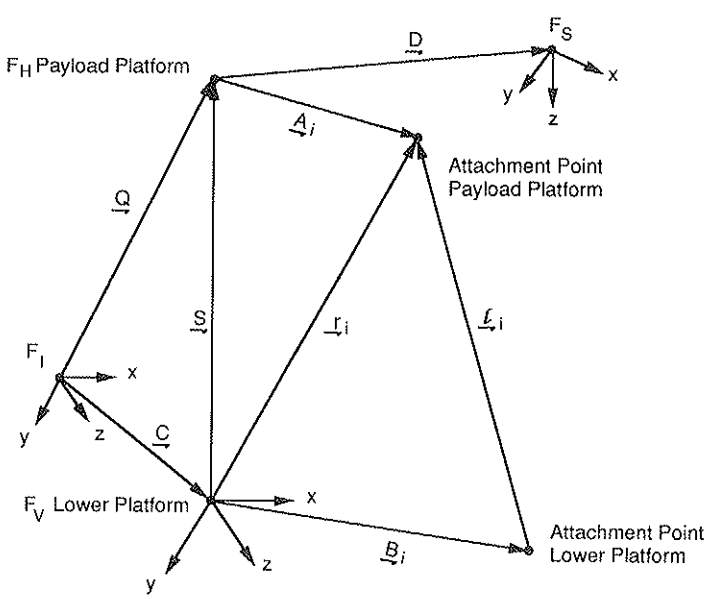

FIGURE 4 Vectors for a single actuator.

are the tilt-coordination Euler angles and

$$\underline{N} = g^{-1}\begin{bmatrix} -\sin\psi & -\cos\psi \\ \cos\psi & -\sin\psi \end{bmatrix}_S \tag{21}$$

In general, the tilt-coordination contribution to overall specific force is produced by adding $\underline{\beta SL}$ to that part of $\underline{\beta}_S$ produced by other effects as shown in Figure 3. Since tilt-coordination is intended to represent almost steady-state specific force, then it is important not to destroy the illusion by having the driver sense the angular velocity or tangential acceleration associated with the onset acceleration of the tilt. Software is included to place limits on both the tilt rate and the tilt acceleration used in tilt-coordination.

REVISED CLASSICAL WASHOUT

Referring to Equation 3 and Figure 3, $\underline{\beta}_S$ is made up of two parts:

$$\underline{\beta}_S = \underline{\beta 1HP} + \underline{\beta SL} \tag{22}$$

where $\underline{\beta 1HP}$ is the contribution due to $\underline{\omega}_{AA}$ and $\underline{\beta SL}$ the tilt-coordination. The path from $\underline{\omega}_{AA}$ to $\underline{\beta 1HP}$ follows standard classical washout practice (*7*). From Equations 7 and 22,

$$\underline{\omega}_{SS} = \underline{R}_S\,\dot{\underline{\beta}}_S = \underline{R}_S\,\mathrm{HPR}[\underline{T}_S\,\underline{\omega}'_{AA}] + \underline{R}_S\,\dot{\underline{\beta SL}} \tag{23}$$

where HPR[x] is the output of filter block HPR FILT for an input $x(t)$.

Equation 3 can now be used to determine ψ_T:

$$\psi_T = \psi_S - \psi_H \tag{24}$$

where ψ_S comes from Equation 22. Take

$$\psi_T = k_{T\psi_S} \tag{25}$$

$$\psi_H = (1 - k_T)_{\psi_S} \tag{26}$$

k_T is taken to be either unity or 0. When k_T is unity, all of ψ_S is generated by the turntable and none by the hexapod. When k_T is 0, all of ψ_S is generated by the hexapod and none by the turntable. Equations 25 and 26 are represented by the SPLIT block in Figure 3. Thus, from Equations 25 and 26,

$$\underline{\beta}_H = [\phi_S \quad \theta_S \quad (1 - k_T)_{\psi_S}]^T \tag{27}$$

In addition, a scaling factor k_{yr} has been included in order to allow ψ_T to be scaled up for special effects.

To generate $\underline{\omega}_{HH}$ and $\dot{\underline{\omega}}_{HH}$ for use in other sections of the algorithm, use

$$\underline{\omega}_{HH} = \underline{R}_H\,\dot{\underline{\beta}}_H \tag{28}$$

and its time derivative. Also define

$$\omega_T = \dot{\psi}_T \tag{29}$$

Next deal with the linear motion equations. Consider a Point P fixed to F_S and located relative to the origin of F_S by $\underline{OP}_S$ where

$$\underline{OP}_{SS} = [x' \quad y' \quad z']^T = \text{constant} \tag{30}$$

Let P be located relative to the origin of F_H by $\underline{OP}_H$ where

$$\underline{OP}_{HH} = [x \quad y \quad z]^T \tag{31}$$

Since $\underline{D}$ represents the location of the origin of F_S relative to F_H, it follows that

$$\underline{OP}_{HH} = \underline{D}_H + \underline{L}_{HS}\,\underline{OP}_{SS} \tag{32}$$

From Equations 6, 15, 30, 31, and 32

$$\underline{OP}_{HH} = \begin{bmatrix} d\cos(\psi_T + \gamma) + x'\cos\psi_T - y'\sin\psi_T \\ d\sin(\psi_T + \gamma) + x'\sin\psi_T + y'\cos\psi_T \\ D_{o_z} + z' \end{bmatrix} \tag{33}$$

$$\dot{\underline{OP}}_{HH} = \begin{bmatrix} -y\omega_T \\ x\omega_T \\ 0 \end{bmatrix} \tag{34}$$

$$\ddot{\underline{OP}}_{HH} = \begin{bmatrix} -y\dot{\omega}_T - x\omega_T^2 \\ x\dot{\omega}_T - y\omega_T^2 \\ 0 \end{bmatrix} \tag{35}$$

Since the classical washout algorithm attempts to match the vehicle's specific force at the origin of F_S, we will initially deal with the case where $\underline{OP}_{SS} = \underline{0}$. Following the development described by Reid and Grant (*6*) for the inertial acceleration of a point moving with respect to a translating and rotating frame, let the point be the origin of F_S and let F_H be the translating and rotating frame. It follows that

$$\underline{a}_{SH} = \underline{a}_{HH} + \underline{aa}_H \tag{36}$$

where

$\underline{a}_S$ = inertial acceleration of origin of F_S,
$\underline{a}_H$ = inertial acceleration of origin of F_H, and

$$\underline{aa}_H = \ddot{\underline{OP}}_{HH} + 2\underline{\Omega}_H\dot{\underline{OP}}_{HH} + [\underline{\Omega}_H\underline{\omega}_H + \dot{\underline{\omega}}_H]\underline{OP}_{HH} \tag{37}$$

where

$$\underline{OP}_{SS} = \underline{0}$$

$$\underline{\Omega}_H = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix}_{HH} \tag{38}$$

$$\underline{\omega}_{HH} = [p_{HH} \quad q_{HH} \quad r_{HH}]^T \tag{39}$$

Now from Equation 36

$$\underline{a}_{SI} = \underline{a}_{HI} + \underline{L}_{IH}\,\underline{aa}_H = \underline{a}_{HI} + \underline{aa}_I \tag{40}$$

Note that $\underline{a}_{HI}$ is made up of the sum of the inertial acceleration of the x-y carriage and the acceleration of the hexpod frame F_H relative to the x-y carriage.

At this stage in the development, consider how the simulator acceleration command signals would be formed if there were no high-pass filtering of the linear motion commands (i.e., remove blocks HPS FILT and HPI FILT in Figure 2). Designate the variables altered by this lack of filtering by ($\tilde{}$). Thus Equation 40 becomes

$$\underline{\tilde{a}}_{SI} = \underline{\tilde{a}}_{HI} + \underline{aa}_I \tag{41}$$

In classical washout it is attempted to make $\underline{f}_{SS}$ as similar to $\underline{f}'_{AA}$ as possible. In the absence of filtering take

$$\underline{\tilde{f}}_{SS} = \underline{f}'_{AA} \tag{42}$$

Thus

$$\underline{\tilde{a}}_{SS} = \underline{\tilde{f}}_{SS} + \underline{g}_S = \underline{f}'_{AA} + \underline{g}_S \tag{43}$$

and

$$\underline{\tilde{a}}_{SI} = \underline{L}_{IS}\,\underline{f}'_{AA} + \underline{g}_I \tag{44}$$

Thus, from Equations 41 and 44,

$$\underline{\tilde{a}}_{HI} = \underline{L}_{IS}\,\underline{f}'_{AA} + \underline{g}_I - \underline{aa}_I \tag{45}$$

and $\underline{\tilde{a}}_{HI}$ is the motion command signal to be sent to the hexapod and the x-y carriage. Let

$$\underline{\tilde{a2I}} = \underline{\tilde{a}}_{HI} = \underline{L}_{IS}\,\underline{a2S} = \underline{L}_{IS}(\underline{f}'_{AA} + \underline{g}_S - \underline{aa}_S) \tag{46}$$

Now, to protect the hexapod and the x-y carriage, the signals $\underline{a2S}$ and $\underline{a2I}$ are passed through high-pass filters before being sent to the hardware. Because of the presence of the turntable, the orientation of the x- and y-axes of F_S with respect to those of F_I can vary without limit. Thus, the application of different degrees of filtering to the x- and y-components of $\underline{a2S}$ is best accomplished by filtering them in the F_S frame. In Figure 2 this is handled by the HPS FILT block (which leaves the z-component of $\underline{a2S}$ untouched). The result of this process is then expressed in F_I components by $\underline{a2I}$. As demonstrated elsewhere (*7*), high-pass filtering in F_S does not ensure that drifting and offsets will not occur in the simulator hardware. This requires high-pass filtering in the F_I frame. This is done by passing $\underline{a2I}$ through HPI FILT and then double integrating this filtered acceleration to produce the simulator displacement $\underline{Q}'_I$. It was also pointed out that filtering in F_I downstream of $\underline{L}_{IS}$ can lead to crosstalk among the $\underline{f}_{SS}$ components felt by the driver in the simulator (*7*). In the present case, with the possibility of large values for ψ_S, this can be a particular problem. To minimize these effects HPI FILT should be selected to be as mild as possible (i.e., select large values for natural frequency).

Initially the tilt-coordination crossfeed signal $\underline{f1}$ (see Figure 2) was formed from $(\underline{f}'_{AA} - \underline{aa}_S)$ in order to maximize the amount of $\underline{a2}$ sent through tilt-coordination. However, it was found that some of the high-frequency components in $\underline{aa}_S$ (due to $\dot{\underline{\Omega}}_H\underline{OP}_{HH}$) produced a destabilizing loop closure that could cause the algorithm to oscillate. This was corrected by allowing only the low-frequency part of $\underline{aa}_H$ to be used in tilt-coordination, namely $\underline{aa1}_H$, where

$$\underline{aa1}_H = [-x\omega_T^2 - y\omega_T^2 \quad 0]^T \tag{47}$$

This was achieved by writing $\underline{a2S}$ as

$$\underline{a2S} = [\underline{f}'_{AA} - \underline{L}_{SH}(\underline{aa}_H - \underline{aa1}_H)] + \underline{g}_S - \underline{L}_{SH}\,\underline{aa1}_H \tag{48}$$

and arranging things as shown in Figure 2.

In Figure 2 $\underline{Q}'_I$ is the displacement command sent to the hexapod and the x-y carriage. To take full advantage of the simulator's design, the x- and y-components of $\underline{Q}'_I$ must be partitioned between the hexapod and the x-y carriage. It is assumed that the bandwidth of the hexapod is wider than that of the x-y carriage, thus it makes sense to base the partition on frequency content. This can be arranged to ensure that the largest displacements are carried out by the x-y carriage. Several alternatives were examined before the complementary filters approach was selected.

The block diagram of the complementary filters (LPC FILT) is included in Figure 2. They are applied to the x- and y-components of $\underline{Q}'_I$. The high-pass filters HPS FILT and HPI FILT are tuned to limit the low-frequency commands to the x-y carriage. The low-pass filter LPC FILT is tuned to send the high-frequency signals to the hexapod and the lower-frequency signals (which tend to produce large-amplitude motions) to the x-y carriage. The corresponding transfer functions for the x- and y-components are

$$\overline{\underline{C}}'_I = \overline{\underline{a2I}}\,[\mathrm{HPI} \times \mathrm{LPC}] \tag{49}$$

$$\overline{\underline{S}}'_I = \overline{\underline{a2I}}\,[\mathrm{HPI}(1 - \mathrm{LPC})] \tag{50}$$

and

$$\overline{\underline{Q}}'_I = \overline{\underline{C}}'_I + \overline{\underline{S}}'_I = \overline{\underline{a2I}}\,\frac{1}{s^2}\,\mathrm{HPI} \tag{51}$$

In solving the differential equations corresponding to Equations 49 and 50, the initial conditions $\underline{C}'_I(0)$ and $\underline{S}'_I(0)$ are selected so as to start the simulator from a desired location. Usually this will be with all the actuators extended to half their stroke, although in special cases a bias toward some other location may be useful.

HARDWARE DRIVE SIGNALS

Although the scale factors, input limiters, and high-pass filters of the motion drive algorithm are intended to reduce the chances of the hardware's exceeding its limits, they cannot prevent this from happening for all system inputs. For this reason, software limiting is placed between the outputs from the washout algorithms and the hardware. For the hexapod and the x-y carriage, the limits are placed on displacement and velocity of the actuators. For the turntable, a limit is placed only on velocity. The limiting algorithm is fully described elsewhere (*8*). (The only addition has been the use of $\omega_b = 1/\Delta t$ in the velocity-limiting algorithm.) The limiting

blocks are shown at the output side of Figures 2 and 3. The drive signals including output limiting are ℓ_{3i} for the hexapod, $\underline{C}_l$ for the x-y carriage, and ψ_{TT} for the turntable.

INTERACTION BETWEEN TILT-COORDINATION AND TURNTABLE MOTION

The addition of the turntable creates the potential for unwanted ω_T interactions with tilt-coordination. Hence tuning of the motion-drive algorithm increases in complexity.

To demonstrate this interaction, consider Equation 23 for $\underline{\omega}_{SS}$. The term $\underline{R}_S\,\underline{\beta\dot{S}L}$ can contain unwanted contributions to $\underline{\omega}_{SS}$ representing false motion cues. From Equations 18 to 21 it follows that

$$\underline{\beta\dot{S}L} = \frac{1}{g}\begin{bmatrix} \sin\psi_S(fL_y\dot{\psi}_S - f\dot{L}_x) - \cos\psi_S(fL_x\dot{\psi}_S + f\dot{L}_y) \\ -\cos\psi_S(fL_y\dot{\psi}_S - f\dot{L}_x) - \sin\psi_S(fL_x\dot{\psi}_S + f\dot{L}_y) \\ 0 \end{bmatrix} \tag{52}$$

Assuming that tilt rates are small, $f\dot{L}_x$ and $f\dot{L}_y$ can be dropped into Equation 52, giving

$$\underline{\beta\dot{S}L} = \frac{\dot{\psi}_S}{g}\begin{bmatrix} -fL_x\cos\psi_S + fL_y\sin\psi_S \\ -fL_x\sin\psi_S - fL_y\cos\psi_S \\ 0 \end{bmatrix} \tag{53}$$

Thus, from Equations 9, 25, 29, and 53,

$$\underline{R}_S\underline{\beta\dot{S}L} = \frac{\omega_T}{gk_T} \times \begin{bmatrix} -fL_x + (1-\cos\theta_S)(fL_x\cos^2\psi_S - fL_y\sin\psi_S\cos\psi_S) \\ -fL_y + (1-\cos\theta_S)(fL_y\sin^2\psi_S - fL_x\sin\psi_S\cos\psi_S) \\ \sin\theta_S(fL_y\sin\psi_S - fL_x\cos\psi_S) \end{bmatrix} \tag{54}$$

In Equation 54 it is seen that the products $\omega_T fL_x$ and $\omega_T fL_y$ appear as factors in every term. This is the undesired interaction because it leads to false cues in $\underline{\omega}_{SS}$ that could be sensed by the driver in the simulator.

COMPUTER-BASED SIMULATOR TESTS

To assess the capabilities of the proposed motion algorithm and hardware configuration, a computer simulation was carried out for a number of typical driving maneuvers. In these tests the size of the simulator was fixed with the hexapod actuators having a stroke of ±0.67 m about 0 and the x-y carriage having the same ±13.72 m travel in both directions about 0. In all cases the motion algorithm parameters were selected to produce representative system response. (The evaluation of simulator motion performance made hereupon is based on the authors' experience with simulator motion.) The car response data were produced by specifying the inputs to a simple vehicle model representing a 1814-kg car as documented by Reid and Grant (*9*).

Entry and Steady Turn Maneuvers

The entry and steady turn maneuver was entered at 60 km/hr, and the car's trajectory was a circle of 150-m radius. This was a fairly mild turn, generating about 0.25 g of side force on the driver (see Figure 5). Three simulator configurations were tested for this particular maneuver, designated as EST1, EST2, and EST3.

In EST1 all the simulator motion subsystems were active. The simulator x-y carriage displacement and turntable angle are shown in Figure 6. The displacement shown in this plot is significantly different from that for the car because of the high-pass filters and the use of tilt-coordination to represent sustained lateral specific force. Figure 5 gives plots of the driver's lateral specific force in the cab frame for the car and the simulator. The simulator does a good job of representing this motion cue with a rapid onset at the beginning and the correct steady-state value. The small dip in specific force in the simulator following the onset cue is due to tilt-coordination limiting the buildup of the tilt-coordination cue. The initial simulator specific force cue does not reach the car's initial value because of the overall filtering action of the motion algorithm. Figure 7 shows the car's sustained yaw rate and the washed-out yaw rate of EST1. Because of the high-pass nature of the human vestibular system, however, the yaw rates sensed by the driver in these two cases are quite similar.

In EST2 the yaw component of HPR FILT (see Figure 3) has been deleted (opened up) with the remainder of the simulator configuration kept the same as EST1. The simulator trajectory is shown in Figure 6. Under these conditions the simulator approaches a steady-state yaw rate as shown in Figure 7. Note the oscillatory nature of the simulator's yaw rate response. This is an example of the interaction between tilt-coordination and turntable motion given by Equation 54. The corresponding tilt-coordination angles will also be oscillatory in order to produce a constant specific force on the driver in the cab frame (see Figure 5).

In EST3 the turntable has been turned off and the hexapod is used to produce all yawing effects. The high-pass filters have been tuned to take this change into account. As shown in Figure 6 the x-y carriage displacement is now primarily a lateral displacement although a small longitudinal displacement is present. From Figure 7 it can be seen that the yaw rate cue is of very short duration, being primarily an onset cue. This results in a sensed yaw rate that is significantly different from that produced by the car. The lateral

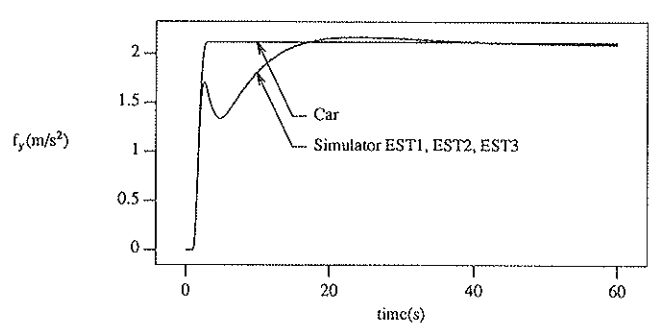

FIGURE 5 Driver's lateral specific force in cab frame for entry and steady turn.

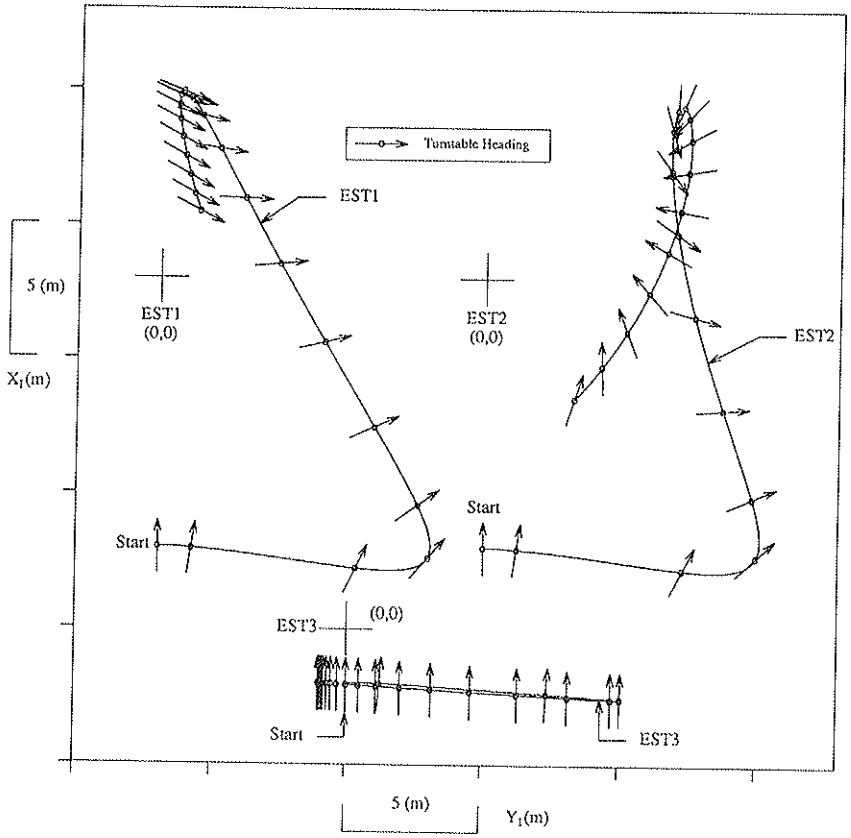

FIGURE 6 Simulator trajectories for EST1, EST2, and EST3.

specific force is unchanged from EST1 and EST2 as shown in Figure 5.

Braking Maneuver

The braking maneuver (BRK) was moderate (0.25 *g*) and began from a steady forward speed of 80 km/hr. All the simulator subsystems were active. The resulting driver's longitudinal specific force in the cab frame is shown in Figure 8 for both the car and the simulator. The simulator produces a good onset cue followed by a sag in specific force due to tilt-coordination limiting. There is a good f_x transient cue when the car comes to a full stop followed by a large false cue caused by tilt-coordination limiting, which restricts the rapidity with which the tilt-generated specific force can be removed. This braking maneuver used up 21 m of *x-y* carriage travel.

Single Lane Change

The single lane change (with a maximum lateral acceleration of approximately 0.125 *g*) was entered from 60 km/hr. Two simulator configurations were tested for this maneuver, and they were designated as LC1 and LC2.

In LC1 all the simulator motion subsystems were active. This case represents an attempt to minimize the amount of filtering and tilt-coordination in order to take full advantage of the large displcements of the simulator. This resulted in as

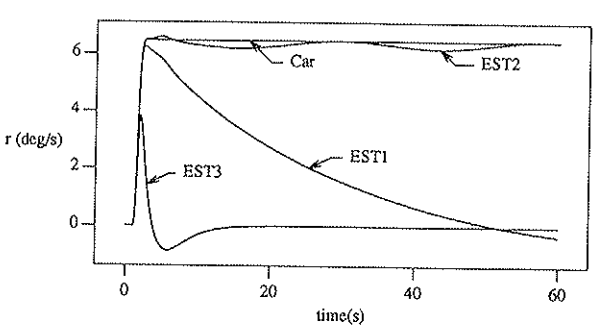

FIGURE 7 Yaw rate for entry and steady turn.

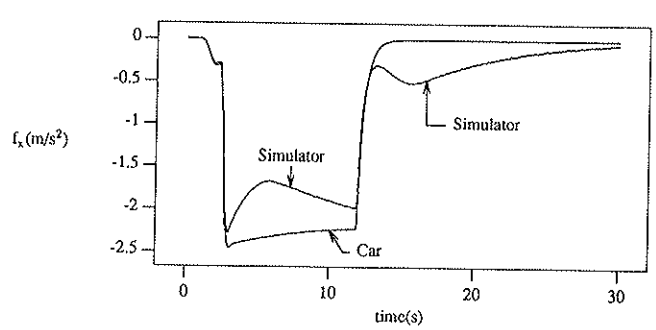

FIGURE 8 Longitudinal specific force for braking maneuver.

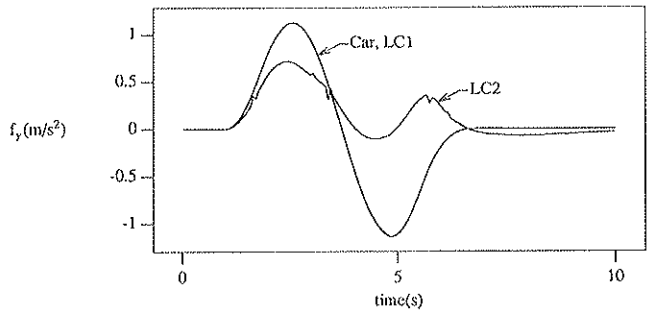

FIGURE 9 Driver's lateral specific force in cab frame for single lane change maneuver.

close to direct duplication of the car's motion as was possible. Only mild high-pass filtering in the x- and z-channels remained. Tilt coordination and filtering of the angular degrees of freedom were eliminated. The resulting simulator trajectory used about the same lateral travel as the actual car (approximately 4 m). It was primarily a lateral motion with a very small amount of longitudinal motion. The simulation of $\vec{f}$ and $\vec{\omega}$ in the cab frame for the driver was almost perfect (see Figure 9 for $\vec{f}$).

In LC2 the turntable and the x-y carriage were turned off. The amount of filtering was increased and the tilt-coordination turned back on. All of the yawing motion is provided by the hexapod. From Figure 9 it can be seen that this has resulted in a degraded simulator specific force cue. This is primarily the result of turning off the x-y carriage. The simulator yaw rate still duplicated that of the car because the maneuver is sufficiently limited in yaw displacement that the hexapod can handle it with no trouble.

SUMMARY

A computer simulation has been developed that can be used to study the performance and specifications of large-amplitude motion-bases intended for driving simulator applications. Both the motion drive algorithm and the physical motion of the simulator are modeled. The simulator configuration selected for study consisted of an unrestricted turntable on top of a hexapod motion platform supported by a large-amplitude x-y carriage.

Algorithms have been selected that divide the motion among the three major subsystems. The commands sent to the x-y carriage are based on their frequency content while those sent to the turntable are often selected to reduce the hexapod motion commands to 5 degrees of freedom.

A tilt-coordination algorithm has been developed that accounts for the presence of the turntable. In addition, an unavoidable interaction between tilt coordination and turntable angular velocity has been identified.

The testing of the motion algorithm on several common car maneuvers has highlighted the benefits possible from the proposed simulator configuration. The large-amplitude x-y carriage can be used to generate excellent specific force cues while minimizing the need for tilt-coordination in certain cases. The turntable provides excellent yaw rate cues.

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APPENDIX

Notation

s = Laplace variable
Δt = computer step size
ωB = angular velocity of frame F_B with respect to frame F_I
$\vec{(\ )}$ = vector
$\underline{b}_B$ = components of $\vec{b}$ expressed in frame F_B (a three-element column matrix)
$\underline{B}$ = matrix
$\underline{B}_T$ = transpose of $\underline{B}$
$(\ )_B$ = variables related to frame F_B
$\dot{x} = \frac{dx}{dt}$
$\bar{x}$ = Laplace transform of $x(t)$

The discussions and conclusions in this paper represent the opinions of the authors and not necessarily those of the TRC or NHTSA.

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