Nonintrusive Measurement of Driving Performance in Selected Decision-Making Situations

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ABSTRACT

Driving simulators and instrumented vehicles both require subjects to control an unfamiliar apparatus, which can result in a potential confounding of task variables and individual differences in adaptability. An experimental methodology, which allows subjects to use their own vehicles on a closed driving range, was developed to study driver decision making. Traffic signals located at a Y intersection together with inductive loops to record vehicle speed and position at selected locations are controlled by a PDP 11/23 computer located in an instrumented van beside the intersection. Auxiliary signs and distractors are used together with instructions to present a variety of driving decision situations. Research objectives and limitations of the system are discussed.

Driving performance measurement has evolved through a number of research methodologies, including both experimental and observational techniques. Experimental methods necessarily involve some artificiality, and the types of maneuvers that can be studied are limited by safety considerations. Subjects are typically required to drive unfamiliar vehicles or simulators, which introduces questions of learning and the adaptability of skills from one vehicle to another. Observational techniques are most useful for traffic and highway engineering studies that examine drivers' responses to roadway modifications. Unobtrusive methods are used to collect data without drivers' awareness. As with any real-world data collection, the lack of experimental control can lead to questions of cause and effect. Ideally, a comprehensive research program should include both observational and experimental components (1,2). In this paper is described an experimental methodology, which allows subjects to drive their own vehicles on a driving range equipped to monitor performance, developed at the Liberty Mutual Research Center. Instrumentation consists of adaptations of existing traffic engineering equipment and nonintrusive devices designed for use with any vehicle. The description is prefaced by a short discussion of existing experimental methodologies. A thorough review of driving performance technology, including the trade-offs among different experimental techniques, is presented by Allen and Weir (3).

EXISTING METHODOLOGIES

Experimental driving performance research methodologies can be categorized according to the equipment used to simulate the driving task and roadway environment. Two major categories of equipment are driving simulators and vehicles equipped with data acquisition instrumentation. Driving simulators vary in complexity from simple part-task devices to whole-task simulators that represent all aspects of driving. Approximately 20 whole-task simulators exist in the United States and Europe for research purposes (3). They can be categorized according to their visual displays, which include electronically generated imagery, computer-generated imagery (vector or raster scan), and scale-model terrain boards. These approaches replaced older technology that used point-light sources, video, or motion pictures for the visual display (4). Driving simulators also vary in terms of their motion (fixed versus moving base), the dynamic computations used to process driver inputs, and the size of the visual field. The complexity of driving simulators is constrained by the capabilities of the digital processor, which determine the rate of response to driver control inputs, the update rate of the visual display, and the data acquisition rate.

Instrumented vehicles have generally been developed to address specific research objectives and typically have digital recording equipment on board to manage data acquisition. Analog sensors are attached, for example, to the steering wheel, brake, and accelerator pedals, and accelerometers are positioned to record various directional forces. Signal conditioning and analog-to-digital conversion equipment is required to provide appropriate digital signals. More sophisticated vehicles have equipment for measuring vehicle lateral position in the travel lane, physiological measures (5), and driver eye movements (6).

Studies that use instrumented vehicles can be divided according to whether the driving takes place on a closed course or on public roads under normal operating conditions. Occasionally, studies have been conducted on public roads that have been temporarily closed to traffic. Studies of this type generally require permission from local authorities and residents, as well as cooperation from police.

Research objectives, together with legal and safety considerations, determine the feasibility of on-road versus closed-course or driving simulator experimentation. For example, research on the effects of alcohol and drugs on driving has generally been conducted either on closed courses or in simulation laboratories because of potential legal and safety

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problems associated with on-road driving. Even for nonimpaired subjects, the types of driving situations that can be studied using actual vehicles are limited by safety considerations. One advantage of driving simulation is the capability of presenting situations that require responses to other moving vehicles or obstacles without actually endangering the driver. However, the safety provided by driving simulators has also been a source of criticism, especially for research on decision making under conditions of risk. Subjects in driving simulators, and to a lesser extent in closed-course environments, are aware of their safety and that the "stakes" involved in their decision making are different from those in real-world driving. They undoubtedly adjust their behavior accordingly.

Currie (7) argued that the threat of personal injury is critical for obtaining realistic decisions in driving performance research. More recently, however, Allen et al. (8) compared simulator and closed-course performance on a decision-making task. Although their results were similar for both methodologies, the closed-course experiment included some aspects that are not typical of research using actual vehicles, including simulated loss of vehicle control accidents and slow (safer) operating speeds (25 mph speed limit). These features could have had the effect of removing the actual threat of personal injury by providing built-in margins of safety between the simulated and actual limiting conditions. For example, the simulated limiting lateral acceleration associated with loss of vehicle control was 0.4 *g*, which is considerably less than the actual threshold associated with average passenger automobiles (0.7 to 0.8 *g*) (8).

In addition to safety, driving simulators offer logistical advantages over closed-course or open-road research including the capability of presenting numerous combinations of experimental conditions. Weather conditions are also standardized in driving simulators, which provides the distinct advantage of being able to adhere to data collection schedules. Both approaches involve significant commitments of equipment, development effort, and time, Ultimately, therefore, the selection of a research tool reflects the priorities of the experimenter, the availability of research apparatus, and trade-offs among such concerns as desired level of experimental control, realism, cost, safety, and time available to complete the experiment.

Driving simulators and instrumented vehicles both share the requirement of having drivers control an unfamiliar apparatus. Handling characteristics of instrumented vehicles often are unique due to the weight of recording equipment, and such vehicles are therefore not especially representative of everyday driving as experimental subjects know it. Instrumented vehicles often require the presence of one or more experimenters in the vehicle, which, depending on individual driving habits, can distract the subject from the experimental task. Driving simulators without motion also provide unrealistic feedback concerning vehicle handling. In fixed-base simulators with wide-angle visual displays, conflicts between visual and vestibular cues can result in vertigo or kinetosis, or both (3).

Driving performance research at the Liberty Mutual Research Center has used both experimental techniques. Experience has indicated that the problem of vehicle familiarity is significant. Drivers, especially older ones, often have difficulty adapting to the unfamiliar control and display layouts and handling of instrumented vehicles and driving simulators. Research using these techniques may thus become a study of individual differences in adaptability to unfamiliar vehicles, requiring lengthy practice sessions and performance criteria to ensure comparable familiarization.

DECISION MAKING IN DRIVING

Driving performance research has traditionally involved measuring the limits of skills related to the perceptual-motor aspects of driving (2,1). Research findings have been used to determine the information needs of drivers and to develop modes and formats of information presentation. However, experimental work reported by Naatanen and Summala (9) and Shinar (2) supports the argument that motivational and cognitive factors are more important than perceptual-motor skills in determining actual on-road driving behavior. This conclusion is based on discrepancies between laboratory and on-road studies of sign perception. Whereas in the laboratory, sign identification depended on characteristics of the display (brightness, simplicity, uniqueness), identification in the real world depended on what is termed "subjective importance," or the subjective risk of ignoring the sign (2). Although drivers were found to be capable of identifying most signs they pass while driving, they chose not to operate at the limits of their capabilities by ignoring messages that they perceived as unimportant.

This conclusion is stated more generally by Naatanen and Summala (9,p.152), who argue that "the demands of the driver's task are more a function of choice than of the characteristics of the task itself." One major implication of this conclusion is that is is not driving skills per se that are critical to traffic safety but rather how the driver chooses to use those skills, for example in the maintenance of margins of safety (e.g., following distance, sizes of gaps accepted). Shinar (2) discusses driving within the context of human information processing, identifying four basic components: attention, perception, decision making, and response. The importance of decision making is stated as follows (2,p.95): "To negotiate a car on the road successfully, the driver has to continuously process new information and use it to make appropriate decisions." Also (2,p.96), "We act on our perceptions by making decisions. Making the right decision at the right time (particularly in emergency situations) is critical."

Ideally, it would be useful to demonstrate the importance of information-processing errors, including faulty driver decision making, with accident data. Unfortunately, the quality of even the most in-depth accident data rarely allows conclusions about driver behavior immediately preceding an accident. Investigators are forced to use information sources of questionable reliability, such as interviews with witnesses. Methodological problems associated with interviews in accident research are discussed by Sheehy (10). Several accident studies, however, have attempted to isolate the information-processing errors involved in accident causation. Using in-depth accident data, Brewer and Sandow (11) found that intoxicated drivers involved in accidents were more likely than others to have been engaged in a distracting precrash activity. Zaidel et al. (12) reported that between 25 and 50 percent of all accidents may have involved driver inattention. Barrett et al. (13) reviewed available accident statistics and concluded that from 60 to 70 percent of all accidents result from errors in decision making.

The importance of information processing and especially decision making in driving is thus evident from both experimental and accident studies. Driving involves active seeking of information and constant selection of the amount of risk drivers are willing to tolerate. Everyday driving requires numerous decisions concerning speed selection, vehicle position (both laterally on the road and longitudinally as in following distance), gap acceptance in entering traffic or passing, and response to traffic signals. These situations typically involve the added constraint of requiring complex decisions within a limited amount of time, often less than 1 sec. Efficient dynamic decision making is thus critical to safe driving and accident avoidance.

METHODOLOGY

Objectives

On the basis of these considerations, two objectives were established for developing a research tool. First, the methodology should be capable of presenting a wide range of decision-making situations that are commonly understood by all drivers. Required decisions should vary in the number of choices, the difficulty of the decision, and the time allowed for making the decision. Second, because of the problem of adaptation to unfamiliar vehicles, the method should allow drivers to use their own vehicles. The use of actual vehicles is constrained by the requirement of providing a safe and controlled environment within which to conduct the experimentation.

To accommodate the first objective, all common decision-making situations in driving were considered. These include the acceptance of gaps in passing and entering or crossing the traffic stream; choice of speed, lane position, and following distance; and response to traffic control devices. For safety reasons, it was decided to select a situation in which only one vehicle would be involved. The most common such situation is the response to traffic signals at an intersection. The choices and outcomes are familiar to anyone who has spent time as a driver or passenger. Varying the configuration of signal and sign combinations at the intersection and the timing of the traffic signals would thus allow presentation of a range of decision-making situations. In response to the second objective, it was decided to use the driving range at the Liberty Mutual Research Center. Allowing the use of any vehicle required devising ways of obtaining experimental quality data without significant intrusion into the vehicle.

Closed Course

The driving range at the Liberty Mutual Research Center was constructed and used primarily for skid control training and research. It consists of a paved skid pan and turnaround loop separated by a two-lane straight segment of road. As shown in Figure 1, the road configuration of the range has been adapted to represent a closed course. The turnaround loop has been delineated to represent a Y intersection. The two-lane approach road is treated as a one-way road for the approach to the intersection. Drivers can thus be instructed to drive in one of the two lanes or allowed to choose between the two, depending on the experiment. After passing through the intersection, drivers follow the loop around to the approach road that returns them to the skid pan area. They follow the perimeter road back to the starting location, which is indicated with a standard stop sign. Along the way they pass a speed limit sign, which is changeable. Secondary tasks, including curve negotiation and obstacle avoidance, can be implemented along the perimeter road with cones. These tasks serve primarily to divert the drivers' attention from the main focus on decision making at the traffic signals.

INSTRUMENTATION

Hardware

Hardware was developed to present experimental conditions and record drivers' responses. Experimental conditions are presented through changes in the traffic signals and sign messages. Drivers' responses are recorded from sensors located on the driving range. Both tasks are controlled by a Digital Equipment Corporation (DEC) PDP 11/23 computer with dual floppy disk drives. A DEC VT-220 terminal and DEC LA-50 printer are the primary peripheral devices for

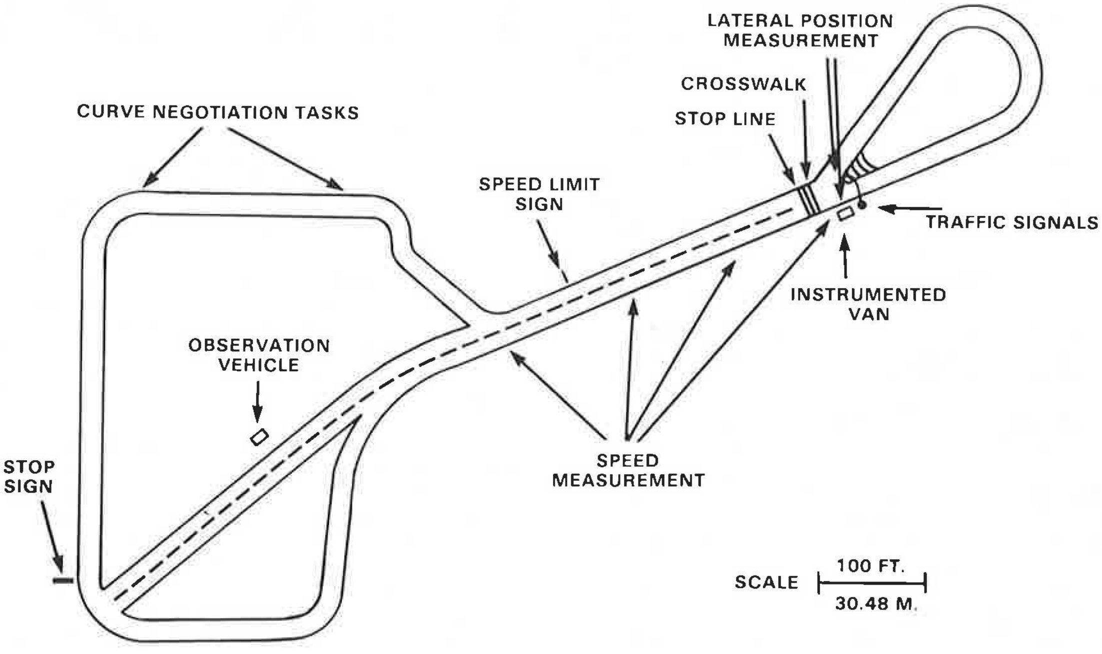


FIGURE 1 Experimental driving range and closed course.

FIGURE 2 Signalized intersection and instrumentation van.

user input and output. The computer is located inside an instrumented van that is positioned beside the intersection during experimentation. In addition to the computer, all instrumentation for data acquisition and control of the experiment is located in the van. The experimenter controls the experiment and monitors data collection from the van.

The central components of the signalized intersection are the traffic signals. Separate signal heads are positioned over each lane. Each head has a single face consisting of standard red, yellow, and green lenses that can display either circular or directional arrow indications. This allows the lanes to be controlled together or separately. The timing of the traffic signals is controlled by the PDP 11/23 via the system clock. The signalized intersection and the instrumented van are shown in Figure 2.

A crosswalk and stop line are painted on the road to define the near boundary of the intersection. Square (5-ft) inductive loops identical to those used to detect traffic at intersections are located before the stop line (beneath the pavement) in each lane. This allows the computer to record the exact times of vehicle arrival at and departure from the stop line and to determine which lane the vehicle is in.

Four pairs of rectangular inductive loops are located on the straight approach road (three before and one after the intersection). Each loop crosses both lanes. The computer uses the time between the two signals associated with the vehicle passing each pair of loops, together with the known distance between them, to compute spot speeds. A single rectangular loop is located before the first pair of speed loops to initiate data acquisition.

Instrumentation was developed to enable the computer to record driver and vehicle braking activity in the approach to the intersection. A brake-light sensor consists of a phototransistor connected to the transmitting circuitry of an FM radio. The output of the transistor is adjusted to compensate for different ambient light conditions. The receiving circuitry is connected to the computer. Times associated with both brake application and release are recorded so that the duration of each brake application can be determined. The sensor unit is housed in a small box with an antenna that is attached to the brake light of the vehicle. Tape is used so that no intrusion into the vehicle is required.

Beyond the intersection, in each of the two lanes, pairs of magnetometers are buried in the pavement. Magnetometers are probes that use a cylindrical sensing head to detect vehicle presence. They are used to detect lane position errors where the vehicle crosses the delineated lane boundaries.

The instrumentation van is equipped with a videocassette recorder (VCR), a monitor, and a video camera that is positioned to record vehicle position over the entire approach to the intersection. The control program starts and stops the video recording. The camera is equipped with a character generator so that the date and identifying information can be superimposed on the film at the beginning of the session and the time from the beginning of the trial can be superimposed during data collection. The instrumentation is shown schematically in Figure 3.

Software

The data collection program is implemented in FORTRAN-IV. The main functions of the program are to set up the experimental conditions and collect data from the sensors on the course. The experimental conditions consist primarily of traffic signal durations, speed limit and other sign messages, and subject instructions. Data collection from the induction loops, magnetometers, traffic classifier, and brake-light sensor involves identifying the type of event and determining the exact time of occurrence from the computer's clock. The program also turns the VCR on and off and schedules the changes of the traffic lights.

The program performs calculations by which the raw data are transformed into measures of performance. Speed data are used to determine accelerations and decelerations and to identify speed limit violations. Vehicle speed is also used for real-time computation of the signal durations, so that the yellow signal onset can be specified as a number of seconds or feet before the intersection. The time at which the vehicle passes the stop line is compared with the red signal onset time to identify stop line vio-

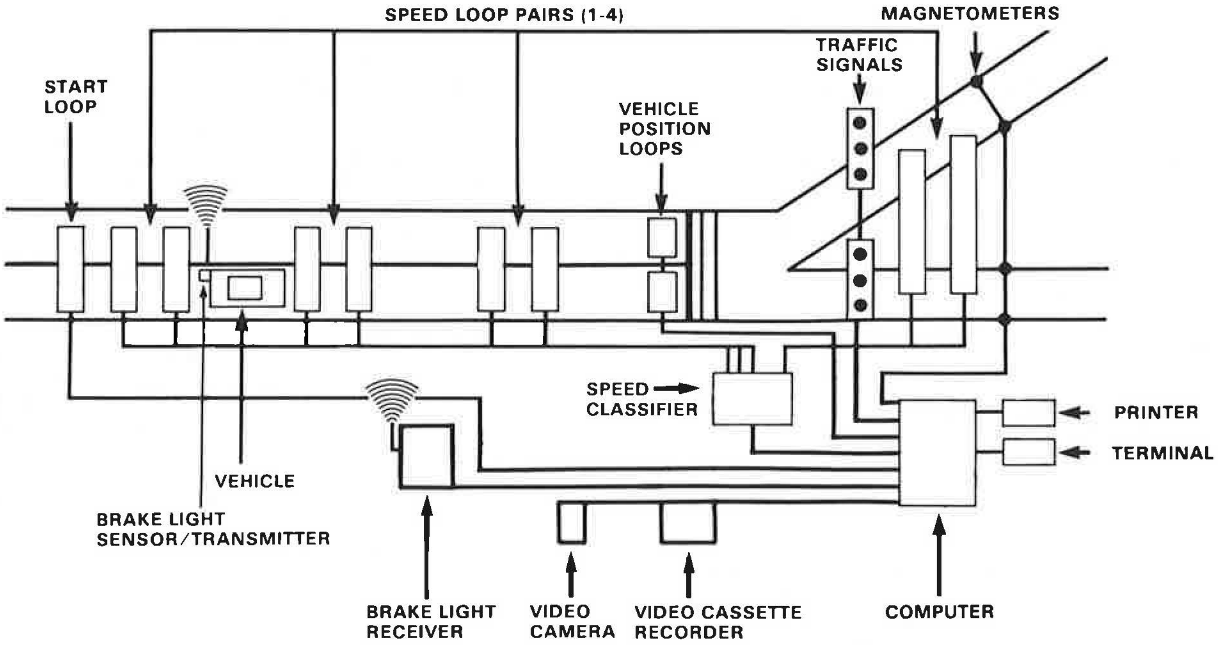


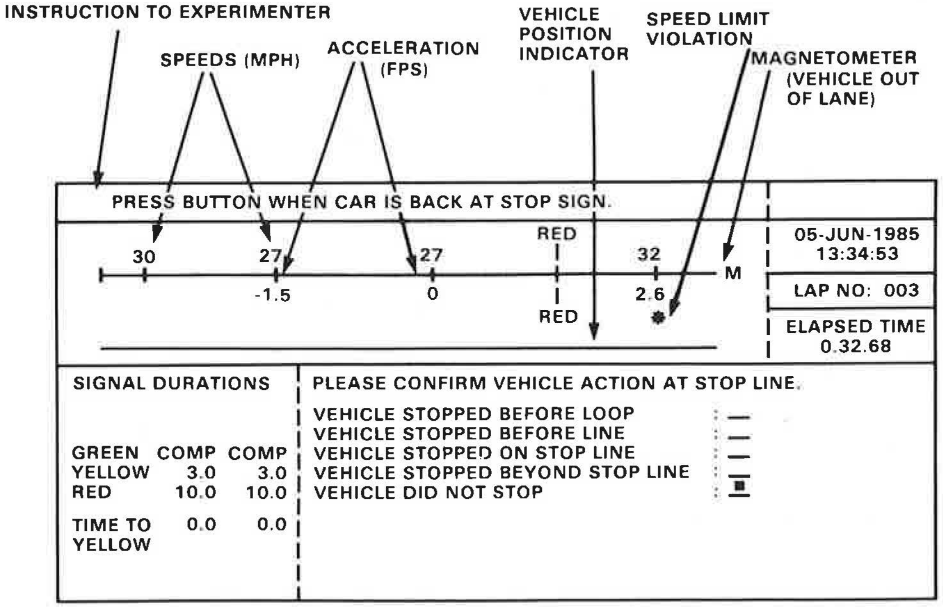
FIGURE 3 Control instrumentation.

lations. Algorithms, based on the timing of the different events, are used to determine whether the vehicle stopped at the intersection on each trial.

The raw and transformed data are used to update the cathode ray tube (CRT) screen as each trial progresses, so that the experimenter can monitor the experiment. The program saves data from each lap for subsequent statistical analysis and copies it to floppy disk and to the printer for backup. Figure 4 shows a sample CRT screen used to monitor the experiment. The main field represents the approach to the intersection. The vehicle position indicator moves along the screen as the vehicle approaches the intersection. Computed speeds and accelerations, as well as speed limit violations and the status of the traffic signals, are shown on the screen as they become available.

DATA COLLECTION

Data collection is initiated when the experimental vehicle crosses the start loop. The time associated with each event is recorded by the program. As the vehicle passes the second loop of each pair of speed loops, a single computed speed is recorded along with the time of the speed event. Two times are recorded as the vehicle passes the stop line, one as the nose of the vehicle crosses the near boundary of the loop and another as the tail of the vehicle crosses the far boundary of the loop. One event time is recorded if a magnetometer is activated, to indicate a lane deviation. In addition, the times associated with signal changes are recorded. Brake activity is also recorded in the area between the start loop and the intersection, such that pairs of



PRESS BUTTON WHEN CAR IS BACK AT STOP SIGN.

05-JUN-1985
13:34:53

LAP NO: 003

ELAPSED TIME
0.32.68

SIGNAL DURATIONS

GREEN	COMP	COMP
YELLOW	3.0	3.0
RED	10.0	10.0
TIME TO YELLOW	0.0	0.0

PLEASE CONFIRM VEHICLE ACTION AT STOP LINE.

VEHICLE STOPPED BEFORE LOOP : _
VEHICLE STOPPED BEFORE LINE : _
VEHICLE STOPPED ON STOP LINE : _
VEHICLE STOPPED BEYOND STOP LINE : _
VEHICLE DID NOT STOP : ■

FIGURE 4 CRT screen used by experimenter.

times (application and release) are associated with each brake application. Therefore, for each traversal of the intersection, there are recorded times for the start loop, four spot speeds, two stop-line pulses, a magnetometer reading if the vehicle departs from the travel lane beyond the intersection, and two pulses for each brake application. The four spot speeds are also recorded.

The accuracy of the data collection is determined primarily by the peripheral real-time clock used by the computer. This clock is set to run at 100 Hz, which provides speeds to the nearest 1 mph. The circuitry used to record brake activity is considerably faster than the real-time clock, so that the accuracy associated with the brake activation and release is 0.01 sec. Traffic signal control uses the internal clock of the computer, which at 60 Hz is slightly slower than the real-time clock. Traffic signal changes thus are accurate to the nearest 0.01667 sec.

EXPERIMENTAL CONDITIONS

The traffic signals and signs allow representation of decision-making situations that differ both with respect to the number of alternative choices and the difficulty of the decision. The basic two-choice decision is whether to stop or continue through the intersection when the signal changes from green to yellow. The difficulty of this decision depends on both the speed of the vehicle and its distance from the intersection at the time of yellow onset. For a given approach speed, drivers far from the intersection will almost always stop, and drivers close to the intersection will generally continue. Between these two extremes lies a "region of uncertainty," where the decision becomes more difficult. The midpoint of this region represents the point at which drivers are equally likely to stop or continue when faced with the yellow signal. The physical location of this region depends on vehicle speed. For this reason, real-time computation of the location of the vehicle at yellow onset, as a function of approach speed, is necessary to control decision difficulty.

The duration of the yellow signal also determines the difficulty of the decision. Real-world decision making at signalized intersections assumes driver knowledge of the yellow signal duration in that decisions are made during the yellow signal phase, when the driver has no way of knowing the duration of the yellow. The information concerning yellow duration becomes available while the driver is executing the decision, such that the feedback can be used to aid decision making in subsequent passes through the intersection. Therefore, although yellow duration can easily be varied, care must be taken to consider the drivers' expectations, which have been developed in the trials immediately preceding the current one.

When the signals are operated together, the basic decision has two alternatives, stop or go. When the signals are timed differently, the driver may be faced with a four-choice or two-stage decision (left or right and stop or go). Independent timing allows the difficulty of the decision in one lane to differ from that associated with the other.

The traffic signs can be used to impose constraints on the decision-making task. The posted speed limit sign can be varied from 20 to 35 mph. The warning sign in the approach to the intersection can be varied to indicate that either the right or left lane is closed. A planned changeable message sign will allow each of the intersection legs to be associated with a predefined destination. The location of these signs can be varied to control when the information becomes available to the subject.

The influence of unexpected distractions on driver decision making can also be examined. Two prototype simulated pedestrians that can be propelled along the crosswalk in response to a computer-generated signal are currently being tested.

The instructions presented to the subject can be varied to establish different experimental conditions. Real-world decision making at signalized intersections depends on motives of the driver, such as the purpose of the trip and the importance of punctuality. Monetary incentives, selectively rewarding different components of performance (e.g., timely completion of the task rather than decision accuracy) can be used to modify subjects' decision making. Because the experimental setup is necessarily artificial in some respects, it is not possible to simulate all factors that ordinarily contribute to driving decisions. Care must be taken to include as many relevant aspects as possible in the reward and penalty structure because subjects tend to adopt strategies that limit their attention to those dimensions that will yield the maximum reward and ignore all others (14).

PERFORMANCE MEASURES

Performance measures include measures of decision making, driving, and parameters of the equation used by traffic engineers to compute yellow signal durations at signalized intersections (15). Decision-making measures include the probability of stopping at the signals, which is derived over a number of trials in each condition, and the accuracy of the decision. Decision accuracy is the percentage of trials in which no error was made. Stopping beyond the stop line, entering the intersection after the light has changed to red, and selecting the wrong lane are examples of errors.

Measures of driving performance include speed at each of the spot locations and tracking errors (driving outside the lane boundaries) after leaving the intersection. Speed limit violations are also recorded. The timing capabilities of the videocamera can be used to determine the exact time of initiation and completion of a lane change maneuver made in response to an unexpected event.

Traffic engineering measures include stopping deceleration, perception-brake reaction time (PBRT), and vehicle start-up times. Stopping deceleration is the rate at which drivers decelerate when they are stopping at a traffic signal. Recent research (16) has demonstrated that the long-assumed deceleration rate of 15 ft/sec^2 is no longer representative of the driving population and has been replaced by 10 ft/sec^2 in the equation used to compute yellow durations. PBRT is the time from the onset of the yellow signal until the application of the brake pedal at signalized intersections. It is a measure of decision speed. Vehicle start-up time is the time between the green onset and the vehicle leaving the intersection.

RESEARCH OBJECTIVES

The instrumentation described comprises a methodology for studying decision making in the approach to a signalized intersection. The major research objectives are to evaluate drivers' decision-making skills, to quantify decision types, and to evaluate information systems. Decision-making skills will be examined as a function of driver age and sex, to determine the relationship of decision accuracy and speed to age, sex, driving experience, and vehicle familiarity. In the process, the types of decisions common to everyday driving will be categorized and analyzed to establish fundamental components. Dimensions of decisions such as the number of choices, the difficulty, and the constraints added by sign messages or other distractions will be identified through this research. Unexpected obstacles (e.g., rolling ball, simulated pedestrian) and confusing or contradictory requirements will be used to create stressful situations. The effects of these conditions on different categories of drivers will be studied.

LIMITATIONS OF THE SYSTEM

All experimentation involves trading realism for data that can be used to make inferences about cause and effect. Researchers emphasize the aspects most important to their research objectives and minimize the detrimental effects of others. The current methodology was designed to emphasize the use of any vehicle and the decision-making aspects of driving. Allowing subjects to drive any vehicle required devising ways of collecting data without invasion of the vehicle for placement of sensors. This required placing instrumentation on the driving range. The major limitation associated with this approach is that data collection is restricted by the locations of the sensing equipment. Speed and lateral position data are available only at the locations of the vehicle sensors. Furthermore, spot speeds at relatively few locations cannot provide the sensitivity associated with driving simulators and instrumented vehicles, which typically record speed continuously and at rates of up to 100 samples per second. The measurement of vehicle lateral position poses a general problem in that most existing environmentally based methods are inferior to vehicle-based approaches. Use of video requires clever camera placement and labor-intensive data reduction. Finally, although allowing subjects to use their own vehicles reduces the problems associated with vehicle familiarity and learning, it raises questions of comparisons among the different vehicles, for example in terms of acceleration, braking, and steering differences. These questions can be partly addressed by experimental designs that use repeated measures with subjects driving their own and common vehicles.

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Publication of this paper sponsored by Committee on Simulation and Measurement of Driving.