Measuring Road User Behavior with an Instrumented Car and an Outside-the-Vehicle Video Observation Technique

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The limitations of human information processing capabilities are apparent in modern road traffic. Research methods for studying road user behavior range from unobtrusive observations of actual traffic to highly controlled laboratory experiments. Often the incompatibility between controllability and validity makes the choice of a suitable method difficult. Described in this paper are recent developments in two research methods used at the TNO Institute for Perception. In-car measurements using an instrumented car enable a detailed analysis of the behavior of the individual driver. The behavior of arbitrary road users can be analyzed quantitatively by outside measurements with video techniques. Recently developed computer-based techniques allow the quick, efficient, and flexible use of both methods. The methods are illustrated by examples of recent research in which driver behavior is analyzed in terms of time-related measures. At the control level of the driving task, several results can be explained by the Time-to-Line-Crossing (TLC) measure. At the guidance level, the Time-to-Collision (TTC) measure defines the severity of interactions between road users. The correspondence between the results of both approaches suggests that drivers directly use such time measures for vehicle control and decisionmaking strategies in traffic.

Traffic safety problems are often caused by limited human capabilities in reacting to a wide range of traffic situations. With higher speeds and increasing traffic densities, the road user cannot evaluate all information correctly. Therefore, it is important to become familiar with the functional limitations of the individual road user.

To collect basic knowledge on driver information processing and to translate this knowledge into optimal roadway and vehicle ergonomics, a wide variety of research methods is necessary. These methods differ on the controllability of relevant aspects or circumstances, the unit of measurement, the selection of measurable aspects, and the validity of the results for traffic safety. Incompatibility between controllability and validity exists in most traffic safety research.

The ultimate way to study road user behavior is to analyze accident data. Although accident data are a direct measure of traffic safety, they are concerned only with the outcome of the traffic system. Furthermore, the recording of accident data is usually incomplete, difficult to access, and often not usable in evaluation studies because of the problem of small numbers. A major problem is also that suitable control data such as exposure measures and characteristics of the task environment are seldom available.

Some of the methodological shortcomings of accident data analysis may be overcome with well-controlled laboratory research methods. Driving simulators are a valuable tool for specific research questions. The required completeness of a driving simulator facility depends on the nature of the research question. In many cases, a part-task simulation may be sufficient. For example, in measuring threshold values for the perception of lateral speed, the total dynamic visual road scene has to be presented but subjects do not have to actually steer a vehicle. They only have to decide on a non-zero value for that variable. Such part-task simulations are useful for analyzing the driving process in detail. However, generalization of findings to normal driving behavior is often difficult.

The lack of reliability of accident analysis data and the limited validity of laboratory simulation makes the development of real-world observation techniques relevant for road user behavior research. At the TNO Institute for Perception two techniques have been refined recently, an instrumented car and a video observation and analysis technique. Modern technologies enable a quick, efficient, and flexible use of these research methods. Each of them will be described in this paper. In addition, the use of both techniques to enlarge our understanding of the strategies adopted by drivers in actual traffic will be illustrated by an example of recent research in which behavior was analyzed in terms of time-related measures.

INSTRUMENTED CAR FOR ROAD USER STUDIES (ICARUS)

The use of instrumented cars as a "general purpose" driving laboratory for road user studies has increased gradually since 1960. At that time, conventional electronics and tape recorders were used to meet basic data monitoring and storage requirements (*1*). In recent years, the development of microprocessor and microcomputer technology stimulated the use of flexible data acquisition systems in instrumented cars (*2,3*). The major advantage of the equipment used in the TNO instrumented car ICARUS is that it provides quick and standardized pro-

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TABLE 1 SOME SPECIFICATIONS OF VARIABLES AS MEASURED IN THE INSTRUMENTED CAR ICARUS

Variable	Sensor	Manufact.	Model	Range	Accuracy
steering-wheel angle	potentio-meter	Bourns	6574-1-103	$\pm 45^{o}/270^{o}$	±0.1%
yaw velocity	gyro	Notronic	76506/ D 1963551	$\pm 100^{o}$/s	± 1 %
vertical accel.	strain gages	Statham Instruments	A5-2.5-350	±2.5 g	±10 %*
lateral "	"	"	A4- 1 -350	± 1 g	±10 %*
longitudinal "	"	"	"	"	" *
driving speed	Hall transducer	Siemens	FP211D155	0-144 km/h	0.16 km/h (10 Hz)
lateral position	see text	TNO		-1 to +2.5m	± 1 %

* unfiltered

cedures to set up and execute experiments. An overview of the variables measured and the system configuration is presented below. While in the ICARUS, the subject is accompanied by an experimenter and a technician. The technician takes care of the equipment and the experimenter gives instructions to the driver and supervises the experimental procedure. When working with inexperienced subjects or in risky situations, a driver-training instructor acts as experimenter who can take over with dual controls.

Measurement of Variables

The variables of the driving process can be grouped into different categories, that is, driver inputs, driver outputs, physiological parameters, and vehicle motion characteristics. Table 1 presents the technical specifications and details about manufacturer and type of sensor for the major variables.

Driver Input

The variables in this category include all input information available to the driver and describe the relevant aspects of the environment, that is, preview, road geometry, road signs, and interacting traffic. Driver input consists also of specific variables related to the movements of the vehicle.

Driver visual input is difficult to record. Although the view in front of the car can be recorded easily with video equipment, it is difficult to gain further knowledge about the driver's information selection process. In earlier versions of the ICARUS much effort was spent to study the driver's information selection by adding the driver's head and eye movements to the video picture (*4*). In the mid-1970s, however, interpretation and data analysis problems with eye-movement results made us decide to reduce this type of research. Cognitive-oriented research on visual selection processes, driver attention, and in-car displays may stimulate a renewed interest in eye-movement analysis (*5,6*). Time-domain analyses of looking strategies can also be made by using occlusion techniques. The ICARUS is provided with a spectacles-mounted liquid-crystal occlusion device PLATO (Portable Liquid-crystal Apparatus for Tachistoscopic Occlusion) with open and closure times of less than 3 ms. Milgram (*7*) gives a detailed description of this device and an example of its use will be presented later.

A programmable electro-luminescent display (Deeco, M3EL 512 × 256 PS) and voice inputs are available to analyze the influence of existing and future control and communication aids inside the car. Information on driver visual input can also be gathered by the experimenter on a pushbutton unit for labeling special events in the driving environment such as overtaking maneuvers, interacting traffic, or the presence of road signs.

In some experiments, driver performance and workload are measured by introducing an additional task in which the driver has to react to specific auditory or visual stimuli.

Driver Output

As a result of the perceived information, the driver may anticipate and react to the traffic situation by changing course or acceleration. These actions also have to be recorded. Steering wheel movements are measured by a potentiometer attached to the steering column (for specifications see Table 1). Pedal actions are measured with potentiometers and switches, gear-lever position, and all other controls with switches. The horn-lever switch can be used for driver response.

Vehicle Motion Characteristics

The driver's actions define performance in terms of vehicle motions, accelerations, velocities, and road positions.

The three translational accelerations are measured with three vehicle-fixed one-dimensional accelerators mounted just behind the driver.

Forward velocity and distance traveled are measured with a pulse-counter and Hall transducer mounted on the drive shaft. The rotational velocities around three axes are measured with small gyros.

The lateral position of the vehicle in relation to the road geometry describes lateral vehicle control on straight and curved roads. The ICARUS is equipped with a special device developed by the Institute. It continuously measures the distance between the vehicle and a reference line. Any sufficient change of contrast at the side of the road can be taken as reference. The transducer is mounted at the back or beside the ICARUS and scans the intensity of reflected light in a lateral plane across the road through a fast rotating prism in front of a photoamplifier. Contrasting light levels (reference line) cause peaks in the scanning signal, which are used to measure the prism rotation angle at that specific moment in relation to the vertical position. A tangent-transformation gives the lateral distance to the reference line. A given sector of the lateral plane can be selected by an electronic adjustable scanning window to avoid incorrect measurements because of passing vehicles or other disturbing objects. The lateral position transducer operates in a wide range of ambient light. During night conditions, however, it is necessary to illuminate the road in the lateral plane by additional spotlights on the vehicle.

Physiological Parameters

Indications of driver performance and workload may be derived from variables describing the driver's physiological state. Several physiological variables can be measured, for example, heart rate, respiration rate, galvanic skin response, and special features of the electroencephalogram (EEG).

System Configuration

The variety of projects requires a system that allows flexible, efficient, and reliable registration of a given subset of variables and presents stimuli dependent on the experimental design. Therefore, the system is built around a computer with floppy disk data storage. Figure 1 shows a schematic diagram of the basic configuration. The analog to digital (A/D) input channels with a resolution of 16 bits, D/A output channels of 12 bits, and the digital channels of 24 bits each cover a given set of variables. A special interface unit allows the use of all kinds of analog input variables.

A set of batteries, a 24 V/DC generator (Motorola, 8SA3005, P-10-24) attached to the engine, and two converters of 220 volts/AC, 500 watts each (Blessing Electronics, BTY 24/500/S) deliver the power supply for all the equipment. An automatic power-off safety switch prevents additional damage in case of a collision.

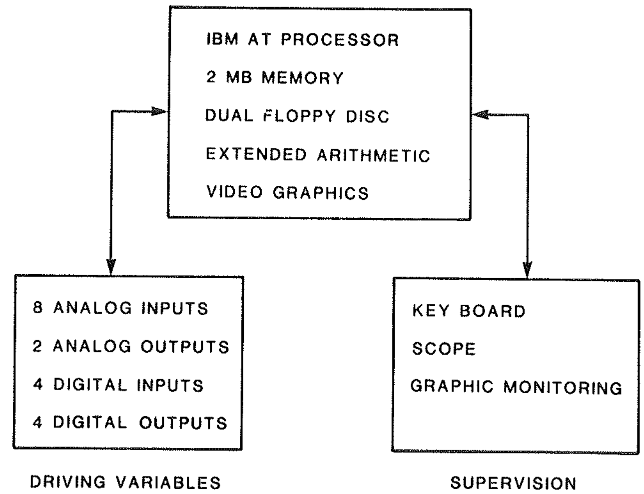

FIGURE 1 Basic configuration of the data-management system in the instrumented car ICARUS.

Standard procedures are used for checking, calibrating, and monitoring the analog and digital channels with the help of a graphics display in front of the technician. All data of each experimental run are stored on floppy disks in data files that also contain all information related to experimental conditions, system configuration, and calibration. A storage capacity of more than 1 Mbyte enables an unrestricted sampling time of several hours for eight channels at 10 Hz. The maximum sampling frequency depends on the number of channels and is approximately 300 Hz for eight channels or 2500 Hz for one channel.

VIDEO ANALYSIS OF ROAD TRAFFIC SCENES (VIDARTS)

The use of an instrumented car is appropriate in studies where both the input to the driver and the driver output to the system are essential. For studying interactions between road users or between road user and environment, it is often sufficient, or even better, to observe behavior in terms of vehicle movements. These can be observed unobtrusively in actual traffic situations. Recording traffic scenes allows reliable data collection and detailed analyses of behavior.

The development of a quantitative method for analyzing road traffic scenes started with a comparison between film and video. Both techniques have specific advantages and disadvantages, but video was highly preferred with respect to cost, practical aspects, and potential for future technical developments (*8*). A semiautomatic procedure for analyzing video scenes was developed, enabling a quantification of movements of any given vehicle in actual traffic.

Van der Horst (*9*) describes an early version of the video analysis system. A recent implementation on an IBM/AT computer with a video digitizer card extended considerably the flexible and interactive use of the system.

General Procedure

The procedure consists of making videorecordings with one or more fixed cameras on the spot and a subsequent off-line quantitative analysis at the laboratory with a specially developed video plotting device. A fully automated real-time image processing procedure would be preferred, but such an approach is not realistic because of the current state of technology. First, a real-time analysis might be needed in video monitoring road traffic for traffic surveillance, traffic control, or traffic management. In most of our applications, however, the requirement for real-time processing is not urgent. Second, in many applications it appears to be effective to preselect relevant events before a detailed quantitative analysis. Furthermore, a process with interactive communication between the system and a human operator reduces the complexity of the analysis procedure.

The quantitative analysis consists of selecting positions of some points of a vehicle by positioning an electronic cursor on a video still. By a transformation based on at least four reference points, the x- and y-coordinates of the video plane are translated into positions on the road plane. By analyzing successive video stills, a sequence of positions over time is obtained from which other variables such as velocity, acceleration, heading angle, and time-to-collision measures are derived. Sometimes a more simple procedure can be applied, that is, measuring time moments of passing given successive road positions instead of measuring positions at successive time intervals. For example, by measuring the moments when two lines with a known distance in between are passed by a vehicle, a simple speed measurement can be obtained.

Data Collection and Analysis

Videorecordings

The first step in data collection consists of making videorecordings of traffic scenes at intersections or road sections. A suitable place for mounting the camera has to be found at the location, preferably at a height of more than 4 m above the road surface. A primary requirement is that the observations do not influence the driver behavior. For that reason, placing a video camera on the roof of a van or on a telescopic mast (*10,11*) was rejected. A good and unobtrusive camera position can be found either in an adjacent building, on a balcony, in a lamppost, or in other elements present at the location.

Basically, the videorecording equipment consists of three parts—the camera, a combined synchronization/timer/field-encoder unit, and a videorecorder. Until now, black-and-white videocameras have been used because of their superior horizontal resolution. A wide variety of fixed focal length and zoom lenses in the range from f = 5.8 to 100 mm is available to ensure an appropriate field of view (for a ⅔-in. camera between 78° and 5° horizontally). When the outlook of the location is too limited or the area is too large to be covered by one camera, additional cameras, videowiper(s), or recorders are optional. It is important that all equipment is synchronized correctly and that each video signal to be recorded separately is coded identically by the timer/field-encoder unit. This unit superimposes a numerical display of date and time of day (up to 1/50 sec) onto each video image and a special digital code at the beginning of the video lines. This 24-bit digital code (one-to-one related to the time of day) uniquely labels each video field and is used for the computer-controlled search for any given image during the analysis procedure.

Usually, the recordings are made by a Umatic videocassette recorder (speed 50 fields/sec). When no direct judgments from tapes have to be made by human observers and the frequency of occurrence of relevant events is low, a time-lapse videorecorder can reduce considerably the amount of material. A reduction factor of 4 (12.5 fields/sec) enables a full 12-hr period to be stored on one 180-min VHS videocassette. Table 2 gives the specifications of the videorecording equipment.

Video Plotting Procedure

The basic configuration of the video plotting device is shown in Figure 2. An IBM/AT computer (640 Kb of RAM memory, 20 Mb hard disk, 8 expansion slots) forms the central part of the system. Two expansion slots are used for two interface cards that provide up to 4 parallel input and 4 output channels of 24 bits each.

One of the laborious tasks in analyzing videotapes is the precise positioning of the tape at the right image. The videorecorder operates under full computer control. Any given picture is searched automatically by the computer by the special digital time code stored in each video field. The decoder for reading the digital video code is one of the few institute-made devices. A low-cost FOR-A time-base corrector (type FA-400PS with a correction range of 2 fields and a horizontal resolution of >320 lines) is used to enhance the sync part of the video signal before it is processed by the rest of the system. The video processor with frame grabber and an 8-bit 1024 × 1024 video RAM memory (of which 520 × 576 pixels are effectively in use) (Matrox, PIP-1024) enables a flexible use of the equipment because many features can be implemented in software. For example, for simple speed measurements, a programmable electronic grid can be generated; for measuring positions, a cursor can be manipulated either by computer or human operator control. Also, simple image processing procedures, such as automatically detecting traffic signal changes directly from the video image, can be implemented rather easily in software. A special additional keyboard with 24 programmable function keys enables the operator to communicate efficiently with the system. For the first few images of a sequence, the operator has to position the cursor on a given point of the vehicle. When a few images have been analyzed, an algorithm predicts the expected position of the point based on the x- and y-positions in previous images. Then, the operator only has to indicate small corrections on those estimated positions.

Transformation From Video-Image Plane to Road Plane

In earlier studies on analyzing film or videorecordings quantitatively, a grid transformation was used for the conversion of image coordinates to road coordinates (*12,13*). However, assuming that (a) all points of the road surface are in one flat

TABLE 2 SPECIFICATIONS OF VIDEORECORDING EQUIPMENT AS USED FOR VIDARTS

Equipment	Type	Manufact.	Model	Horizontal resolution (lines)	S/N ratio (dB)	Minimum illumination (lux)
B/W camera	1/2" CCD	Philips	LDH0600/00	>450	50[1)]	1.5
"	2/3" CCD	JVC	TK-S310	>530	50[2)]	2
"	2/3" vidicon	Sony	AVC 3250CE	>550[3)]	44	150
timer[4)]		FOR-A	VTG 33			
recorder	Umatic	Sony	VO 5800 PS	>340	48	
"	"	"	VO 5850 P	>340	48	
"	VHS	Panasonic	NV-8050-E	>300	45	
video wiper		Sony	CMW-110CE			
mixer/wiper		Videomatte	VM1			

All equipment is based on the PAL video standard (interlaced 2:1, 625 lines/50 Hz).

1) at 20 lux

2) at 2000 lux

3) in center, in corners > 400 lines

4) modified version with built-in synchronisation/field encoder unit.

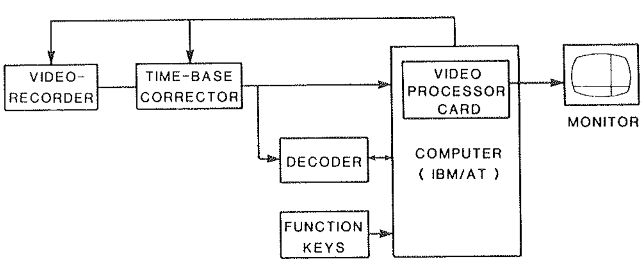

FIGURE 2 Basic configuration of the video plotting device

plane and (b) no distortion errors from the optics of the camera occur (correct central projection), the method of two-dimensional projective coordination (*14*) is much simpler to apply.

The transformation of video image coordinates (X_v, Y_v) to road coordinates (X_r, Y_r) is given by a broken linear function of the following form:

$$X_r = \frac{C_1 \cdot X_v + C_2 \cdot Y_v + C_3}{C_7 \cdot X_v + C_8 \cdot Y_v + 1}$$

and

$$Y_r = \frac{C_4 \cdot X_v + C_5 \cdot Y_v + C_6}{C_7 \cdot X_v + C_8 \cdot Y_v + 1} \qquad (1)$$

The coefficients C_1 to C_8 can be calculated if the coordinates of at least four points are known both in the image plane and in the ground plane. Substituting the X_r, Y_r, X_v, and Y_v coordinates of the four points in Equation 1 results in a system of eight linear equations with C_1 to C_8 as variables. This system can be solved if no combination of three points in either plane is on a straight line. This method offers the practical advantage that nothing has to be known about the internal and external orientation of the camera. All information is included in the way the four reference points are projected on the image plane. The smaller the pitch angle of the camera the more sensitive to measuring errors the transformation will be. In general, accuracy will improve when the optical axis of the camera is as vertically oriented as possible (the higher the camera position the better) and the four reference points are spread maximally over the area to be covered.

To have a check on the transformation and to conduct an optimization procedure on the transformation, some additional reference points have to be included. A number of eight to ten points appears to give reasonable results.

In actual road scenes it will almost always be possible to find natural markings that are clearly readable from the video image.

Computation of Motion Parameters

Accuracy in the measurement of positions may be influenced by many factors. A relatively high position of the camera(s), a large pitch angle, and careful selection and accurate measurement of reference points are first steps in reducing systematic errors. An optimization of the transformation coefficients based on all available reference points minimizes the influence of random errors in the measurement of the reference points. Parallax errors can be avoided by taking the contact point between tire and road surface as the precise point to be measured. By filtering the video coordinates before the transformation to the road plane, by determining the resulting position from two or three separate points of the vehicle, and by smoothing successive positions by means of a second-order polynom filtering, the overall accuracy can be improved considerably. For most applications at urban intersections, the overall accuracy for measuring vehicle position is estimated to be better than ± 0.05 to 0.1 m. Further details are presented in Van der Horst (*15*).

Vehicle velocity is obtained by differentiating successive positions with respect to time, and acceleration is found by differentiating successive velocities. For most applications it is not necessary to analyze every individual video frame; a selection of one picture out of every 12 (one picture/0.24 sec) appears to be a reasonable compromise between accuracy and duration of plotting.

APPLICATIONS

In recent years both ICARUS and VIDARTS have been applied in a series of road user studies. Instrumented car research resulted in fundamental knowledge on course and speed perception (*16,17*) and its consequences for roadway delineation systems (*18*). Video observation research gave new insights into driver decisionmaking processes at intersections and railway grade crossings (*19–21*). VIDARTS also proved to be a useful tool to analyze the interactive decision process between bicyclists and car drivers at particular intersections (*22*).

Both techniques will be illustrated by a short description of research projects in which driver behavior is analyzed in terms of time-related measures.

Time-to-Line-Crossing Analysis Based on ICARUS Measurements

Most of the traditional models on steering control are based on the assumption that the driver acts as a path error-correcting mechanism continually allocating attention to the steering task. However, it can be shown easily that this assumption is incorrect. Godthelp et al. (*23*) developed the Time-to-Line-Crossing (TLC) approach as a description of driving strategy that considers the driving task merely a supervisory task. With the TLC approach, predictions are made on the basis of a preview-predictor model about the time periods during which, for instance, path errors can be neglected. This prediction process assumes that (a) the vehicle starts from its momentary lateral position and heading angle and (b) the steering wheel remains fixed at its momentary position. At each moment, TLC can be calculated from the ICARUS lateral position, heading angle, speed, and commanded steering angle. Thus, the time needed by the vehicle to reach either edge of the lane is quantified. Figure 3 shows an example of a time history of these signals with the TLC measure.

In an experiment on straight lane keeping, Godthelp et al. (*23*) illustrated that TLC may serve as a valid predictor of a driver's self-chosen occlusion times for a broad range of speeds (20 to 120 km/hr). Subjects made a series of runs in the right lane of an unopened freeway with normal lane markings. Half of the runs were made with normal vision and the other runs were conducted with a voluntary occlusion. In the latter conditions, subjects wore the occlusion device as mentioned earlier. In its normal state, the occlusion device was closed, that is, the visual field was completely occluded. When the horn lever was pressed, the device switched to the "open" mode, which lasted 0.55 sec. Subjects were instructed to drive safely in the right lane and to request 0.55-sec looks whenever necessary. It was made clear to the subjects that this was not an experiment in risk taking and that wandering beyond the lane markings should be prevented. Normal precautions were taken regarding randomization of conditions, fail safe circuitry, etc.

The results of this study showed an almost perfect correlation between representative values of the TLC distribution and the occlusion times as voluntarily chosen by the subjects. This finding indicated that experienced drivers use consistent internal representations regarding the influence of speed on the duration of periods available to neglect path errors in vehicle control. Godthelp and Kaeppler (*24*) replicated this experiment with cars of different handling characteristics and found the same consistencies for understeering cars. However, in oversteering vehicles, drivers tended to accept relatively large occlusion periods despite the occurrence of very low TLC levels at the higher speeds.

The TLC approach allows us to gather more detailed information about the process of driver adaptation to vehicle characteristics. A recent study (*25*), with a procedure similar to the experiments described above, focussed on whether a driver's adaptation to road width variation, as quantified in occlusion times, could also be explained from TLC data. Again, subjects made runs at different speeds (20, 60, and 100 km/hr) on a straight highway. The major independent variable (lane width) was varied in steps of 0.5 m, giving four width levels—2.05, 2.55, 3.05, and 3.55 m. For each run, median occlusion times and 15-percent TLC levels were calculated (15 percent of the absolute TLC values in a given run is below the "15-percent level"). Table 3 gives 15-percent TLC values and occlusion times (T_{occ}) averaged over subjects and replicated for different speed and road width levels. For the three largest lane widths, 2.55, 3.05, and 3.55 m, the same consistent relationship between T_{occ} and the 15-percent TLC values was found as in the earlier experiments. This indicates that drivers use a correct internal representation about the relation between

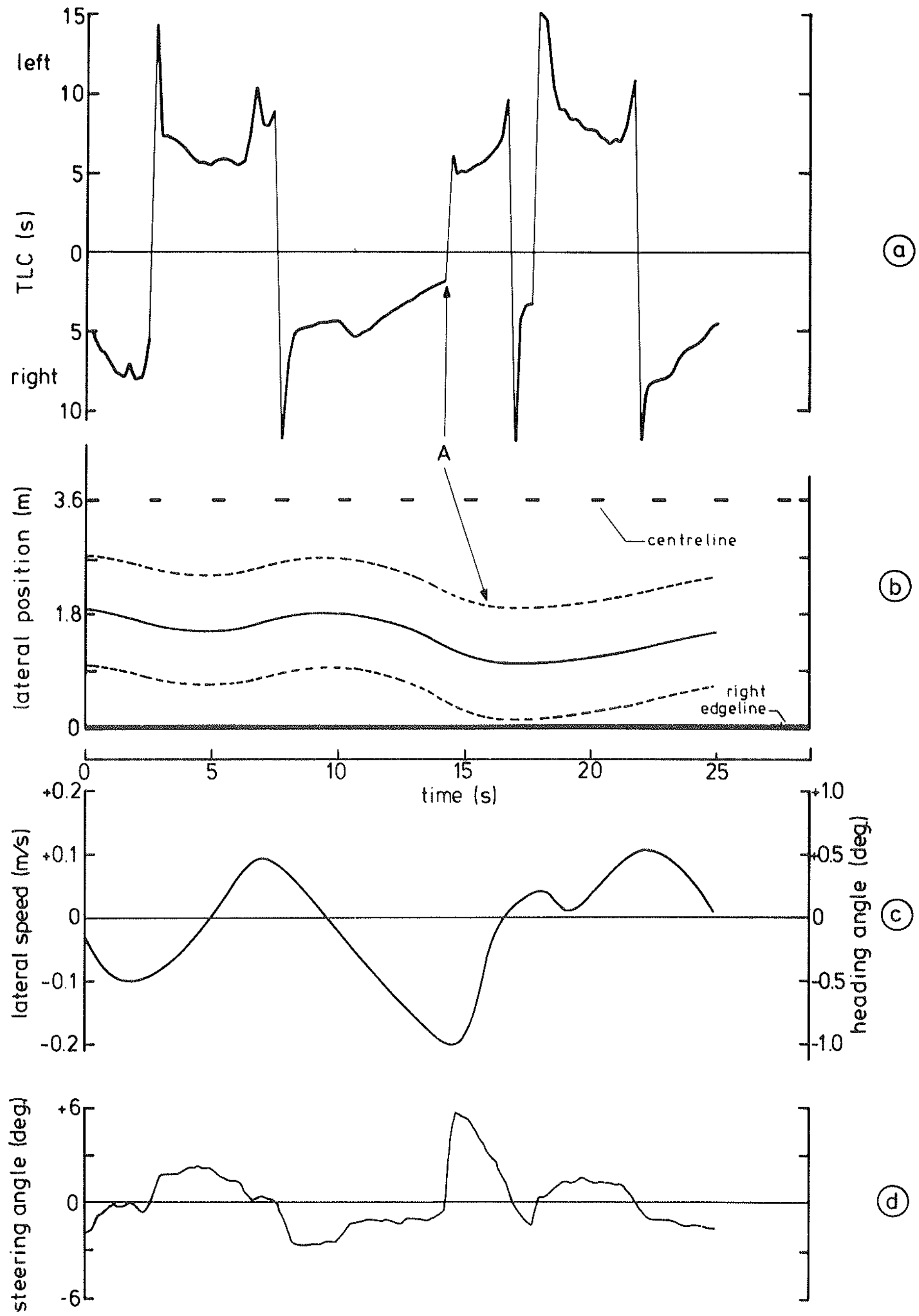

FIGURE 3 Sampled time history for a TLC signal resulting from the corresponding lateral position, heading angle, and steering-wheel angle.

lane width and the duration of the time available to neglect path errors. However, the 2.05 lane width data are clearly different and show that drivers tend to accept relatively large occlusion periods as compared to the 15-percent TLC values. This finding might point to a misinterpretation of the driving situation with this narrow lane. A more detailed analysis of this phenomenon is presented elsewhere (*25*).

In the occlusion experiments presented here, the TLC approach is used to quantify the potential role of visual open-loop and path-error-neglecting strategies. Basically, TLC represents the time available for a driver to neglect path errors until any part of the vehicle reaches one of the lane boundaries. The strategies adopted by drivers during error neglecting can be analyzed further by quantifying the decision rules used by drivers who switch from error neglecting to error correcting when approaching the edge of a lane. Godthelp (*26*) analyzed these rules for a straight lane-keeping task. In a condition with normal visual feedback, subjects were instructed to neglect vehicle path errors and to switch to error correcting only when the vehicle heading could be corrected comfortably to prevent crossing the lane boundary. Again, runs were made with ICARUS at three speeds (20, 60, and

TABLE 3 OCCLUSION TIMES (T_{occ}) AND 15 PERCENT TLC VALUES FOR THREE SPEEDS AND FOUR LANE WIDTH LEVELS

Speed	Lane width: 2.05 m		2.55 m		3.05 m		3.55 m	
(km/h)	$TLC_{15\%}$	T_{occ}	$TLC_{15\%}$	T_{occ}	$TLC_{15\%}$	T_{occ}	$TLC_{15\%}$	T_{occ}
20	2.0	2.4	4.8	3.6	5.9	3.8	7.8	4.3
60	1.4	1.4	3.1	2.0	3.9	2.5	4.9	2.9
100	1.2	0.9	2.7	1.4	3.6	1.9	4.0	2.1

Times are given in seconds.

100 km/hr). The results showed that the lateral distance from the lane boundary at which drivers switch to error neglecting increases linearly with lateral approach speed. This mechanism results in an approximately constant TLC of 1.1 sec. This result is consistent over a broad range of speeds.

It can be concluded from this TLC analysis that an integration of variables measured with an instrumented car may enlarge our understanding of the strategies adopted by drivers in various vehicle control situations.

Time-to-Collision Measurements Based on VIDARTS

In research on traffic safety problems at single locations and in evaluating safety measures, the information available from police accident records is of little use in analyzing the chain of events leading to an accident (*27*). The processes that result in near-accidents or serious traffic conflicts have much in common with the processes preceding actual collisions; only the final outcome is different (*28*). Techniques have been developed in several countries to systematically observe traffic conflicts using individual observers. Large differences in local circumstances result in a variety of definitions, observation methods, and severity scores. Therefore, in 1983 an international calibration study at Malmö, Sweden was conducted to compare the various traffic conflict techniques (*29*). Except for a comparison of the scores by eight different observer teams, the subjective scores could be related to several objective measures obtained by our video observation technique (*30*).

The Time-to-Collision (TTC) measure appeared to be one of the major factors in explaining a common severity dimension based on the subjective scores by the observer teams. The TTC as defined by Hayward (*12*) is the time for two vehicles to collide if they continue at their present speed and on the same path. Figure 4 shows what happens when a car approaches a fixed object. The time histories at the left represent an evasive action of normal braking; at the right, one of very hard braking. Point A indicates the TTC when the evasive action is started, representing the available maneuvering space at the moment of braking. Point B gives the minimum TTC value, reached during the approach. In more complex interactions of two moving road users, the collision course often is ended before Point B. In such cases, the TTC curve would not be concave. But even then, the minimum TTC value indicates how close an actual collision was. Both TTC values (at Points A and B) play an important role in determining the severity of a conflict. In general, only interactions with a minimum TTC less than 1.5 sec are considered critical. Trained observers are able to consistently apply this threshold value (*30*).

In an explorative study to identify and describe the rules applied by road users in a priority situation, behavior at a general rule (right-hand, right-of-way) intersection and a yield sign intersection was analyzed with VIDARTS (*20,31*). All encounters between traffic from two legs of the yield sign intersection were analyzed. The distribution of minimum TTC values showed only a few encounters with a minimum TTC less than 1.5 sec; a distinct 1.5-sec threshold value for minimum TTC appeared to be present (Figure 5). An analysis of approach profiles of free riding straight-on and left-turning motorists from the minor road revealed a similar minimum time to the intersection of 1.5 to 2 sec before deciding to proceed. The right-turning motorists did not show a minimum in their approaches.

These results suggest that time-related measures are important in describing road user behavior in actual traffic situations. Consequently, the question arises whether time measures such as the TTC are used directly by road users as a cue to decisionmaking in traffic. This hypothesis is the subject of continuing research (*32*).

The video technique appears to be an especially helpful tool for studying interactions between road users, because several dynamic elements in the approach process can be investigated in an integrated manner.

FINAL REMARKS

As major failures in the road traffic system are eliminated, research methods to improve traffic safety and operation will

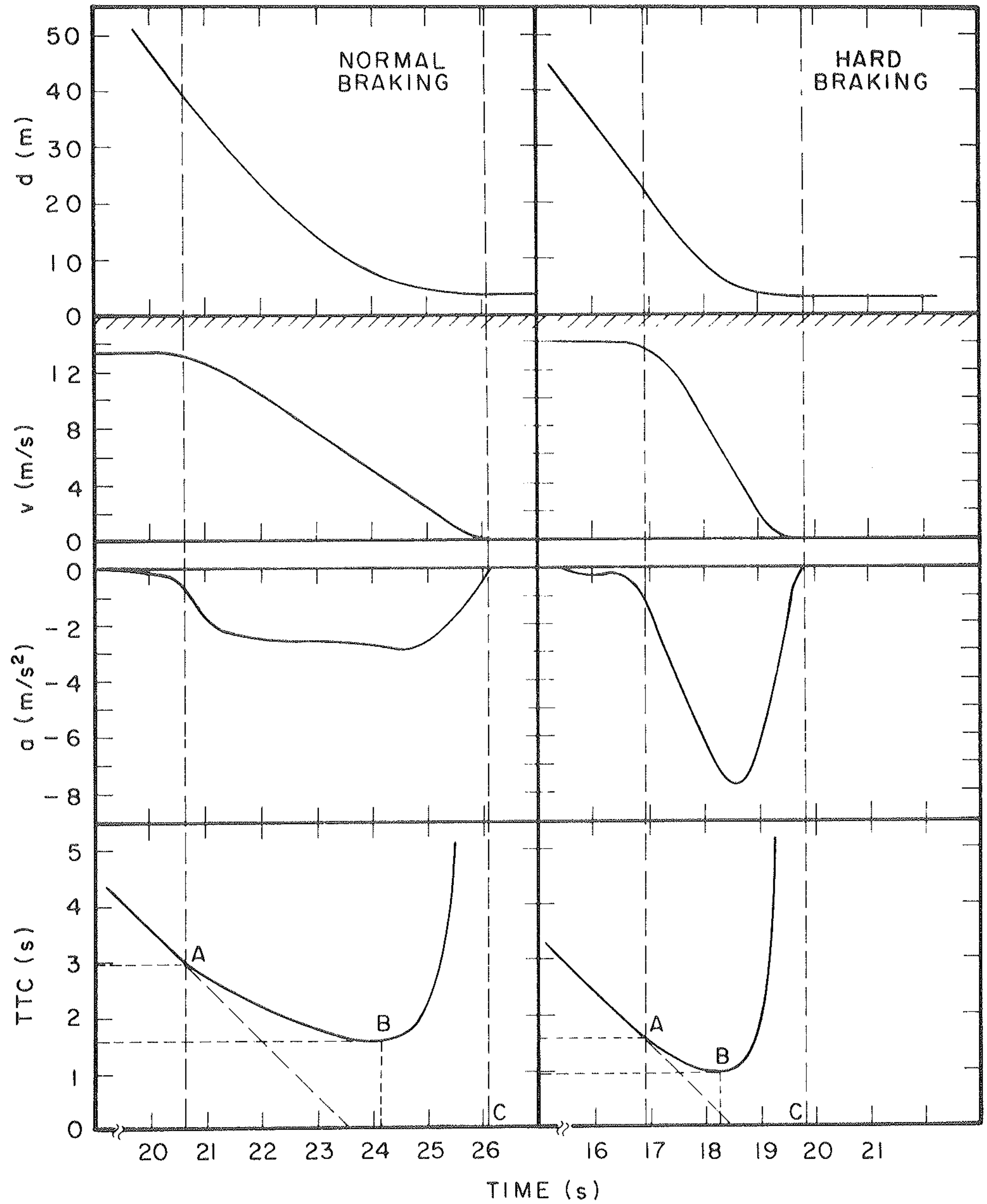

FIGURE 4 Examples of time histories of normal braking (left) and very hard braking (right) of a car approaching a fixed object. From top to bottom: *d* = distance to object, *v* = velocity, *a* = acceleration, and *TTC* = time-to-collision.

have to be more complex and refined. More detailed information on how the road user functions will be needed.

This paper addressed research methods for studying road user behavior with an emphasis on instrumented car and video observation techniques. The method used depends on the objectives of the specific research. The variables available by using an instrumented car such as the ICARUS enable a detailed analysis of driver behavior. The ICARUS was equipped recently with a telemetric system to study interactive behavior between road users for simple situations such as car-following and to measure behavior in a car equipped with relatively simple instrumentation.

The video observation technique has been proved to be very helpful in analyzing interactions between road users or between a road user and the environment in actual traffic. However, the work of the human operator is still time-consuming and strenuous and further automation is needed. The development of an automated system for road traffic scene analysis has made a promising start (*33*).

The correspondence in the results of the analysis of driver behavior in terms of time-related measures such as TLC and TTC suggests a fundamental relationship with driver control and decisionmaking strategies. This is the subject of continuing research.

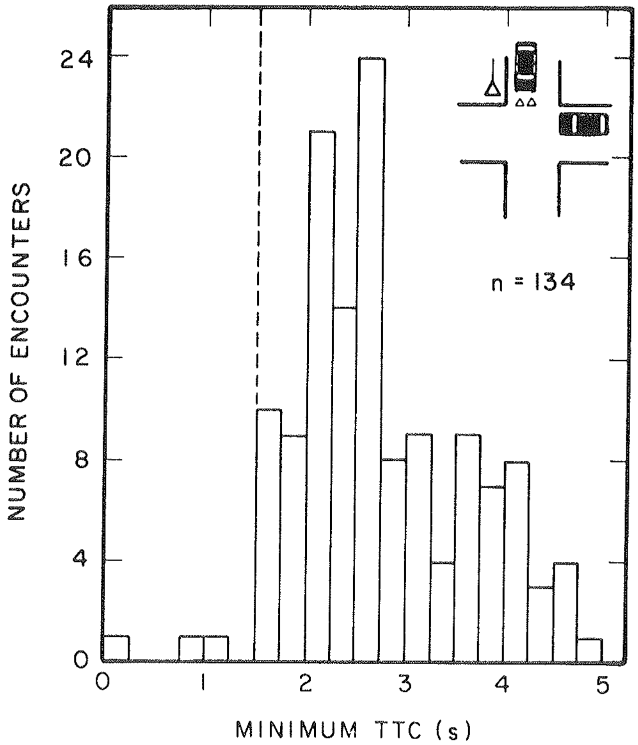

FIGURE 5 Distribution of car-car encounters with a minimum *TTC* < 5 sec at a yield-sign intersection.

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