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Contents

Perceptual and Field Factors Causing Lateral Displacement

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•WHEN an object is placed near the path of a driver, a lateral movement away from the object occurs as the driver approaches. The amount of this lateral displacement has been shown to be directly dependent on the distance of the object from the path of travel (2, 6). Thus, Taragin (6) has shown that there is a shift in position for objects located up to 6 ft to the right of the driver's path of travel. However, the process that the human operator must carry out in order to locate himself relative to fixed objects in his path has not been specified. The present research was an attempt to isolate the variables involved in this location process.

From a perceptual standpoint, the transverse location of an object in a driver's path may be considered a problem in trigonometry. The transverse distance, a, or an object may be derived from the simple trigonometric expression:

$$a = 1 \tan \theta$$

The conditions are shown in Figure 1.

Thus, at any point in space, the observer may determine the distance, a, by estimating both 1 and θ. For small angles, $\tan \theta = \theta$, and therefore, the equation becomes simply

$$a = 1 \theta$$

However, a problem arises for the driver because of the interaction of distance and angle. At long distances, the angle θ is so small that errors in estimation preclude a solution of sufficient accuracy to determine whether the object is in the driver's path. Similarly, at short distances, θ increases so rapidly that solutions also become inaccurate. Therefore, there should be a range of distance for which judgment of the angle θ has maximum accuracy. On the basis of this angle estimation model, as the driver approaches the object, he eventually moves into an optimum range of discrimination. If the angle is smaller than some critical value he will displace from the object, the magnitude being directly related to the size of the angle at the distance at which the discrimination is made. According to this model, lateral displacement should begin at some fixed distance from the object independent of the absolute location of the object and independent of travel speed.

An alternative model exists, however. Because the driver is moving continuously toward the object, the angle as well as distance is changing continuously. If the driver tracks the object over a period of time and estimates the rate at which the angle is changing, he can also determine the lateral location of the object relative to his path of travel. This derivative is a nonlinear function of time and is, furthermore, dependent on the speed of travel. If the driver were to operate on this basis, he would be solving the equation:

$$\frac{d\theta}{dt} = \frac{av}{a^2 + 1^2}$$

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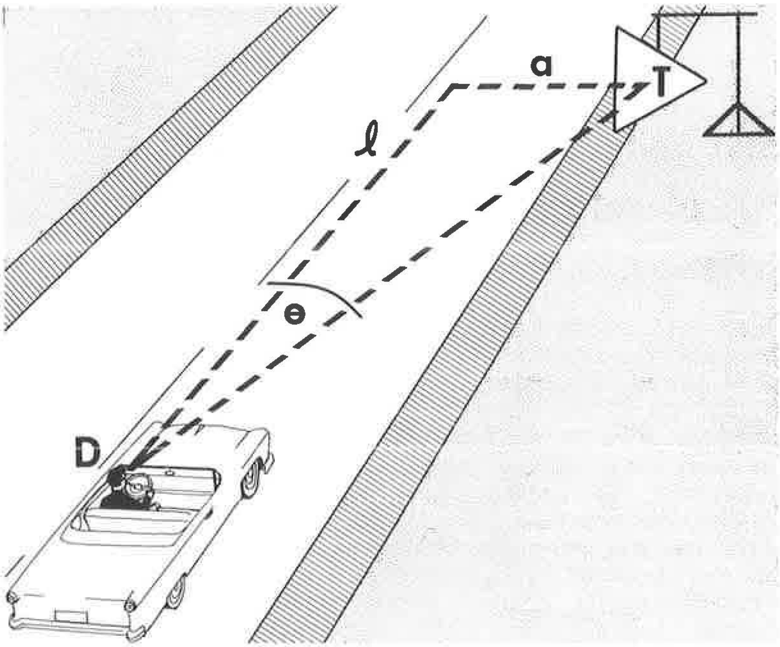

Figure 1. Geometry of object location problem.

Estimation of the rate of change of the angle between himself and the object in his path has several advantages for the driver. First, his judgment very quickly becomes a simple binary one. If the rate of change does not exceed a certain critical value, regardless of sight distance and object location, the driver can predict a collision course. Second, the driver has a physical anchor for speed judgment and one source of error may be minimized. Third, vehicle speed must be taken into account in any steering inputs imposed on the vehicle.

On the basis of the derivative model a set of hypotheses arises which is very different from the angle estimation model. The hypotheses may be stated as follows:

1. The magnitude of lateral displacement will be directly related to vehicle speed.
2. Lateral displacement will begin at a distance dependent on vehicle speed.
3. The derivative of the visual angle at the point where displacement begins will be independent of speed and object location so long as displacement occurs.

A final consideration that exists in the displacement effect concerns the spatial characteristics of the stimulus object. In the description of both models, it was implicitly assumed that the object was a point in space which served as a simple visual reference. Actually, all practically realized displacing objects have some extension. It would appear reasonable that the nature of the contours of the object would influence the driver's perception of the location of the object. The study of Case et al. (2) did find that the size of the object significantly affected displacement.

It might be expected that the angle would be taken to the contour of the object nearest the path of travel. If, however, the shape of the object is of limited extent and has one dominant contour, the driver might be expected to use that as a point of reference. An example is a triangular object with the base oriented perpendicular to the driver's regard. It may be expected that, when that base is farthest from the roadway (the apex being nearest the travel path), there should be less displacement than when the situation is reversed. Obviously, this is a limited case for there should be a limit to contour effectiveness if the farthermost border has too great an extent. Within these limits, it is reasonable to hypothesize that the dominant figure contours should influence the magnitude of displacement. In this study, an equilateral triangle was used to test this hypothesis.

In summary, this study was an attempt to isolate the perceptual variables that cause lateral displacement and to discriminate between two alternative models of that process.

APPARATUS AND PROCEDURE

To determine where and when lateral displacement began and the magnitude, it was necessary to devise a method for measuring lateral position continuously. An optical tracking system was developed by Melpar, Inc., for this purpose. It was a housing anchored on the rear bumper of a vehicle containing 37 individual photodetector units mounted to face downward. The detector is shown in Figure 2. Each unit contains a light source and lens system to focus the beam on the roadway, and a mirror system that focuses light reflected back from a specially prepared road onto a photoresistor. A schematic of the detector unit is shown in Figure 3. To get sufficient light reflected back to the photoresistor, a 2-in. retroreflective strip was placed on the pavement. With this material, a high proportion of the incident light from the lamp is reflected back into the mirror and hence to the photoresistor.

The photoresistor itself was connected directly to a transistor amplifier. If no light fell on the photocell, so that its resistance was high, the amplifier was biased below cut-off. When, however, the incident light was high and resistance dropped, sufficient current flowed to close a relay. Thus, whenever one of the detector units passed over the reflective line, it and only it, would fire. As the vehicles moved laterally, a different unit was activated. Because the units were on 2-in. centers, lateral position could be estimated to the nearest inch. With a total of 37 detector units, displacement could be measured over a range of 6 ft.

To record the diplacement data continuously, the digital output of the amplifier relays was used to switch an appropriate step in a 37-section potentiometer. This analog voltage was then recorded on a Brush recorder. With this complete system, it was possible to plot the path of a vehicle continuously as it traveled down the test track. By leaving 5-ft gaps in the reflective line every 100 ft, it was possible to determine lateral placement as a function of distance from the displacing object.

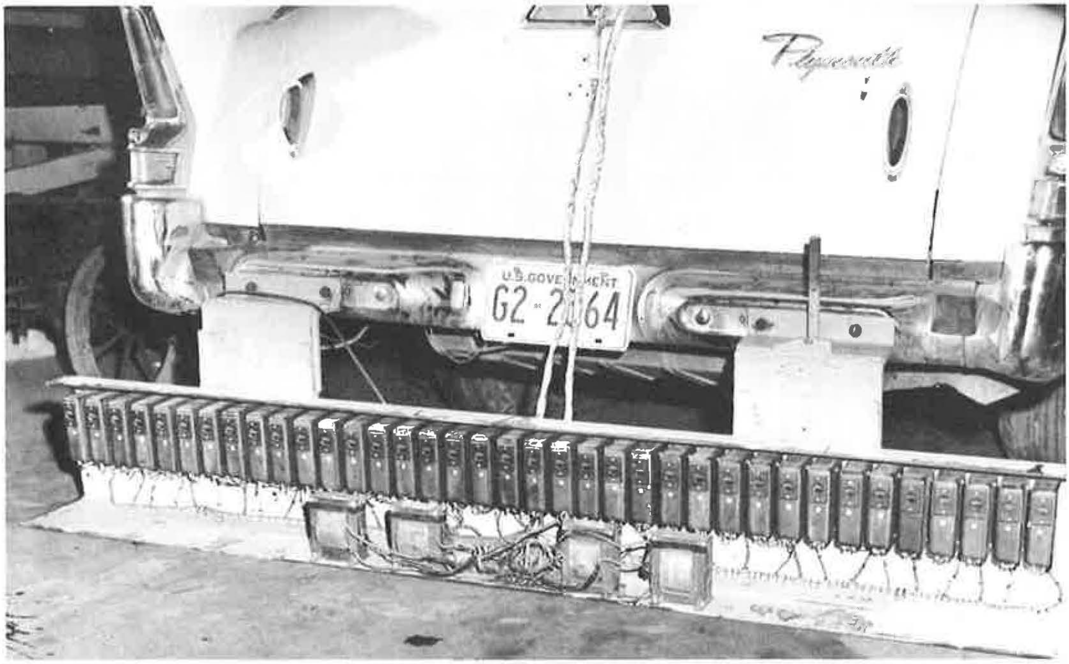

Figure 2. Lateral displacement detector.

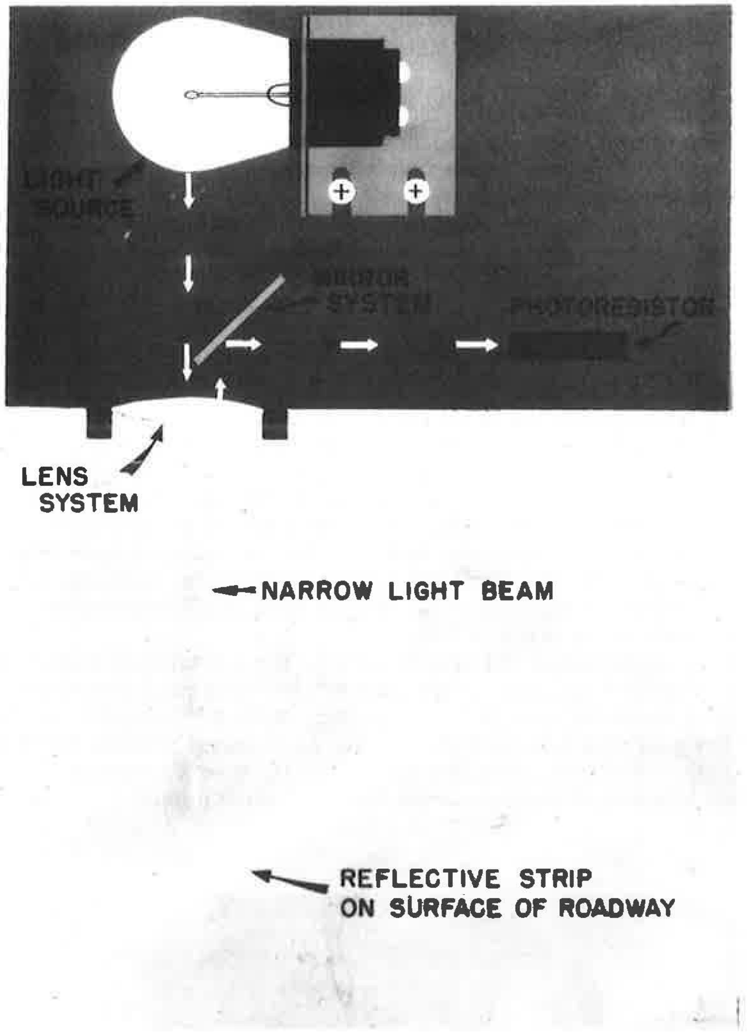

Figure 3. Photodectector unit.

The test track was a 1-mi section of a jet aircraft runway. The runway was of concrete, 100 ft in width plus an additional 25-ft wide asphalt shoulder on each side. The runway was made up of four 25- by 20-ft sections of concrete. The maximum vertical curvature of the section used was less than 0.1 percent. A single section nearest the edge of the runway was used. Thus, the travel path was effectively a lane 25 ft wide with its limits being demarcated by the asphalt shoulder on the driver's right and the longitudinal joint on his left.

The reflective strip was laid in the center of the lane. It was placed with an accuracy such that the deviation from the center was never more than 1 in. over the mile course. The reflective material was a metallic buff color that was clearly visible to the observer. No way was found to camouflage this line and still retain sufficient retroflectivity to insure reliable operation of the placement detector. The arrangement of the test situation is shown in Figure 4.

The displacing objects used were two identical equilateral triangles 6 ft on a side, mounted on a boom. This boom was 12 ft long, of sufficient length to minimize any effect that the mounting base might have on displacement. The boom could be moved in

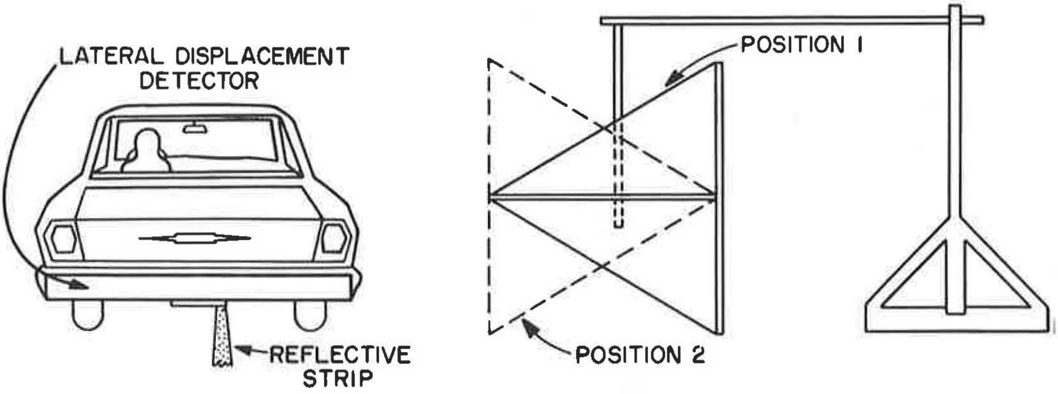

Figure 4. Test situation.

or out and the triangle could be rotated about its mounting point to have either the base or the apex nearest the path of travel. One object was placed 2,000 ft from the beginning of the course, and the other, 4,000 ft. Four lateral locations for each object were selected. From an analysis of the angle estimation model, the distance at which the tangent function begins to exhibit an obvious change in slope is about 200 ft. This model predicts a direct relation between lateral displacement and the size of the angle; hence, object location was chosen in units of angular separation at the distance of 200 ft. The closest location was chosen at this point to subtend an angle of 2°. Three other positions were chosen so that they subtended angles of $2\frac{1}{4}^\circ$, $2\frac{1}{2}^\circ$, and $2\frac{3}{4}^\circ$. In lineal distance from the driver the object was placed 7.0, 7.8, 8.9, and 9.6 ft.

In these experiments, each object was placed at random among the four locations. In addition, the orientation of the triangle was arranged randomly. The complete matrix of conditions was randomized using orthogonal latin squares so that any interaction effects between the two objects were counterbalanced.

Four vehicle speeds were used: 15, 30, 45, and 60 mph. Each subject was tested at each speed for all combinations of object location and orientation. In total, each subject went through a 4 by 4 by 2 factorial design. In addition, the design was replicated four times.

All the electronic equipment for measuring and recording lateral position was mounted in a station wagon and included a 1.5-kv generator on top. A driver subject and the experimenter were the only occupants of the vehicle. Four assistants adjusted the position and orientation of the displacing objects according to a prearranged schedule.

The subjects were five male drivers, ranging in age from 25 to 40 years. All were licensed drivers with five or more years of driving experience. None were told the purpose of the tests. Rather, they were told that the study was aimed at finding out how well they could maintain the vehicle at a constant assigned speed.

RESULTS

The maximum lateral displacement was determined for each condition and each subject. These data were subjected to an analysis of variance, and the summary is given in Table 1. As may be seen, differences among the main variables are significant at the 0.01 level. The analysis also shows a significant interaction among these variables.

Figure 5 is a plot of displacement as a function of object location for each of the four speeds. These curves include data for the base orientation only. The line shown is the mean displacement for the five subjects. The general form of the curve is the same as that for each individual subject. The straight-line relationship shown is similar to Taragin's (6) data, but the magnitude of lateral displacement is less.

The displacement at each object location increased markedly with speed as summarized in Figure 6. Again, these four curves are for the the base orientation only.

TABLE 1

ANALYSIS OF VARIANCE FOR LATERAL DISPLACEMENT UNDER 32 EXPERIMENTAL CONDITIONS

Source of Variation	Sum of Squares	d. f.	Mean Square	F
Vehicle speed (VS)	2,911.7	3	970.5	46.88[a]
Object distance (OD)	3,658.4	3	1,291.3	62.38[a]
Object orientation (OS)	252.5	1	252.5	12.20[a]
Driver (D)	9,610.8	4	2,402.7	116.07[a]
VS × OD	110.5	9	12.3	-
VS × OS	135.0	3	45.0	2.13
VS × D	2,015.9	12	168.0	8.12[a]
OD × OS	240.1	3	80.0	3.86[a]
OD × D	1,979.4	12	164.9	7.97[a]
OS × D	34.9	4	8.7	-
VS × OD × OS	226.2	9	25.1	1.21
VS × OD × D	1,007.2	36	279.8	13.52[a]
VS × OS × D	297.4	12	24.8	-
OD × OS × D	637.6	12	53.1	2.06
VS × OD × OS × D	796.4	36	22.1	-
Error: within treatments	9,917.8	480	20.7	-
Total	33,831.8	639		

[a] Significant with probability less than 0.01

The data demonstrate that lateral displacement is directly dependent on travel speed as well as object location.

In the rate of change of angle model it was hypothesized that lateral displacement would begin at a distance from the object that was directly dependent on vehicle speed. Figure 7 shows the relation between vehicle speed and the distance at which displacement began. The parameter is the lateral location of the displacing object. As may be seen the beginning point varied from approximately 50 ft at 15 mph to about 275 ft at 60 mph. The data are consistent in showing a significant increase in starting distance for all four object locations and, thus, the hypothesis is confirmed.

A third hypothesis that derived from the angular change model was that the rate of change of angle at which displacement began would be independent of both object location and vehicle speed. To test this hypothesis, it was necessary to determine from each run the point at which lateral displacement began. This determination was confounded by two factors. First, there was a certain variability in lateral position for all subjects. Thus, considerable error was possible in the judgment of the beginning of displacement because it was frequently uncertain whether the change was in response to the displacing object or just random changes in position. Second, not all conditions yielded a significant displacement, in which case no determination of starting distance was possible. In general, this occurred when the object was located farthest from the travel path and at the lowest speed (15 mph). In general, lateral displacement occurred reliably for the three highest speeds, and the three closest object locations. The distance at which displacement began could reliably be estimated for these cases. Further analysis was done only on these data.

For these combinations of speed and lateral location of the object, the rate of change of angle was determined for each speed and each driver subject, and an analysis of variance was done on these data. The summary is shown in Table 2; none of the differences are significant. It seems reasonable to conclude, therefore, that there is a constant rate of change of angle between the driver and the object at the point where displacement is begun.

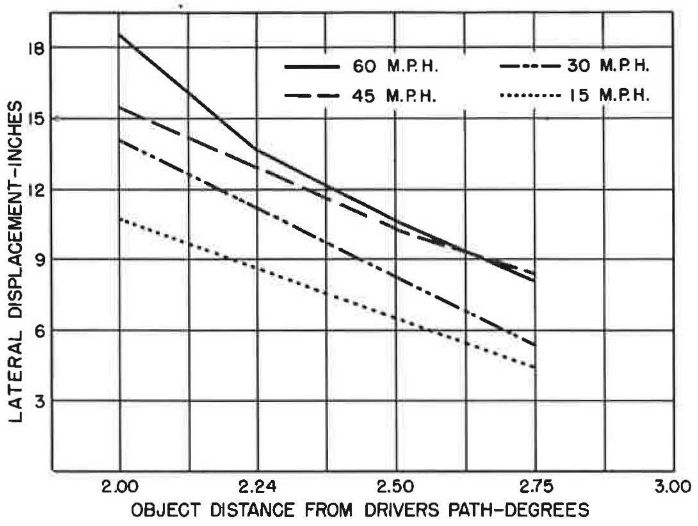

Figure 5. Lateral displacement as a function of object location at different speeds.

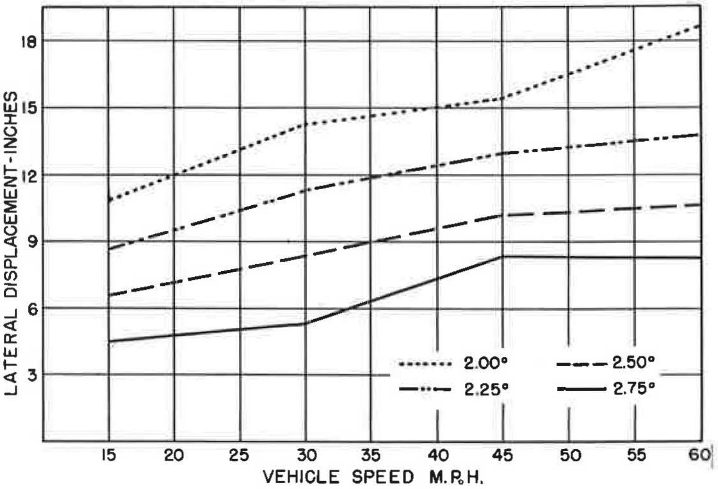

Figure 6. Lateral displacement as a function of vehicle speed for different object locations.

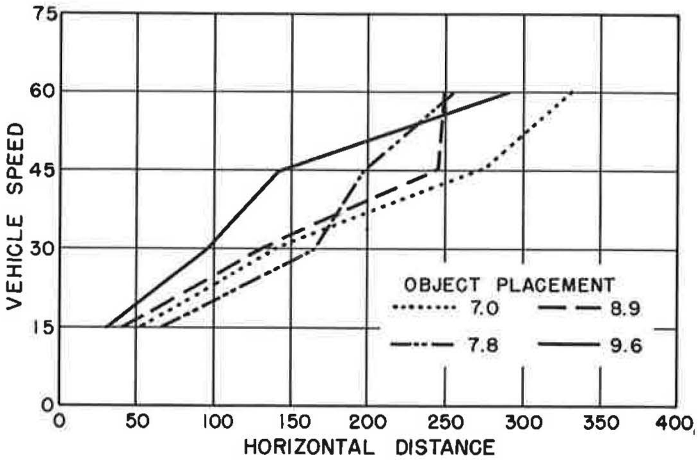

Figure 7. Relationship between vehicle speed and distance from object at which displacement began.

TABLE 2

ANALYSIS OF VARIANCE FOR ANGULAR CHANGE

Source of Variation	Sum of Squares	d. f.	Mean Square	F
Between vehicle speeds (VS)	17.3	2	8.65	4.62
Between drivers (D)	7.1	4	1.78	-
Interaction: VS × D	34.9	8	4.36	2.33
Error: within treatments	56.2	30	1.87	-
Total	115.5	44		

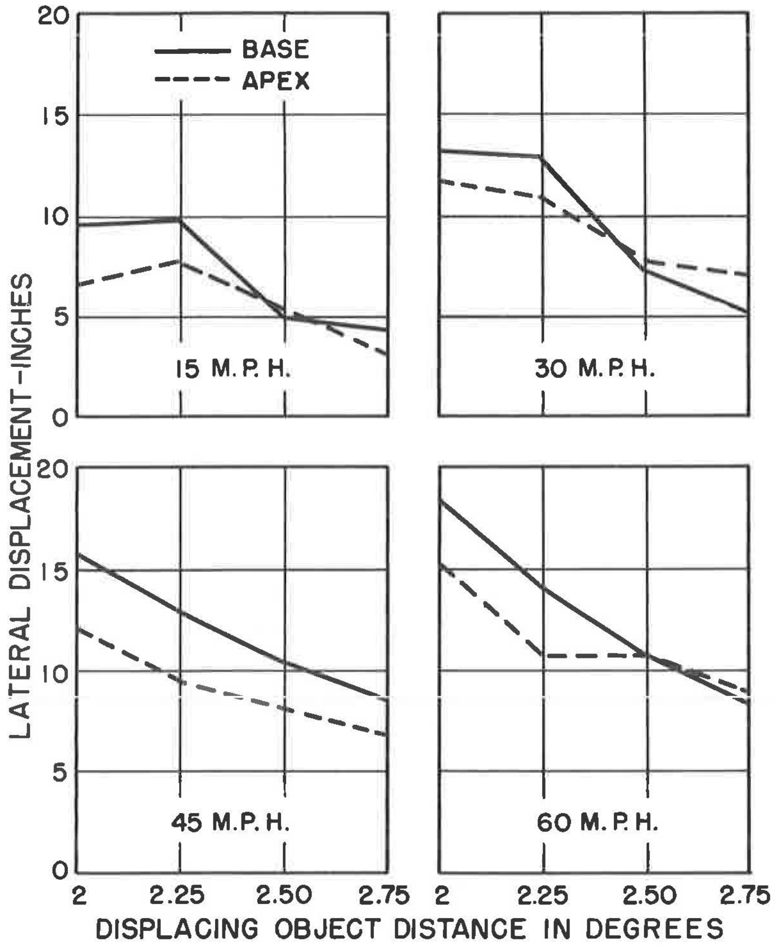

Figure 8. Effect of three highest vehicle speeds on angular change (three closest object distances combined).

The final result of this investigation concerns the spatial relations between the contours of the displacing objects. It was hypothesized that displacement would be greater when the base of the triangle was nearest the path of travel than when the apex was so located. The analysis of variance in Table 1 shows that there was a significant difference between object orientation. In Figure 8, displacement is plotted as a function object location for each orientation and for each speed. The difference between the base and apex orientation increases with speed of travel and decreases as object distance increases. Again, the results offer verification for the hypothesis that lateral displacement should be dependent on the geometric characteristics of the displacing object.

ANALYSIS

The data clearly indicate that a model of lateral displacement based on the rate of change of visual angle accounts best for the obtained results. The three hypotheses originally specified for this model were validated and thus, as the model predicts, there was a direct relationship between the magnitude of displacement and travel speed. A second hypothesis, that lateral displacement would begin at a longitudinal distance that was functionally related to vehicle speed, was also confirmed by the data. Third, it was hypothesized that the determining factor in displacement would be the derivative of the visual angle which would be constant over all conditions. The results of this study offer strong confirmation of this hypothesis.

Thus, the study leads to an explanation of lateral displacement that is based on the driver's ability to detect the rate of change of visual angle of objects near his path of travel. The problem for a driver approaching an object near his path of travel is one, from a perceptual standpoint, in which, phenomenally, the image of the object moves across the retina. However, this model is actually a special case in the general field of the visual perception of velocity. The major differences are that (a) the angular velocity of the target in the driving situation is nonlinear and (b) the visual angle subtended by the object itself increases as the observer approaches.

From this viewpoint, it is worthwhile to compare the angular velocity at which displacement begins with the classical research one on the threshold for visual velocity. The work of Brown (1) indicated absolute thresholds in the range of 1.0 to 10.0 min of arc per second, whereas the more recent work by Rock (5) indicated an absolute threshold range of 0.2 to 0.5 min of arc per second with luminance carefully controlled. In the the present experiment, the range of angular velocity at the beginning of displacement was from 4 to 40 min of arc per second. It is obvious, therefore, that the driver is responding to the presence of an object near his path of travel at a point where its angular velocity is at his absolute threshold.

Within the framework of this model, it is possible to define the process of displacement. If the driver, traveling at a certain speed, increases his fixation distance along the roadway, two things occur. One, the angular velocity of elements in his field of view decreases rapidly. Eventually all elements become subthreshold, regardless of their lateral separation. Two, objects located at increasing distances from the path of travel are seen outside the near fovea. Beyond this 2° to 4°, sensitivity to velocity decreases rapidly. Thus, there is a visual operating field, essentially conical, determined by a physiological characteristic and a physical function which defines the limiting size of this field. This is shown in a slightly different fashion in Figure 9. As fixation distance increases on the abscissa, the lateral position of an object must increase rapidly to maintain a visual velocity threshold. With a visual field of 3°, it may be seen, that at 60 mph, at a distance of 300 ft, objects more than 16 ft from the driver's path are outside his visual field. Conversely, all objects less than 14 ft, although within the operating field have subthreshold angular velocity at this distance. Actually, it is only lateral locations within the hatched area that have a highly detectable angular velocity at 60 mph. Thus, as a driver approaches an object lying within his visual operating field at this speed, at a distance of about 300 ft, if there is no detectable component of angular velocity, the object will appear to be in his path, and he will begin to displace.

The process for detecting lateral position becomes a fairly direct one for the driver. He must adjust his point of fixation to that distance at which there is a sharp decrease in angular velocity for objects at the margins of this visual field. This point is available from a variety of cues in the driving environments such as pavement texture and shoulder contrast.

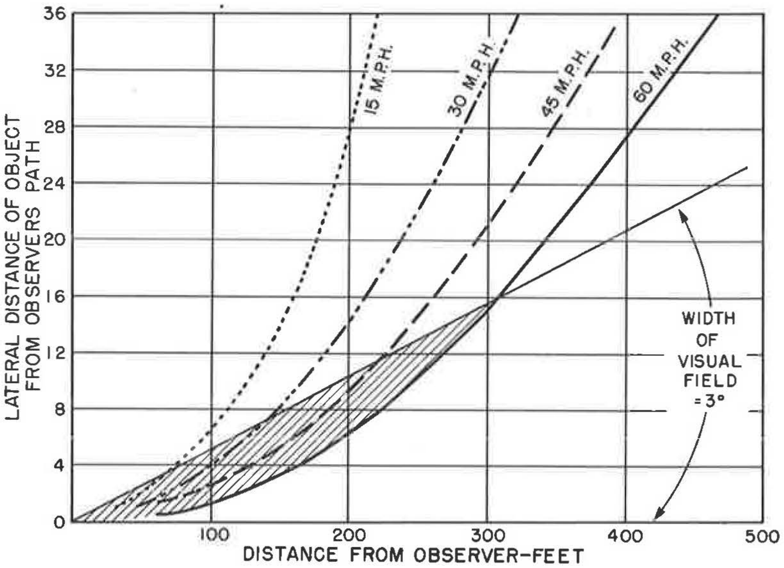

Figure 9. Visual velocity threshold contours at four speeds.

As obstructions first enter his field, the driver is able to make a simple binary judgment. If the obstruction has a detectable lateral movement it cannot be in his path, and no displacement is necessary. If it has no detectable lateral velocity, it is located in his path, and hence he begins to displace.

These considerations indicate that the driver is given a very small margin of time and distance within which to operate on objects located laterally along the path of travel. Assuming no restrictions in sight distance, he has only 3 to 4 sec in which to decide whether a displacement is necessary and how much is required. By operating at the absolute threshold of angular velocity, the driver not only has a stable reference for detection but also maximizes the time available for object location as well as the time for making compensatory steering responses.

It would seem reasonable to expect that those factors found from classical research to influence the perception of visual velocity would be applicable to lateral displacement. Thus, the object size may be expected to influence displacement because of the effect of stimulus size on visual velocity (1). This factor of size as it affects lateral displacement has been studied by Case et al. (2). They found that there was a significant effect on the displacement starting point and also the magnitude of the displacement as a function of the displacing object's size.

It may also be expected that the shape of the stimulus will influence the visual perception of velocity. The results of this study demonstrated that there was a significant reduction in displacement of approximately 15 percent when the apex of the triangle was oriented toward the driver's path of travel. Phenomenally, of course, these results imply that the apex-oriented object has a higher visual velocity than does the base-oriented one. The higher the velocity, the less will be displacement because displacement occurs in relationship to perceived velocity of the displacing object in this model.

The effect of shape has been studied by Motokowa (4) by means of electrical stimulation of the eye. His findings bear directly on the effects on lateral displacement found in this investigation relative to the triangular displacing object orientation. His work suggests that the physiological correlate of visual velocity is the amount of suppression of retinal response exerted on the retinal pathway through which the image of the moving object has passed.

This concept, called retrograde suppression, can account for most of the perceptual results in the study of visual velocity. Thus, Motokowa suggests that as a moving stimulus passes across the retina, a field is generated about that object which suppresses activity in the area removed from the immediate vicinity of the stimulus itself. Thus, as a stimulus moves across the retina, it generates retinal activity as it proceeds and acts to extinguish or neutralize the retinal activity in the path through which it has already passed. Hence, the lower the velocity, the more intense the stimulus; or the larger the object, the greater will be the degree of this retinal suppression—all leading to a perception of lower angular velocity. In essence, the strength of the suppressing stimulus is the correlate of the perception of velocity.

The intensity of the suppression is also related to the nature of the contours of the stimulus. Other experimentation by Motokowa (3) has shown that the strength of the field about an object is determined by the contours of that figure as well as its size and brightness. For a triangle, as used in the present displacement study, the field of activity is at a minimum at the intersection of the figure contours. Consequently, the strength of the field that acts as a suppressor on trace activity in the retina is at a minimum. The perceived velocity of the figure will be a maximum with that orientation. It is, then, in the basis of the differences in fields of suppression that the reduction in lateral displacement obtained in this study can be explained when the apex is oriented closest to the driver's path of travel.

Every attempt was made to obtain a maximum displacement in the design of this study. It was initially predicted that the magnitude of displacement in this study would exceed that obtained by Case et al. (2) or Taragin (6) because an effective 25-ft lane width was employed with no other obstacles in the driver's path. This prediction was not borne out in the study. Actually, the magnitudes of displacement were one-half to one-third less than reported in the field studies just mentioned. Two reasons may account for this unexpected result. One is in the nature of the displacing objects. In this study, the absolute size of the object was 15 sq ft, which is considerably smaller than the displacing objects used by Case et al., whose minimum and maximum sizes were 28 and 64 sq ft, respectively. In Taragin's study, two of the objects were considerably larger than the triangles used in this experiment. In terms of the model of displacement proposed in this paper, it would be expected that the apparent velocity of the displacing object will be greater for the smaller object and hence appear farther from the driver's path of travel.

A second condition concerns the factors influencing the driver's ability to judge his line of travel accurately. In this study, the reflective strip that was placed on the pavement to measure lateral position was clearly visible to the driver subject. All five drivers appeared to orient themselves relative to this marking so that it was nearly centered under the vehicle. In essence, the striping served as a direct reference by which the driver could define his path of travel. By having a stable reference at which the driver may fixate, the detection of movement of an object near his projected path should be improved. With no such reference for fixation, the driver's point of regard may be expected to vary laterally. This should reduce the accuracy of his estimation of the apparent velocity of the object and hence add ambiguity about the judgment of object location. It seems reasonable that such uncertainty would amplify a driver's response to the displacing situation, leading to a greater magnitude of displacement. If this explanation is valid, it should be possible to reduce the magnitude of lateral displacement in a field situation by providing the driver with a tracking reference line. A test of such a hypothesis is currently under way at the Bureau of Public Roads.

It is interesting, relative to the model, to examine the Interstate standard that requires all roadside objects to be a minimum of 6 ft from the travel lane. At this separation, the object will have a highly detectable angular velocity for distances up to 300 ft from a driver traveling 60 mph. This is consistent with the data in this study, as shown in Figure 10. What the Interstate standard for the location of shoulder objects actually does, then, is to insure that within the visual operating field of the driver all fixed objects shall generate a suprathreshold rate of angular change. It is obvious from the present study that this design standard is applicable and valid only for highways in which travel speed is approximately 60 mph. Where the highway speed limit is substantially lower, a closer positioning may be tolerated. The data in Figure 10 clearly show that the object may be within 2 ft of the edge of the lane at very low speeds.

It also becomes apparent why objects located close to the roadway may affect highway capacity. Given a situation in which there are two lanes of traffic of fairly high volume traveling at around 40 mph, what happens when an obstruction is placed on the shoulder, sufficiently close to the travel lane? In terms of the model proposed here, drivers are responding to objects at the maximum distance from the object which their speed permits. Because the amount of displacement is directly dependent on speed, a driver may reduce displacement by reducing his travel speed, which in addition, increases the time he has for locating the shoulder object. If, because of traffic opposing him, the driver must eliminate or minimize displacement, he will have to reduce his travel speed. In so doing, he minimizes both the probability of collision with a shoulder object and encroachment in the opposing traffic lane. One obvious consequence of this process is to limit the capacity of the lane.

A final aspect of this investigation relates to the more general problem of the visibility of stationary objects on or near the highway. This problem, especially acute at night, has received considerable attention in the safety field for many years. In general, it has been conceived primarily as a problem in object detection. From the results of the present study, it would seem reasonable that not only the detection of an object is important, but also the ability of the driver to locate that object relative to the path of travel. If the driver detects the object, it is also necessary to ascertain a collision or near-collision course. Obviously, the brightness of the object or its contrast with its surroundings, object size, and its shape are fundamental factors in this dynamic localizing process. For example, one would predict on the basis of the model that a small object located close to the roadway would generate a greater relative visual velocity than a larger one. Thus, a car parked on the shoulder in which the oncoming driver perceived only the reflection from an unlighted taillight would be far more likely to be placed outside his path of travel than would the whole vehicle illuminated by a street light. The same problem also arises when there is headlight glare from oncoming cars which effectively reduces the contrast of the roadside object. Thus, the problem of visibility of roadside objects involves more than simple detection of the object's presence. Any thorough analysis of this problem must include not only detection but also the accuracy of roadside object location as well as the driver's ability to locate himself in his path of travel.

SUMMARY

This study was an attempt to analyze certain of the underlying factors that cause the lateral displacement of a vehicle away from a roadside object. The investigation was conducted in daylight and under free field conditions. For several conditions of object location and vehicle speed, the lateral position of the vehicle was measured continuously over a 5,000-ft specially prepared test track.

The findings indicate that lateral displacement is a special case in the field of visual velocity perception. Relative to the observer, the displacing object effectively moves laterally across the retina with a definable angular velocity. Drivers react to this apparent velocity of the object by determining when and how much they should displace on the basis of the time and distance at which that velocity increases sharply.

The results were related to previous work carried out by other investigators interested in the lateral displacement phenomenon. They offer rationalization for the effects of lateral displacement on highway capacity and as an important consideration in collision avoidance under low illumination levels and headlight glare.

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Driving Behavior and Related Problems

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This research report is based on the concept that differences in driving patterns may be determined by accurate measurements integrated over a route of sufficient length to reveal differences in driving behavior.

The measuring device used in collecting data, records: (a) driver actions, (b) vehicle motions and (c) traffic and/or highway events. All readings are in digits, and the device may be mounted in a car within a short time.

It was found that different classes of drivers tend to exhibit different driving patterns. Based on this fact, the paper points out related fields in which the "drivometer" may be used. These include driver training, traffic-stream flow, evaluation of highway design from the standpoint of driving, and the measurement of the "drivability" of vehicles.

•TWO RELATED studies of driving behavior have been conducted at the University of Michigan Transportation Institute during the past three years.[1] One study, devoted mainly to determining the relationship between driving behavior and accident experience, has been sponsored by the National Institutes of Health (Project AC-53). The other study, which made an operations analysis of the driving task, has been sponsored by the Ford Motor Company Fund. Fletcher N. Platt, manager of Ford's traffic safety and highway improvement, served as a consultant.

The research has been based on the hypothesis that different classes of drivers such as the accident prone and the accident free, the beginning driver, and the experienced driver exhibit different driving patterns which may be measured and related to the driving environment.

It was also hypothesized that differences in driving profiles may be determined only by accurate measurements integrated over a route of appreciable length such as 10 to 15 miles. The skill of the driver, like that of the golfer, is shown by his score for the entire course.

PREVIOUS WORK

Research related to the present study includes that of Lauer, Suhr and Allgaier, who performed research to develop a criterion for driving performance (1). They state that the ordinary road test has been found to have a low reliability as a criterion of driving performance.

In their investigation, each subject was given a simulated driving test in the laboratory under controlled conditions. The second test consisted of driving an instrumented car over an 8-mi standard route. A tachograph record was obtained for each subject while the trip was being made. The tachograph record included: trip time, model speed, maximum speed, and number of fluctuations. The driving performance was rated by means of the Roger-Lauer scale, which was reported to have a reliability of

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Paper sponsored by Committee on Road-User Characteristics.

[1] A preliminary report on these studies "Driving Behavior and Traffic Accidents," Bruce D. Greenshields, was presented at the 1962 International Road Safety Congress, Salzburg, Austria, September 1962. The material herein reviews the previously published material and presents additional information.

the order of 0.90. They concluded that the better driver turns the wheel less, uses less gasoline, works the accelerator less, and is less severe on the brake than the poorer driver. The conclusions reached by Lauer, Suhr and Allgaier agree at least in part with the results of the present study.

Another study was made by Billion (2). The part of his study particularly significant to this project is that devoted to the observation and analysis of the behavior of drivers. A scale recording actions of the observed drivers was developed (2, Fig. 3). Drivers were followed and observed for 1 to 2 mi.

The present research is different in that the drivers were observed for a longer period and their actions were recorded mechanically.

In 1933, time-lapse pictures were used to measure vehicle speed and spacing. In 1954, the Yale Bureau of Highway Traffic measured traffic stream flow by means of a special recording speedometer that gave a continuous graphic chart of the varying speeds together with a time-and-distance record (3). From these data a "characterizing number" to describe the quality of traffic flow was derived, combining speed, change of speed, and number of changes of speed. It was evident that change of direction should be included, but, equipment then in use was inadequate.

Because it was possible to measure and characterize the flow of a traffic stream, it was deduced that it should be possible to measure and characterize the behavior of the individual driver. This deduction was supported by a study conducted by the University of Michigan Transportation Institute in 1957 (4) which found that there is a correlation between the way traffic moves and the frequency of traffic accidents in the stream, and that it is possible to pace a driver and closely imitate his driving profile.

The theories and findings of Platt (5) provided an important background for the present research. Platt developed a method of relating traffic situations to the major parameters that occur to a driver and his vehicle. He related in sequence highway and traffic events—driver observations, decisions, actions, errors—near collisions, injuries and fatalities.

These traffic situations were classified and defined in detail, and empirical formulas and equations were developed for estimating the number and kind of situations that might occur to a single driver under particular conditions. This development was followed by a discussion of operations analysis and the scientific method. Fundamental goals and research needs were discussed.

PRELIMINARY INVESTIGATION

The initial part of this investigation demonstrated that the measurement of traffic stream flow and the determination of driving patterns of the individual driver are distinctly different problems.

In the first part of the National Institutes of Health study, it was decided that it should be possible to select drivers at random, pace them over the selected section of roadway, obtain their accident experiences, and then compare their driving performances with accident experiences and determine the relation, if any, between accidents and driving behavior.

The driving-behavior patterns of more than 950 drivers were observed over the selected route of about 5½ mi in length. The behavior indices, based on speed change and direction change, ranged from 0.5 to 20.

Serious defects were found in that procedure, and it was abandoned. Too many drivers failed to remain on the selected route, even though it was chosen because of its few turnoffs. Also, it was found that there are apparently so few high-accident drivers in the average traffic stream, that thousands of observations would have to be taken to obtain a sufficiently large sample of "poor" drivers. Furthermore, the route did not have a large variety of highway and traffic conditions. It did have a high accident record. Trial runs over a more varied and partly urban route yielded driving indices varying from 0.5 to over 900. In addition, the "following car" method cannot be as exact as having the subject-driver in a car equipped with the "drivometer."

The selection of a new route with more and varying amounts of traffic meant that the recording apparatus should include means of recording the changing traffic conditions. It could no longer be assumed that all drivers observed would be traveling in essentially the same traffic environment.

DESCRIPTION AND USE OF EQUIPMENT

In 1960, the Ford sponsored study was initiated. This study was an opportunity to test Platt's theories. The measuring equipment which evolved from past experience, furnishes digital recordings integrated over any selected time or distance. The basic design for recording a series of like events consists of enumerating the events on an electric counter and then taking a picture of the accumulated count at desired intervals. Total counts for a trip may be read directly. For example, an electric counter in circuit with the brake-light switch will be actuated every time the brake is applied.

A photocell actuating a switch records speed change numerically, rather than graphically. A speedometer dial with alternate transparent and opaque divisions is arranged to pass between a light source and a photocell. As the dial moves in either direction with change in speed, the counter is actuated every time the light ray is interrupted. Thus, the count shows the total speed change.

This system (adding counters and actuators) may be extended to any number of events. The drivometer and traffic events recorder used in the investigation records driver actions, vehicle motions, and traffic and/or highway events.

The driver actions recorded include: (a) number of reversals of the steering wheel, (b) number of times the accelerator is depressed and (c) the number of times the brake is applied. The accumulated amount of steering wheel turning is also shown.

The recorded vehicle motions are change of speed and change of direction. Both are recorded by means of a gyrocompass with a photocell relay that records accumulated direction change.

Traffic events are recorded by a group of counters wired to a panel of switches on a small board held in the hand. The switches are coded for various traffic events. (They may be recoded and used to record highway events.)

Events are recorded by an observer sitting in the front seat and operating the keyboard by pushing the proper switches on and off as the traffic situations change. The switches are coded largely by their positions. A symbol near the center of the keyboard indicates the position of the test car. The F switch above this symbol represents a vehicle in front of the test car. When the observer sees a vehicle ahead, he pushes this switch on and leaves it there until the vehicle is no longer in front. When any switch is on the connected counter, operated through a timer, is recording time in seconds. If there are two cars ahead, another switch (C) is pushed on. Switches A to N are coded for other traffic situations, such as "car passing on right," and "parking on right."

The number of switches in the "on" position shows the observer's estimate of the number of events in the visual field at any instant.

A 16-mm recording camera is focused on the counters which are mounted on a dis-

Figure 1. Test car with drivometer mounted on rear seat.

play panel. The camera is set to take a picture every 1/10 mi, at a definite time interval such as 1 sec or 1 min, or if desired, by manually closing a switch. The panel includes a watch and counter to record time in seconds. Another counter, operating only when the car is moving, records the running time.

Figures 1 and 2 show the drivometer and traffic events recorder. In the present arrangement, the drivometer contains only the camera, timer and counters. The auxiliary speedometer is mounted under the cowl and the gyrocompass under the hood.

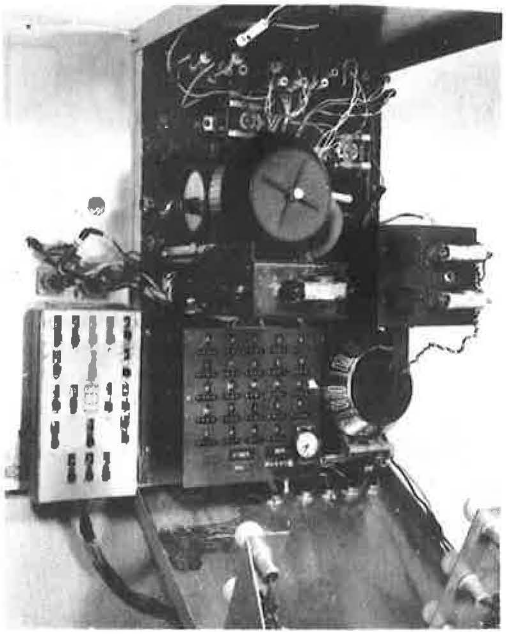

Figure 2. Drivometer with cover removed; recording camera (not shown) attaches to cover.

PHOTOGRAPHIC METHOD OF RECORDING EVENTS

The use of a camera to record events was indicated by experience with time-lapse pictures that furnish a record which may be examined in detail and at leisure. But transcribing data from the pictures is time-consuming, and for this reason, the observer-keyboard method was devised. It remained to be demonstrated, however, that the keyboard method would give as complete and accurate results.

The camera is mounted back of the rear seat to give both front and back views by means of a mirror mounted on the back of the front seat (Figs. 3 and 4).

If the pictures are taken at sufficiently short intervals of time, a continuous average space or perceptual density (number) of events is obtained, regardless of the speed at which the vehicle is moving. Statistical sampling methods have been used to determine the proper interval between pictures. A 2-sec interval has been found to be a short enough time.

The results obtained from scanning the pictures, and those obtained by the events tabulator have been found to be practically equal. In 18 test runs involving the scanning of over 15,000 pictures, the average densities obtained from pictures differed from the densities obtained by the observer tabulation by 0.004. Table 1 compares the camera and observer results.

Using the t-test ($t = 0.177$) and the F-test ($F = 0.16$) it was found that there are no grounds to reject the hypothesis that the observer method is as good as the picture method. Because transcribing the data from pictures is very time consuming, the observer-recorder method is deemed the better. The digital recording of motions or events makes the data immediately ready for statistical analysis; it would be possible to feed the data directly into an electronic computer.

A camera may be used for cataloging fixed highway events such as signs, intersections, and curbs. The camera is mounted to take pictures through the windshield at 0.01-mi intervals. Figure 5 shows a sequence of four such pictures. They are on 35-mm film with approximately 1,600 frames per 100-ft roll.

CLASSIFICATION OF HIGHWAY EVENTS

In the tabulation of the traffic and highway events, it was recognized that it would be impossible to record everything that the driver sees. Several schemes of classification or selection of events were considered.

All events may be divided into two classes: those related to the driving task, and those unrelated. An unrelated event is defined as one that has no potential for requiring

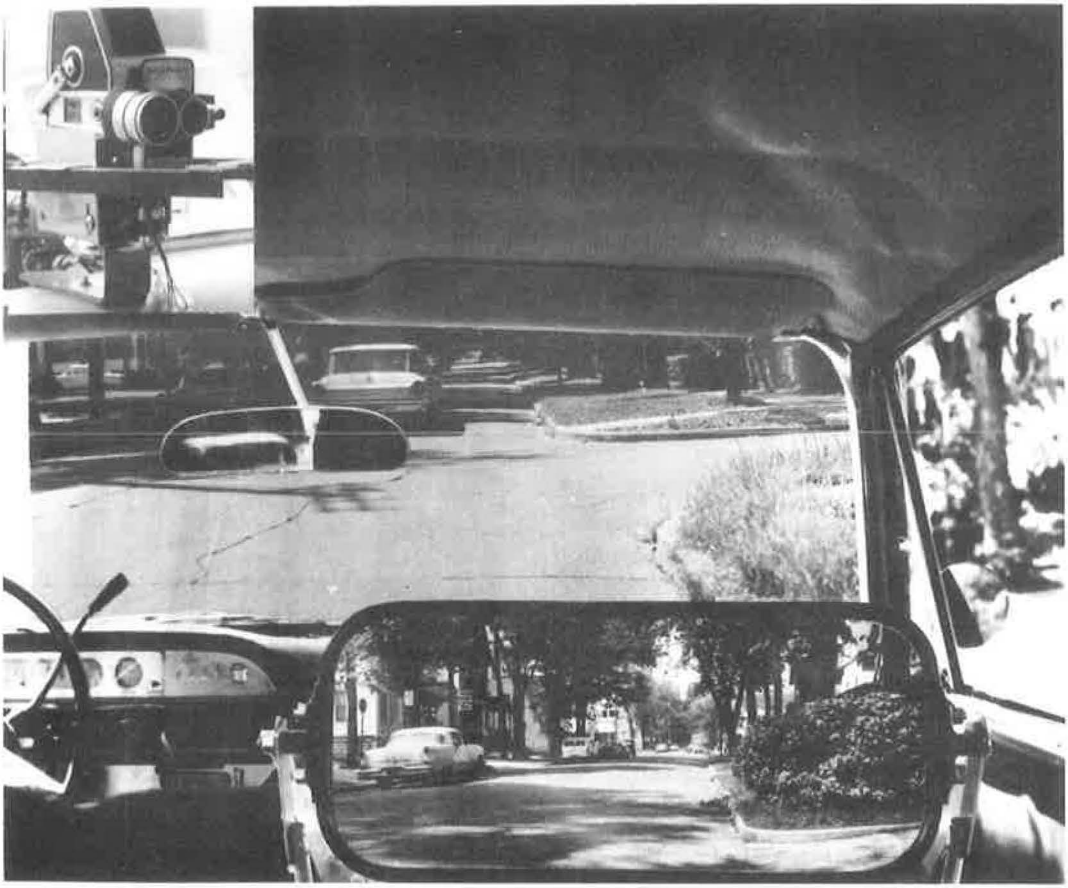

Figure 3. Front and rear view of street; insert shows camera mounting.

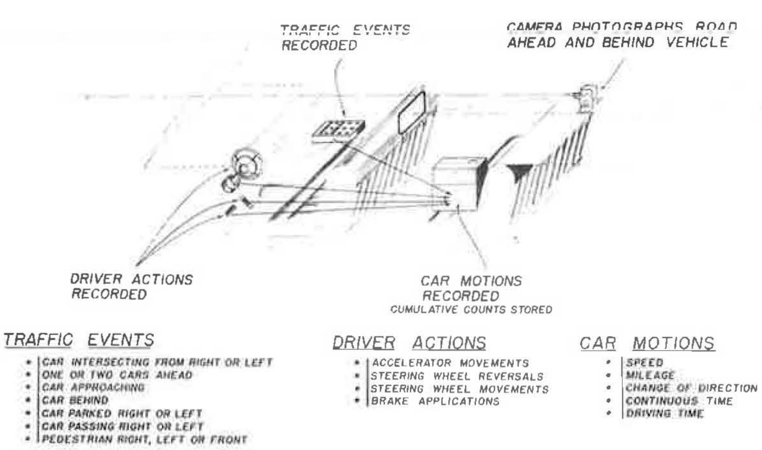

Figure 4. Arrangement of drivometer and traffic events recorder and front and rear view camera.

TABLE 1

PICTURE AND OBSERVER RESULTS[1]

Recording	Avg. No. of Events	Standard Deviation
Camera	$X_c = 0.203$	$\sigma_c = \pm 0.240$
Observer	$X_o = 0.199$	$\sigma_o = \pm 0.213$

[1] Difference of means: $X_c - X_o = 0.004$.

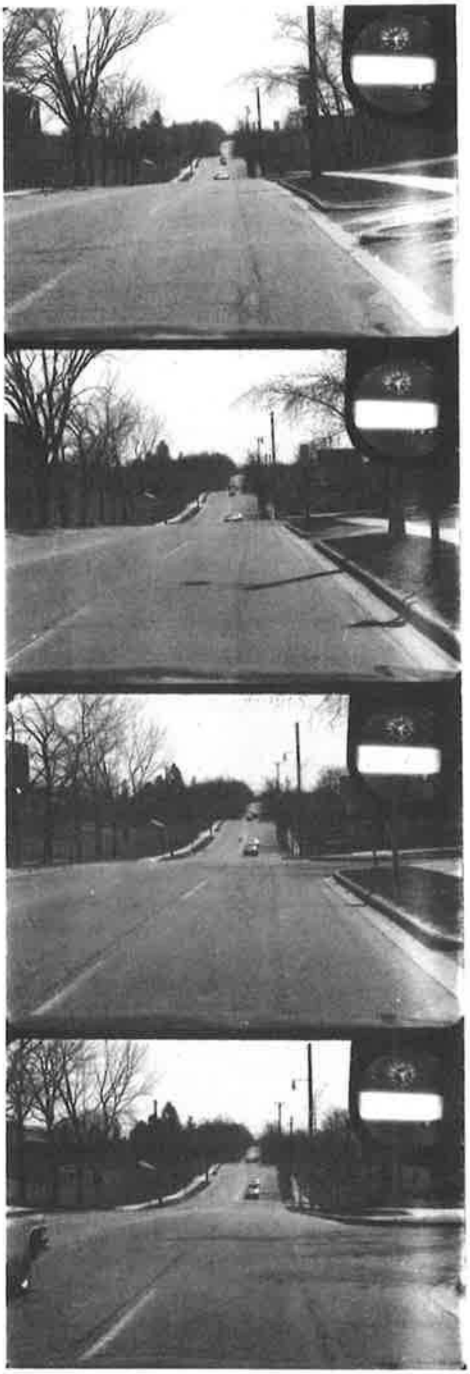

Figure 5. Sequence of pictures for tabulating highway events.

the driver to change the motions of his car. An airplane in the sky may distract the driver, but there is no possibility that he will swerve to avoid it. A moving vehicle or an obstacle close to the roadway can cause the driver to change the speed or direction of his car.

No attempt was made to classify events as hazardous or non-hazardous. An event not directly related to the driving task may distract the driver and cause an accident. Sometimes, the lack of events can be dangerous by blunting the driver's alertness through monotony.

All traffic and highway events, whether related or unrelated to the driving task, fall into two general classifications: fixed and variable. The fixed events include all stationary features such as curbs, signs, stop lights, trees and buildings. The variable events include all vehicles and pedestrians whether moving, standing, or parked. A parked car may suddenly become a moving car. All events, both fixed and variable, are dynamic with respect to a driver in a moving vehicle. In the one case, the relative velocity depends on the speed of both vehicles; in the other case, the relative velocity is only that of the driver's vehicle.

In the enumeration of events, it is reasoned that the driver pays more attention to objects near him than those farther away. A vehicle directly in front is noted along with a second; but more than that may simply be observed as a string of vehicles. One or several cars parked on the right or left side of the street are perceived simply as parked cars. Perhaps one or several pedestrians in the same area have the same observed effect.

It is thought that the overall effect of like environmental areas (such as residential or shopping) is somewhat the same. The main difference would be in such things as number of intersections, driveways, traffic islands and highway signs.

It is deemed impossible to obtain an absolute measure of the density of events. All that can be obtained is a relative measure of density--perhaps, that is all that is necessary.

RELATING EVENTS TO TIME

In determining the significance of the density of events, they must be related to time, for the driver's ability to respond to events is limited by this factor.

The amount of time a driver has to respond to changing traffic and highway situations clearly depends on the space density of events and the speed at which he is traveling. The greater the density and the higher the speed, the less time the driver has to respond. That this fact is universally recognized is evidenced by speed laws which require the driver to reduce his speed in urban areas.

An events density index expressing this relationship could equal the product of speed and the density of events. The principal objection to this index is that it does not take into account the changing extent of the perceptual field.

A measurement of the extent of this field is that of the distance from the driver to the point on which he focuses his attention as his speed increases. One reference (6) states that the average distance of the focal point increases in a straight-line relationship with the speed, being about 500 ft at 20 mph and 1, 800 ft at 60 mph. In time, these distances amount to about 17 sec and 20 sec.

A simple method of estimating the focal depth or length of perceptual field while riding is to note the point ahead on which the eyes are focused and then measure the distance to that point by reading the odometer. An odometer reading to 0.01 mi is needed. An observer reads the odometer and speedometer and records them. Several trips over a route should give a close estimate of the average depth of focus. A trial series of runs gave results similar to those obtained by Hamilton and Thurstone: 510 ft at 20 mph and 1, 600 ft at 60 mph.

From these results and the experience of driving on congested city streets, it may be judged that the time-distance at which events begin to influence the driver may vary from 20 sec or more on the open highway to as little as 2 or 3 sec on a busy street.

TRAFFIC DENSITY INDEX

Having determined the extent of the perceptual field, the density index may be expressed as

$$E = \frac{N \times S}{L} \tag{1}$$

in which

E = events index;
N = perceptual density or number of events in visual field;
S = speed; and
L = length of perceptual field.

The dimensions in this equation show that the index is equal to the number of events per unit time.

Because the speed S = L/T, Eq. 1 becomes

$$E = \frac{N}{L} \times \frac{L}{T} = \frac{N}{T} \tag{2}$$

This shows simply that the amount of time that a driver has to respond to events increases with travel time and decreases with number of events, and that the events index may be expressed as E = N/T, wherein T is equal to the running time. It is assumed that the driver is making no positive response to his environment when the vehicle is not moving. The depth of perceptual field which varies directly with speed has disappeared from the equation.

In comparing the driving behavior of different drivers over the same route only, the traffic events have to be taken into account for the highway events remain constant.

The density of events was not used in the analysis, but to obtain information about the effect of traffic conditions on driver actions a small group of drivers drove the test route under different traffic densities. Figure 6 shows one of the relationships between events and driver actions. For this relationship

$$X = 6.34 + 1.26\,(TC) \tag{3}$$

in which

X = average number of steering wheel reversals per minute; and
TC = average number of traffic events in perceptual field at any instant.

For example, at an average traffic density of 3 events the average number of steering wheel reversals per minute is equal to 10.1 (Fig. 6). The number of steering wheel reversals should be adjusted if traffic conditions vary appreciably. Thus, a driver experiencing a traffic density of 3.0, in comparison with a driver experiencing a count of 1.0, would be expected to make 2.5 (10.1 - 7.6) or more reversals per min due to traffic conditions.

SELECTION OF TEST ROUTE AND DRIVERS

The test route was to have a fairly wide range of traffic and roadway conditions. It was also to be of sufficient length to reveal differences in driving behavior. The driver is not to be judged by the individual mistakes he made, but by his overall score or driving pattern.

The 15-mi route selected for the project consisted of approximately 4.9 mi of downtown streets, 4.0 mi of residential, 2.9 mi of 4-lane divided expressway and 3.2 mi of 2-lane rural road (Figs. 7, 8, 9 and 10).

The data were recorded so that the behavior patterns on different sections of the route could be analyzed separately.

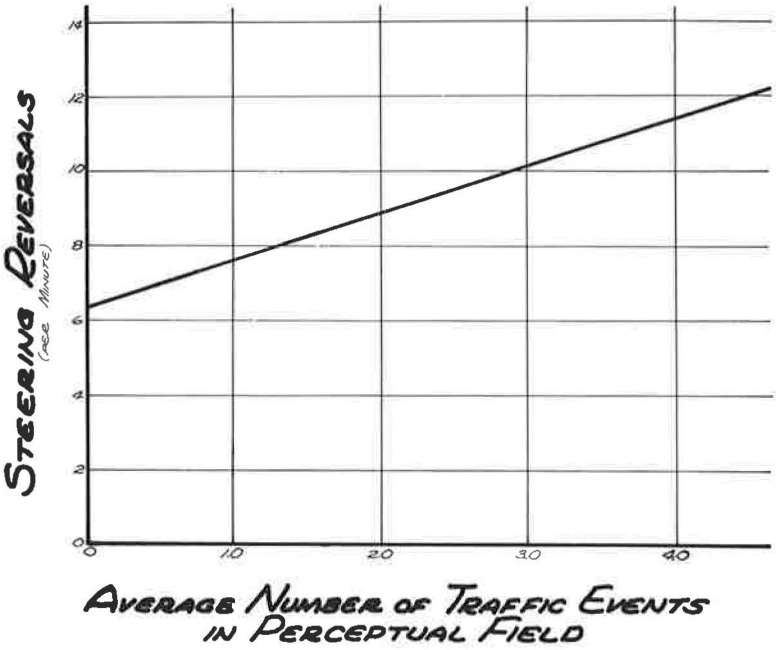

Figure 6. Relationship of steering wheel reversals to traffic events.

Figure 7. Downtown.

Figure 8. Residential.

Figure 9. Expressway.

Figure 10. Rural.

Selection of Test Drivers

The selection of test drivers proved a more difficult task than the selection of the test route. Because a major purpose of the project was to compare the driving behavior of the safe with the unsafe driver, a main task was to find drivers in these two categories.

The unsafe driver, it seemed, would be among those with a high number of traffic violations. With the cooperation of the Michigan Secretary of State's office, drivers on the point of having their licenses revoked because of too many violations were tested. But the accident records of these high violators were discovered to be no higher than the average driver. Some had experienced no accidents. Of course there was interest in the high violators for they are among the problem drivers, and hence they were included in the study.

It also appeared that the high-accident driver would be among those on the point of having their insurance policies canceled. Insurance companies, of course, do not make these names public, but with assurance that the names would not be revealed in any way, they willingly cooperated.

Inasmuch as the overall objective of the studies was to determine whether drivers in several categories have characteristic driving patterns, other groups, such as beginning drivers, were selected for study. They were obtained through driver education teachers.

Collection of Data

In collecting data the usual experimental precautions were taken. For example, the drivers in each group were selected in random order and not informed as to why they were selected beyond telling them the purpose of the investigation was to study drivers of various driving experiences and ages, and that there was no interest in their driving experiences except as data for the experiment.

At the beginning of the test each driver filled out a questionnaire giving miles driven, age, type of car driven, accident experiences and other information. The accident experiences reported were checked against State and insurance records.

All driver tests were made in good weather under practically equal traffic conditions. The same vehicle, an automatic shift 1960 Ford, was used throughout the tests. The sensitivity of the measurements was kept constant even though it became apparent during the study that greater sensitivity would be more meaningful.

ANALYSIS OF DATA

The data were first transferred to IBM cards. Many of the 53 variables recorded have not been used in the analysis because they are believed to be unnecessary for the main purpose of the research. Such items included kind of car normally driven, observers evaluation of driver, number of accidents experienced during past year, and answers to questions such as "Did the equipment disturb you?" and "Were you nervous?".

Another variable that has not been taken into account is the effect of the density of traffic events. As mentioned, the tests were made under essentially the same traffic conditions.

The first data to be analyzed were those taken in connection with the Ford Fund project to obtain some indication of the reliability of the measuring equipment. The data proved to be more meager than anticipated. This was due mostly to failures of the recording device. It is still not known how to completely eliminate the equipment failures, although the equipment has been improved.

The analyses of the data (Tables 2 and 3) gave encouraging results; the analysis of additional data is shown in Table 4.

Table 2 gives a comparison of the driving behavior of driver trainers and high-accident drivers. The speed change as read from the dial is equal approximately to one-fourth of the actual change. Thus the reading of 635, represents actual speed change of 2,540.0 mph.

Based on averages, the high-accident groups have higher counts than the driver trainers on all eight variables. In general, the driver trainers travel slightly faster and make fewer motions than the high-accident group. The driver trainers seem to be more efficient.

The t values and corresponding P values, however, show that singly with the exception of accelerator actions, the variables for the two groups are not significantly different.

Table 3 gives six categories of drivers: (1) high school drivers who have completed a driver training course (HS); (2) driver education teachers (DT); (3) professional drivers such as truck drivers, highway patrolmen, and taxi drivers (PD); (4) high-violation drivers (HV); (5) high-accident drivers (HA); and (6) average drivers (AD). The samples are small and only indicate trends, without statistical verification. Apparently, the two most similar groups in behavior are the high school or beginning drivers and the high-accident drivers.

TABLE 2

COMPARISON OF DRIVER TRAINERS WITH HIGH-ACCIDENT DRIVERS

Classification	Driver Trainers	High-Accident Drivers	t Values	P Values
Number of tests	17	14		
Test run mileage	12.4	12.4		
Total time (min)	24.1	28.1	0.984	0.40 - 0.30
Running time (min)	20.6	24.1	1.27	0.30 - 0.20
Stopped time (min)	3.5	4.0	0.26	0.90 - 0.80
Accelerator actions	138.0	262.0	2.46	0.02 - 0.01
Steering reversals	200.0	384.0	1.53	0.20 - 0.10
Brake applications	39.0	61.0	1.28	0.30 - 0.20
Speed change (mph)	635.0	1,010.0	1.01	0.40 - 0.30
Direction change (dial readings, 0.1 rad.)	171.0	213.0	1.30	0.30 - 0.20

TABLE 3

DRIVER BEHAVIOR PATTERNS

Classification	HS	DT	PD	HV	HA	AD	Avg.
No. of tests	6	17	23	9	14	53	-
Length of run	12.36	12.36	12.36	12.36	12.36	12.36	12.36
Total time	26.30	24.10	26.50	25.00	28.10	25.70	25.50
Running time	23.60	20.60	22.10	23.10	24.10	21.20	21.50
Stopped time	2.70	3.50	4.40	3.50	4.00	4.50	4.00
Acc. actions	240	138	178	132	262	158	160
Steering reversals	322	200	226	250	384	242	248
Brake applications	51	39	39	36	61	38	41
Speed change (mph)	837	635	815	785	1,010	759	762
Dir. change (rad.)	171	217	222	244	213	234	217
Tot. driv. act.	613	377	443	418	707	438	449

TABLE 4

HIGH ACCIDENT VS CONTROL GROUP[1]

Classification	HA	CG	DFC
Number of tests	50	31	10^{-5}
Running time (sec)	1,670	1,540	1.720
Stopped time (sec)	226	229	0.446
Accelerator reversals	118	88	17.473
Steering reversals	134	117	3.221
Speed change (mph)	724	926	3.174
Direction change	394	351	3.663
Brake applications	51	37	36.141
Turning of steering wheel	824	675	2.944
Mean rating	+ 0.0878	+ 0.0634	
Variance	+ 0.00036	+ 0.00022	
Standard deviation	± 0.0190	± 0.0148	

[1] F = 4.20.

The high-violation drivers in general are very similar to average drivers, but they are more agressive as indicated by their comparatively small amount of stopped time, especially in unknown areas. In total actions they are more efficient than either the high school or the high accident groups.

The sensitivity of the measures in detecting the effect of distractions or other influences on driving are, in order: (a) the steering wheel reversals, (b) the speed change, and (c) the accelerator actions. The most sensitive measure has been found to be the steering wheel actions, provided the measurements are precise. For best results, all turnings of about $^{3}/_{8}$ in. or larger (measured at rim of steering wheel) should be counted. In contrast, the sensitivity of the recordings given in Table 3 are of about $1\frac{1}{2}$ in. or larger.

As has been indicated, judged by the differences in the means of the sample population characteristics, drivers generally regarded as good are not significantly different in behavior from those regarded as inferior. However, the question of whether the differences in the means of the separate parameters is significant or not is not really vital to the goal sought. The decisive question is whether some function of a set of characteristics can be found that will discriminate between drivers of different classes.

Multivariate Analysis

The task of extending tests of significance from single population characteristics (such as accelerator actions) to sets of population characteristics is generally referred to as multivariate analysis. The particular multivariate analysis method employed, discriminatory analysis, was suggested by Leo Razgunas, and confirmed as a correct one by Frank Westervelt.

To indicate the purpose of the method, Bennett and Franklin (7) have written:

> The problem which we shall consider is: Suppose that we have n_1 individuals known to be from one population and n_2 individuals known to be from another population. For each of the n_1 and n_2 individuals we observe a number of characteristics $x_1, x_2, \ldots x_k$. Then what linear combination of these k characteristics ($X = a_1 x_1 + a_2 x_2 + \ldots + a_k x_k$) will be best in assigning an unknown individual to one of the two populations; i.e., what single derived value X will in some sense best reflect the difference between the two populations? We shall assume that for each population the k characteristics have a multivariate normal distribution, with different means, but common variances and co-variances. X is commonly called a discriminant function.

Using the discriminant analysis method (Computer Program Bimed. No. 005 UCLA), Table 4 compares 50 high-accident drivers (HA) with 31 good drivers or control groups (CG). The good drivers were driver trainers and professional drivers with good accident records. The last column shows the discriminant function coefficients (DFC).

The mean rating for the 50 HA drivers obtained by multiplying the variable for each individual driver by the corresponding DFC values is equal to + 0.0878; that for the CG drivers is equal to + 0.0634. From the F value of 4.2, the two samples are different at a significance level of less than 0.5 percent.

If the X values are arranged in order of rank, the range is from 0.1426 to 0.0360. Forty-one of the HA group fall within a range of 0.1426 to 0.0719, while 25 of the good-driver group fall within the range 0.0716 to 0.0360. Thus, of the 50 expected to fall within the range of 0.1426 to 0.0719, 9 fall without and of the 31 that should fall within the range 0.0716 to 0.0360, 6 fall without. A general comparison of these two groups of drivers as to age, sex, driving experience, and accident experience, is given in Table 5.

The discriminate function gives the best possible separation between the two groups that can be achieved ignoring sampling errors that may exist. If two additional independent groups are taken, this discriminate function cannot be expected to separate them as well.

TABLE 5

GENERAL COMPARISON OF TWO GROUPS OF DRIVERS

Group	Age		% Male	Driving Exper. (yr)	Mi. Driven Last Year	Total Accidents	Last 5 Years
	Avg.	Range					
Low accident	29.2	20-58	74	12.4	17,700	1.04	0.46
High accident	35.8	16-79	76	18.5	15,200	4.2	2.6

TABLE 6

ADDITIONAL GROUP OF DRIVERS

Group	Age		% Male	Driving Exper. (yr)	Mi. Driven Last Year	Total Accidents	Last 5 Years
	Avg.	Range					
High accident	42.6	23-76	81	18.2	13,750	3.25	2.19

As a partial check on the validity of the discriminant function in detecting the high-accident driver, it was applied to 17 new subjects listed in the high-accident category. It should be noted that there is no accurate way of preselecting drivers as being "accident prone" or not, due to the high incidence of chance. Drivers can be "lucky" or "unlucky." The general characteristics of this group of drivers are given in Table 6.

The X values ranged from 0.12072 to 0.04564. Of the 17 drivers, four fell into the low-accident group. The fact that 14 of the 17 drivers tested fell into the preselected grouping gives some indication of the reliability obtained. But it must be kept in mind that the groups tested were small and the preselections could have been inaccurate. All that is indicated at present is that it should be possible to develop a more reliable road test than is now available. Many more tests must be made before the true reliability of the test will be known.

A comparison of beginning drivers (or high school drivers) and control group drivers is given in Table 7. A statistical comparison of the two groups shows that of the 46 individuals that should fall in the first group, as arranged in rank according to X values, four fall into the control group. Of the 31 that should fall in group two, 7 fall into group one.

Table 8 gives a general comparison of these two groups. Using an independent group of 15 drivers to test the ability of the test to differentiate between beginning drivers and the control group, the X ratings for the HS group range from 0.17054 to 0.32749 and that 7 of the 15 fall into the control group, instead of in the HS group where they should fall.

At present, due to the small size of the sample, it is not known whether the actual discriminatory value of the test is greater or less than just indicated. It is largely for this reason that further research on the testing of drivers with the aid of the drivometer is being undertaken. More rigid controls will be exercised in conducting the new tests.

The fact that there is evidence that drivers in different categories of driving experience have different driving patterns, indicates that the potential uses of the equipment and technique evolved are broader than those covered in this present study.

TABLE 7

HIGH SCHOOL VS CONTROL GROUP[1]

Classification	HS	CG	DFC
Number of tests	46	31	10^{-5}
Running time (sec)	1,726	1,540	10.974
Stopped time (sec)	254	227	5.804
Accelerator reversals	98	88	9.274
Steering reversals	180	117	23.735
Speed change (mph)	952	926	0.899
Direction change	333	351	14.586
Brake applications	52	37	156.339
Turning of steering wheel	872	675	54.834
Mean rating	+0.2807	+0.2106	
Variance	+0.00118	+0.00056	
Standard deviation	± 0.03437	± 0.02373	

[1] F = 11.03; level of significance less than 0.5%.

TABLE 8

GENERAL COMPARISON OF HIGH SCHOOL AND CONTROL GROUPS OF DRIVERS

Group	Age		% Male	Driving Exper. (yr)	Mi. Driven Last Year	Total Accidents	Last 5 Years
	Avg.	Range					
Low accident	29.2	20-58	74	12.4 yr.	17,700	1.04	0.46
High school	16.1	15-18	42	3½ mo.			

POTENTIAL USE OF EQUIPMENT AND TECHNIQUES

Finding that the driving habits of beginning drivers differ from those of more experienced drivers suggests the use of the behavior-measuring equipment in driver training.

In driver training, it is judged that recording traffic events will not be necessary provided the test runs are made under similar traffic and weather conditions.

With this in mind, a driver training unit that is much simpler than the complete drivometer has been constructed. The present model furnishes a visual digital recording of (1) change of speed, (2) number of reversals of the steering wheel, (3) number of times accelerator is depressed, (4) number of brake applications, (5) total time for run, and (6) running time. The readings are shown on ten counters. The recording box with ten counters fits into the glove compartment (Fig. 11).

In addition to the total counts for the trip, the number of steering wheel reversals and the amount of speed change at 1-min or ½-min intervals are shown. This minute-by-minute integration indicates the smoothness of the driving performance.

Albert Gallup, Supervisor of Driver Education in the Ann Arbor High School, had an opportunity to use the drivometer for a short time last summer in making some field studies on driving students and teachers.

Gallup gives part of his findings in the following words:

> From the teacher's point of view the device demonstrated its value by providing a tool to support subjective judgments; by giving immediate evidence of a student's relative progress; by showing when a student had been put in a situation that he could not handle; by indicating when the student reached a point of stress where he was not accepting instruction normally.

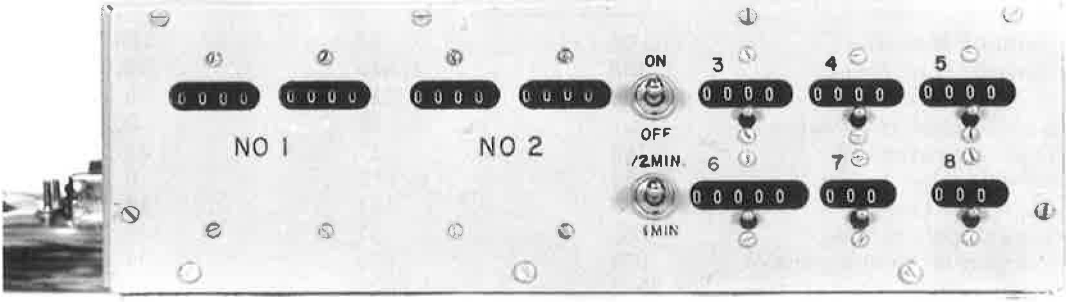

Figure 11. Driver training unit.

> The Drivometer was available for my exclusive use for only a limited period. There is much more to be learned about the device as a teaching aid. But I no longer have doubts now about the potential value of this device as a teaching aid. I have gone back to teaching in my regular dual control car, without the instrument installed, and I keep catching myself wishing that my electronic friend was back to help the student and me to do a better job.

A Driving Simulator

The fact that the drivometer furnishes an integrated measure of driving performance over a course of any desired length suggests a new approach to the driving simulation problem. The problem of driving simulation is simplified if limited to the task of simulating driver actions rather than reproducing driving environment. The simulation of driver environment to the point of seeming reality is very difficult and costly.

Construction of a device which would cause the driver to go through the same sequence of driving operations he would cover in driving over a highway should be much less difficult than simulating the highway environment. The idea of simple driving simulators goes back over thirty years. Several such devices have been developed and are in use.

One may ask why it is necessary to develop a new one if simplified simulators are already available. The answer lies in the manner in which the driving simulator is to be used. It would be used to furnish a sequence of stimuli to obtain a desired driving profile rather than single responses.

Suppose one wishes to make a laboratory check of the driving performance of a beginning driver against the performance of a skilled driver. First, the driving pattern of the skilled driver would be measured and recorded over a selected section of highway. The next step would be to obtain the same patterns in the laboratory by varying the stimuli until the field pattern was obtained.

Responding to the same stimuli, the beginning driver's record would be compared with that of the skilled driver. The drivometer furnishes an integrated record in numbers; the driving simulator would obviously be designed to furnish a similar record. Using this procedure, a file of driver training stimuli and response records could be built up.

The discovery that is is not necessary to have absolute duplication of highway events in studying the differences in individual driving patterns and that even minor physical or emotional disturbances cause measurable variations in driver actions, leads to the conclusion that most, if not all, driving behavior tests may be performed as well on the road as in a simulator. For safety in conducting such tests as the effect of fatigue or alcohol, a dual control vehicle should be used, and the observer should be alert.

The sensitivity of the steering wheel movements is shown in Figure 12 by means of the variation in the number of reversals of the steering wheel per 50-sec interval in a drive from Dearborn to Ann Arbor.

During the past year, experiments have been made with a safety warning device actuated by movements of the steering wheel. Having determined the driver's norm of movements per unit of time, a dial is set for both a high and a low level of actions. Whenever the actions reach a critical level, a buzzer warns the driver.

Evaluating Traffic Stream Flow

The sum of the skills of the drivers in a traffic stream largely determines the safety and efficiency of the stream flow. The other major factor affecting stream flow is the highway environment. Despite high speeds, the limited-access expressway is about three times safer per mile of travel than the average road.

The quality of traffic transmission is a fundamental factor in transportation (3). A successful method of evaluating traffic stream flow should make it possible to detect flows that are potentially dangerous.

Limited experience in measuring the quality of stream flow by an instrumented vehicle moving with the stream indicates that it is far easier to measure the significant differences between two streams of traffic than between the performances of two drivers. Further experiments in measuring and evaluating traffic stream flow are now being conducted.

Effect of Highway Design and Control Devices on Traffic Flow

Along with a study of the way traffic flows, there should be a study of the highway features and traffic-control devices that cause a traffic stream to flow smoothly and safely, or erratically and dangerously. In other words, both cause and effect should be studied.

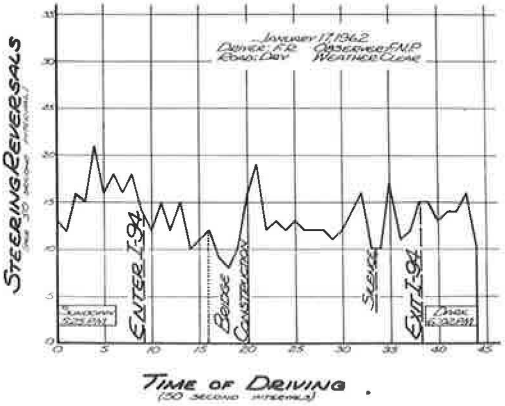

Figure 12. Steering reversals vs time.

The highway features that determine "drivability" are appearance, geometry, and surface condition. A highway characteristics recorder has been designed to operate in a station wagon driven at 35-45 mph. Using 35-mm film, it will record the surface condition, the geometry of the road, and provide pictures of the roadway at 50-ft intervals.

From experiments to date, it is apparent that more can be learned about the interrelationships of the quality of traffic stream flow, the characteristics of the highway, and the frequency of traffic accidents. When knowledge is increased, safer and more efficient highways can be built.

Vehicle Design and Driving Performance

Along with better highways, perhaps it is possible to build safer vehicles. It is logical to suspect that the types of driving controls, such as standard and power, along with other features of the vehicle have a lot to do with driving behavior. Does the stick control enable the skilled driver to give a better, safer performance? Is ease of handling important? The drivometer should make it possible to test the drivability of the vehicle as well as the skill of the driver.

SIGNIFICANCE OF RESULTS

The methods and techniques described are being improved through further research. It is believed they could have broad significance in improving the safety and efficiency of highway transportation. They should lead to a better understanding of the driving task and its relation to the traffic and highway environments, furnish information on the effect of different kinds of vehicles and vehicle equipment on driver actions and safety of operation, and provide new driver training aids and equipment.

Further tests of the driver's behavior under normal and some abnormal conditions should provide information that could be useful in developing mathematical models of the driving task, and methods for evaluating drivers, vehicles, and highways.

ACKNOWLEDGMENTS

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Discussion

PAUL L. OLSON, General Motors Research Laboratories--These comments relate to a procedure employed in Dr. Greenshields' paper and are common to research efforts in which an attempt is made to separate "good" and "poor" drivers.

Table 5 is a comparison between the low- and high-accident groups used in the test. High-accident drivers were defined, apparently, as individuals who were on the verge of having their insurance canceled. A low-accident driver is defined as one who has about one accident in 12 years. Since the bulk of the accidents of the high-accident group occurs in the last five years it is apparent that, at 12 years' driving experience, many of the members of the high-accident group would not have been so classified. Or, to look at it another way, had the study been conducted five years earlier, a good many of the members of the high-accident group would not have been so classified.

Why has the recent driving experience of the high-accident group been relatively poor? The assumption which seems inherent in this study is that, for many of the group at least, after performing acceptably for a number of years, they rather suddenly became poorer accident risks. It is not impossible, if unlikely, that the driving skill of many of the members of this group did deteriorate significantly in the last five years. Some other reasons are suggested, for instance: Do these people drive more miles than formerly? Are they exposed to more congested traffic? Has the traffic situation over their usual routes changed in some significant way? These are certainly possibilities; it could be that they were just unlucky. It is known that truly random, low-probability events have a way of distributing themselves so that some few individuals end up with far more than "their share." It has been demonstrated that drivers who have many accidents in one period will probably not have many in subsequent periods. If corrections are made for such factors as exposure, the number of true repeaters drops still further. It is questionable procedure to take drivers who are on the tail of a Poisson distribution at time t_1 and call them high-accident drivers when there is a low probability of their being so classified at time t_2 or any other time. The point under discussion, of course, is criterion reliability.

Based on the data in Table 5, there is good reason to believe that the criterion on the basis of which the high-accident group was selected was not reliable. In all probability this simply reduced the sensitivity of the statistical tests. On the other hand, one might consider the intriguing possibility that the investigator was really measuring differences between drivers characteristically exposed to different driving conditions. He might even have been measuring the effect of several recent accidents. However, any rigorous investigation in which an attempt is made to dichotomize good and poor drivers must demonstrate that the criterion on the basis of which the split was made had sufficient reliability so that the reader can be reasonably sure that the investigator is dealing with some sort of individual accident potential.

In all fairness, this point is not of critical importance to the inferences drawn in Dr. Greenshields' paper. What is important, is the damage caused by reinforcing the notion that there is a group of accident-prone drivers who can be readily identified on a basis of a quick look at accident records or some other performance index.

Those, who peruse the literature dealing with traffic and traffic safety encounter many investigations which seek to develop instruments to predict or select poor accident risks. Almost universally the researchers in this area pay little or no attention to the problem of criterion reliability. It inclines one to think that this is the mandatory starting point for research of this type. Admittedly, it is not very glamorous, and one is faced with the distressing possibility that there may not be a significant group of accident repeaters, but it would be refreshing to see someone start researching this problem at its beginning—not at a point where it is necessary to make some rather dubious assumptions.

BRUCE D. GREENSHIELDS, Closure—Mr. Olson's comments are much to the point. He stresses what is, perhaps, the most difficult problem in the study of driving behavior: Who is the good driver? Who is the poor driver? Is the good driver always "good"? The author doubts that he is.

The point raised by Mr. Olson is at least partly recognized in the report, which says: "It should be noted that there is no accurate way of preselecting drivers as being 'accident prone' or not, due to the high incidence of chance. Drivers can be 'lucky' or 'unlucky'." As indicated (by quotes) it is doubted that 'accident prone' is the correct term to use. All that is known is that one group of drivers experienced more accidents than the other.

How to solve the problem of classifying drivers without a much more extensive and longer-range investigation than the present one, is unknown. When a method is found to score a driver, perhaps his faults can be corrected.

A New Method of Measuring the Effects of Continued Driving Performance

FLETCHER N. PLATT, Manager, Traffic Safety and Highway Improvement Department, Ford Motor Company

A research instrument has been developed over the last four years and is now available for studying driver performance objectively under actual driving conditions. This report describes a new method of evaluating the effects of fatigue on driving performance using this equipment. A mathematical rating system is developed based on the results of this preliminary experiment and pre-tests. Examples demonstrate how the equations are used for rating the degree of driver fatigue at several stages of the test run. The results of this test are now being used in planning a new experiment for studying driving fatigue on a small population of drivers. The same approach can also be applied to study the effects of drugs, alcohol, and physical deficiencies on driver performance.

•FATIGUE has at least three meanings: subjective fatigue defined as the feeling of being tired; physiological fatigue as determined from bodily changes; and objective fatigue when performance of a task shows a progressive deterioration.

Crawford (1) discusses driving fatigue in the following manner: "It is generally agreed that performance can be impaired by driving for too long a period but it has proved extremely difficult to define what is meant by driving performance, to develop adequate techniques of measuring it, to interpret signs of deterioration in performance and to define the amount of deterioration which might reduce safety."

Because there has been no satisfactory means of measuring driver competence objectively, it has been necessary to study driving fatigue indirectly by measuring physiological changes assumed to influence driving skill, and by assessing decrements in tasks assumed to be related to driving safety.

SUBJECTIVE CLASSIFICATION OF DRIVER FATIGUE

In order to develop objective measures of driver fatigue, it is first necessary to agree on a subjective classification. The following categories, in order of increasing severity, are suggested by the author:

1. An increase in nervous tension resulting in stronger responses to minor irritations.
2. An acceptance of more errors because of a loss of desire to maintain accurate performance.
3. Larger errors resulting from a higher threshold of arousal to danger.
4. A momentary loss of operating control.
5. A complete loss of operating control.
6. A loss of consciousness.

The several levels of fatigue described may occur simultaneously, but it appears that a driver usually follows this pattern as the effects of fatigue increase. Recovery from one stage to a less critical stage occurs occasionally during the early periods of

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Paper sponsored by Committee on Road-User Characteristics.

fatigue, but recovery will occur less often as fatigue progresses. Before the development of the Greenshields drivometer (2) it had been only possible to estimate the stages of driving fatigue by subjective observation and by physiological measurements. However, with the development of this equipment it now appears possible to directly record the performance of drivers in tracking and speed control. These fundamentals of the driving task indicate the first signs of fatigue including tension, errors, acceptance of wider tolerances and early indications of loss of control.

MOTIVATION

One of the complicating factors in human engineering research is motivation of the subjects. Certainly in driving experiments related to fatigue, the problem is one of major importance.

Jordan (3) claims that the problems of motivation have generally been overlooked. In discussing the subject he states, "To the extent that a job challenges the operator, it is intrinsically satisfying." He points out that a job must be difficult and requires skill to be challenging. "At the same time it cannot be too difficult. It must permit degraded performance. Inefficiency beyond certain tolerances cannot be tolerated. Each task must have a built in optimum range of permissible degraded performance on the part of the human operator. The operator must have relatively immediate feedback as to how efficiently he actually is operating so that, to the extent that he is inefficient he can improve his skills and to the extent that he is efficient he can maintain them. Feedback which is either too late or irrelevant in helping the operator is damaging."

The driving task fits Jordan's description of a satisfying task. Driving is usually a challenging experience. There is room for degraded performance, and there is a reasonable amount of immediate feedback under normal conditions. However, when the driver begins to tire he loses much of his attention to feedback. As a result he cannot track the vehicle as well or maintain as constant a speed as when fresh and alert. It is recognized that most people will be highly motivated to do their best when being tested. However, the motivation of the subjects can be modified by the experimentor by pre-test instructions when considered necessary.

The drivers participating in this pilot test were subjected to several motivating factors. They were making every effort to perform in a safe manner as the task was carried out on the highway; however, the subjects knew that a study of fatigue was the sole purpose so there was an incentive to permit fatigue to take over. The drivers also knew which variables were being measured so another bias was inherent. Nevertheless, in a 12-hr drive it is not humanly possible to influence the fundamental results appreciably. In the next experiment, it is planned that drivers will not know the nature of the experiment or the variables being measured to eliminate bias from these factors.

Motivation to perform in a safe manner might be considered as the opposing force to the degraded performance caused by fatigue. The oscillations in vehicle control caused by these two forces probably become less stable as fatigue progresses and an accident can occur when motivation weakens sufficiently to cause instability of control (see Fig. 12).

It may be possible to study the cycles of driver performance caused by the interaction of safety motivation and fatigue by the mathematical program of auto correlation and spectral analysis. The important result of such a study might be to predict the critical point of neutral stability without having to reach the danger point in actual highway driving tests. Also, this appraoch may provide an insight in developing practical methods to reduce fatigue and alert the driver before a dangerous situation occurs.

It seems reasonable to believe that drugs and alcohol will reduce a driver's performance in the same manner as fatigue. However, the motivation aspects of these mental depressants may be quite different. It is anticipated that alcohol and drug tests will be made using the drivometer, and performance rating suggested in this report will also be applicable to these experiments.

NATURE OF THE EXPERIMENT

A two-man team drove a car equipped with a modified Greenshields drivometer on a 1,200-mi trip from Ann Arbor, Mich., to Philadelphia and back. The test was made on four-lane divided highways with limited access because fatigue is accelerated by the monotony of the highway environment. Also, this kind of highway is probably the most important in loss-of-control accidents. Data were recorded by one man while the other was driving. Information included the number of steering reversals, accelerator reversals, speed changes, brake applications, time and mileage. The steering reversal rates per minute and speed change rate per minute were also recorded at certain intervals.

The trip east was started about 10 AM Sunday. Both drivers had about five hours sleep the night before. The drivers changed every one and one-half hours in accordance with recommended practice, with the exception of the first and last shifts. Rest stops were usually one-half hour or longer so that drivers had a reasonable length of time to relax between laps.

The trip west was started at 4:30 PM Tuesday. Both drivers were mentally tired from the day's activities. The drivers changed only when they felt too tired to drive farther. Intentionally, they made no reference to the time or distance traveled so that their changeovers would be based on a subjective feeling of fatigue. Rest stops were as short as possible to accelerate tiredness.

SUBJECTIVE SUMMARY OF TRIPS

The trip east was without serious incident. There were several severe rain squalls between the second and fourth hour. Also, there was a delay of 20 min at the first tunnel (Laurel Hill) and several 35-mph repair zones. Drivers showed some signs of stress occasionally, and moderate signs of lower standards of steering and speed control. Driver A drove the last lap of the trip and continued for nearly two hours to the final destination. During the last hour the driver mentioned speed change hallucinations but the record indicated a constant speed. It showed, instead, major changes in steering reversal rates. One-half hour from the end, the driver was irritated by a relatively minor change in reservation arrangements indicating some degree of fatigue. The trip ended at 11:25 PM without difficulty and both drivers felt well but ready for bed.

The trip west was more productive in terms of a study of fatigue. Both drivers showed subjective signs of fatigue from the very beginning of the trip at 4:25 PM. Numerous experiences show increasing degrees of fatigue. For instance, driver A failed to see several warning signs of an approaching tunnel during the second hour of his first lap. It was raining hard at the time and there was moderately heavy traffic, but neither was an excuse for the serious error. Driver B stopped driving at the end of 38 min of his third lap because of extreme sleepiness. Both drivers showed major effects of fatigue though each one slept occasionally during the time the other driver was behind the wheel. Rest stops were kept to a minimum throughout the whole trip west. The last leg of the trip, at 4:10 AM, was driven solo by driver A and his reactions changed appreciably from the normal pattern as speed dropped from a norm of 60 mph to 48 mph. Attention to the drivometer kept the driver somewhat attentive althought it was probably the most dangerous part of the trip from the standpoint of falling asleep. The combination of less responsiblity (for the other driver) and being on the last leg of the journey on a familiar highway contributed to the change in driver actions. (Details of both trips are given in the Appendix.)

TEST EQUIPMENT

The test equipment was a modified Greenshields drivometer (Fig. 1) mounted in the glove compartment of a 1962 Ford Fairlane 500 four-door sedan. The vehicle was equipped with seat belts, power steering, power brakes and dual brake and accelerator pedals. The drivometer, developed over the last four years, is described in detail in several earlier papers (2, 4). Its purpose is to measure the fundamental actions of the driver in controlling direction and speed of his vehicle, and in addition, to measure the fundamental parameters of vehicle motion.

From previous experiments, it was found that the steering wheel reversal rate (which is the same as vehicle tracking cycle rate) is the most sensitive variable to driver, environment and vehicle characteristics. Speed change rate (the number of increases

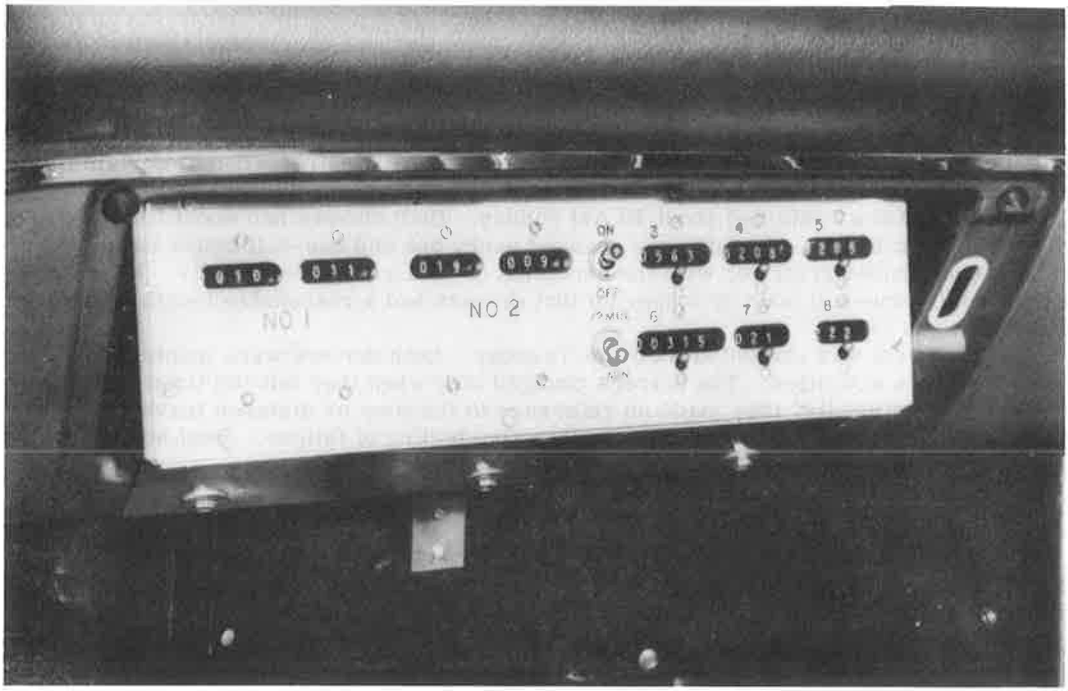

Figure 1. Greenshields drivometer.

or decreases in vehicle speed) is also important. Accelerator reversals and brake applications are also counted.

The two counters (number one) work as a pair recording the steering wheel reversal rate on a minute-by-minute basis. The second pair of counters (number two) records the speed change rate for each minute. While one counter is recording, the other is holding the total count for the preceding minute. Counter three records a cumulative count of steering wheel reversals from the start of the test run. Counters four, five, six, seven and eight record the total number of accelerator reversals, the time the car is in motion, the total speed changes (in mph), the brake applications, and the total trip time, respectively.

As this unit was designed for driver training, it does not have a camera attachment for automatic recording of data as the original model of the drivometer. Therefore, it was necessary for the passenger to record the data periodically during the test runs. Future tests will be made with an automatic camera recording unit.

PROCEDURE AND ASSUMPTIONS

Standard experimental procedure has been followed in this study. First, it was predicted that the drivometer could measure driving characteristics accurately enough to detect the early stages of fatigue. Next, pre-test experiments recording steering wheel reversal rates only were run by several drivers (see Appendix). Hypotheses were then established and a pilot test was made which is reported herein. An empirical performance rating is presented for quantifying the results and providing a systematic procedure. A driver's record is made during a particularly alert period (in this test at the beginning of a run) and the results are used as a norm for that driver.

This work sets the stage for design of a basic experiment to establish the measurable limits of fatigue and its degrees on a population of drivers. Further studies will permit evaluation of direct and indirect causes of driver fatigue and the development of counter measures.

The following assumptions are used in evaluating the test run data and in developing the empirical driver performance rating equations:

1. Driver fatigue will have effect on steering wheel reversal rates, speed change rates and average speed of the vehicle.
2. As the driver becomes fatigued, he will accept wider tolerances of both vehicle tracking and speed control.
3. As the driver gets tired, his speed may increase or decrease depending on whether his sensitivity to speed change or steering reversal rate is lost first.
4. The driver will usually take more risks as he becomes more fatigued. This will be indicated as an increase in tracking tolerance, and consequently, a decrease in steering reversals if speed is constant. Degree of risk may also be indicated by an increase in the speed of the vehicle.
5. As the driver becomes tired, his speed change rate increases but he usually makes some effort to keep it within balance by accelerator reversals or driving at a slower speed to accommodate it.
6. The most severe fatigue is encountered when the speed change rate increases and accelerator reversal rate decreases. This indicates the driver has ceased to care about speed control.

Experiments to date indicate that some drivers have more skill in tracking than in speed control; others are more skillful in maintaining a uniform speed. Relatively few drivers are well coordinated in both controls simultaneously. When a driver becomes tired, his sensitivity to both parts of the task deteriorates. The loss of ability in either tracking control or speed control can be critical from a safety viewpoint. The empirical equations (see Appendix) and the driver performance equation have each been developed and weighted on the basis of the tests reported in this study. It is anticipated that refinements will be made as additional data are collected on a larger sample of drivers.

DRIVER PERFORMANCE RATING SUMMARY

Table 1 shows the performance ratings of both drivers for parts of the two test runs. Figure 2 shows the routes. The following observations can be made:

1. Neither driver performed as well as his standard during any part of the trip.
2. Driver B had better recuperative powers than driver A, and seemed to maintain a consistent level of performance during each lap of the first test run. However, during the second run, driver B's performance showed rapid deterioration in the third lap, which was also noted in the subjective report by the observer.
3. The performance of driver A was relatively better on the second run than on the first, but in both tests the ratings show a major deterioration compared to his standard.
4. The one 90-min period, when data was taken continuously, showed a definite cyclic pattern of the steering wheel reversal rate. This may prove to be related to the attention span of the driver and be a valuable characteristic to interpret in future tests.
5. It is obvious from this pilot study that minute-by-minute data should be taken continuously throughout the whole trip so the performance ratings may be calculated at each 15-min time interval.

TABLE 1

Lap	Minutes	Rating[1] Driver A	Rating[1] Driver B	Lap	Minutes	Rating[1] Driver A	Rating[1] Driver B
(a) Test Run No. 1: Ann Arbor to Philadelphia				(b) Test Run No. 2: Valley Forge to Ann Arbor[2]			
First	120 to 135		71.3	First	1 to 15		41.2
					90 to 105		46.4
					1 to 15	70.6	
					120 to 135	46.8	
Second	1 to 15		46.1	Second	1 to 15		42.5
	16 to 30		44.9		30 to 45		53.2
	65 to 75		52.5		54 to 68	42.2	
					84 to 91	34.0	
Third	60 to 75	28.3		Third	1 to 15		41.8
	75 to 90	19.3			31 to 37		39.9
	1 to 15		62.6				
	16 to 30		46.9				
	60 to 75		56.7				
Fourth	60 to 75	39.0					
	90 to 105	27.1					

[1] Standard ratings: driver A, 70.8; driver B, 71.3.

[2] Minute by minute data discontinued because both participants were too tired to continue recording.

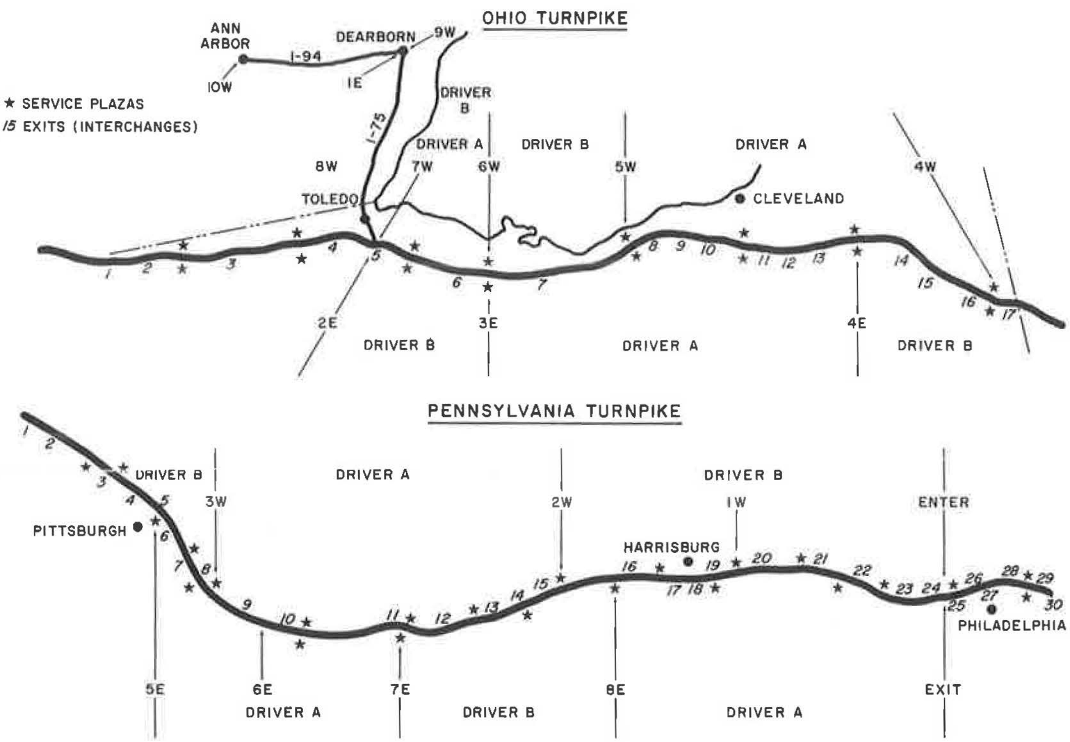

Figure 2. Test route.

CONCLUSIONS

1. The effects of driver stress and fatigue, as reflected in tracking and speed control, can be monitored by the Greenshields drivometer.
2. A series of empirical equations have been developed and combined to form a measure of driver performance compared to the driver's norm. These equations are based on logical hypotheses derived from the results of the research conducted to date.
3. The experimental techniques developed in these test runs will be useful in establishing a broad based study on driver fatigue.
4. Similar methods will be applicable to the study of the effects of drugs, alcohol and physical deficiencies on driver performance and safety.

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3. Jordan, N., "Motivational Problems in Human Computer Operations." Human Factors (June 1962).
4. Platt, F.N., "Traffic Safety Research - A Unique Method of Measuring Road, Traffic, Vehicle and Driver Characteristics." Ford Motor Company (1962).
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Appendix

EMPIRICAL EQUATIONS

Tracking Control Factors:

$$A_t = \sqrt{\frac{\left[(SRR)_X - (SRR)_N\right]^2}{(SRR)_N}} \qquad (1)$$

in which

$(SRR)_X$ = Average steering reversal rate over 15-min period; and

$(SRR)_N$ = Average steering reversal rate normal alert condition for subject (from pre-test).

$$B_t = \text{Standard deviation of } \frac{(SRR)_X}{(SRR)_N} \qquad (2)$$

$$C_t = \frac{(SRR)_{max} - (SRR)_{min}}{(SRR)_{min}} \qquad (3)$$

in which $(SRR)_{max}$ and $(SRR)_{min}$ are from 15-min periods.

Speed Control Factors:

$$A_s = \sqrt{\frac{\left[(S)_X - (S)_N\right]^2}{(S)_N}} \qquad (4)$$

in which

$(S)_X$ = Average speed over 15-min period; and

$(S)_N$ = Average speed normal alert condition (from pre-test).

$$B_s = \frac{(SCR)_X \quad (ARR)_N}{(SCR)_N \quad (ARR)_X} - 1 \qquad (5)$$

in which

$(ARR)_X$ = Average accelerator reversal rate over 15-min period;

$(ARR)_N$ = Average accelerator reversal rate, normal alert condition (from pre-test);

$(SCR)_X$ = Average speed change rate over 15-min period; and

$(SCR)_N$ = Average speed change rate, normal alert condition (from pre-test).

Driver Performance Rating:

$$DPR = 100 - 100 A_t - 100 B_t - 10 C_t - 200 A_s - 10 B_s \qquad (6)$$

Basic assumptions used in developing the empirical equations are as follows:

1. A driver's performance may vary from day to day and hour to hour. A comparative performance rating with an individual's norm is proposed and therefore is nondimensional. (The driver's norm is obtained at the beginning of a test run when he is most alert.)
2. Tracking control is more sensitive to driver performance than speed control.
3. Steering reversal rate should remain constant. A rate above or below the driver's normal (SRR) is a decrease in performance.
4. Deviation from mean (SRR) is a decrease in performance.
5. An increase in range of (SRR) in any 15-min period is a decrease in performance.
6. When (SRR) goes to zero the performance rating (DPR) is a minimum.
7. Average speed increase or decrease compared to norm is a decrease in performance if environmental and highway conditions are constant. (It may be desirable to have correction factors for night driving, highway characteristics and traffic conditions, but it is assumed that initial tests will be run on a limited access, 4-lane divided highway to maintain reasonably constant conditions.)
8. Speed change rate (SCR) is essentially the deviation from the average speed. Therefore, this factor should be minimized for best performance.
9. When the average accelerator reversal rate (ARR) approaches zero, the performance rating (DPR) is a minimum.
10. When speed change $\frac{(SCR)_X}{(SCR)_N}$ and $\frac{(ARR)_X}{(ARR)_N}$ ratios increase simultaneously, the driver is trying to keep performance up, but when the speed change ratio increases and the accelerator reversal rate ratio decreases, the driver's performance is decreasing.

TRIP LOG RUN NO. 1

Origin: Ann Arbor, Michigan
Destination: Philadelphia, Pennsylvania

Date: 6-10-62
Sunday

Driver	Time (EST)	Mileage	Running Time	Miles	Notes
	9:50 AM	5,026.7			Geddes Road, Ann Arbor, Michigan; Lap No. 1
A			48	40.1	I-94 East
	10:30	5,067.1			
			-	-	(1-E) Pick up driver B at home in Dearborn
	10:55	5,067.1			Lap No. 1
B			52	50.8	
	11:47	5,117.9			
			-	-	(2-E) Stop for gas before entering turnpike
	11:54	5,117.9			
B			30	30.5	
	12:24 PM	5,148.3			
			-	-	(3-E) Freemont Plaza 51-min stop for dinner
	1:15 PM	5,148.6			Lap No. 2
A			90	95.8	
	2:45	5,244.4			
			-	-	(4-E) Exits 13-14, rest stop (Plaza)
	3:07	5,247.2			Lap No. 2
B			39	42.1	
	3:46	5,289.3			Ohio Tollgate
B			54	52.7	
	4:40	5,342.0			(5-E) Rest stop (Exit 6) Oakmont, Pa.
	5:00	5,342.0			Lap No. 3
A			60	59.3	
	6:00	5,401.3			(6-E) Stopped at tunnel entrance (Laurel Hill)
	6:20	5,401.3			
A			41	40.3	
	7:01	5,441.6			
			-	-	(7-E) Exit 11 - Bedford, Pa. Stopped for supper
	7:50	5,441.6			Lap No. 3
B			30	29.4	
	8:20	5,471.0			Dark (night)
B			47	43.6	Lap No. 3
	9:07 PM	5,514.6			
			-	-	(8-E) Exit 16 - Plainfield Plaza
	9:10	5,514.6			Lap No. 4
A			110	108.9	
	11:00	5,623.5			
			-	-	Valley Forge Exit; no stop but wrong turn made—5 min delay
	11:00	5,623.5			
A			25	15.5	Schuylkill Expressway
	11:25	5,639.0			Marriott Motel, Phil., Pa.

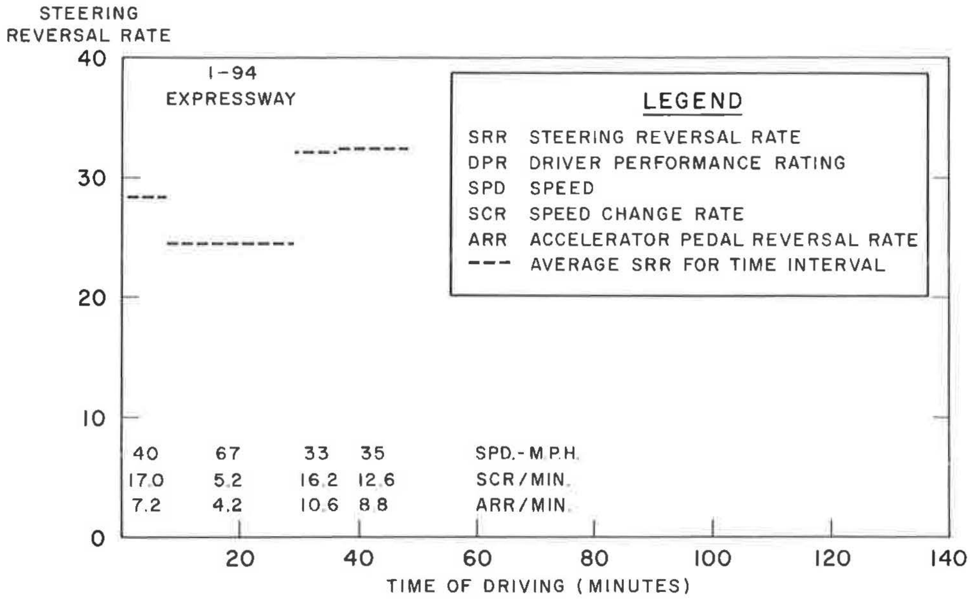


Figure 3. Driver A, 1st lap; weather: rain. If minute by minute data were available, this would have been used as standard for driver A. First lap of test run No. 2 was used instead.

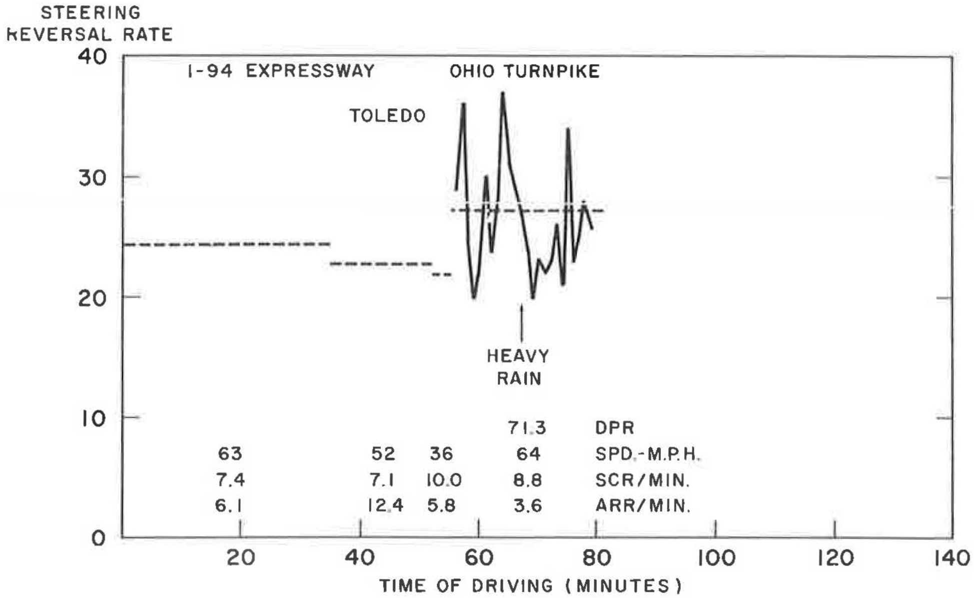


Figure 4. Driver B, 1st lap; weather: heavy rain, showers and gusts. This record was used as standard for driver B.

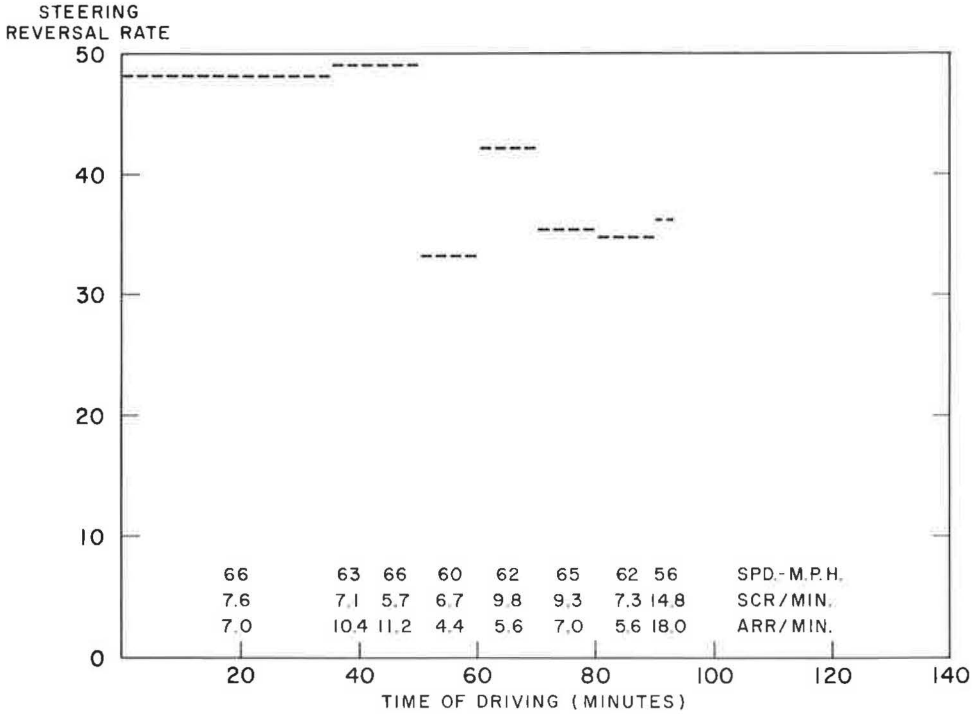


Figure 5. Driver A, 2nd lap; weather: heavy rain, showers and X wind gusts. Very heavy rain; radio very distracting. SRR remained high as a result of tension during first 45 minutes.

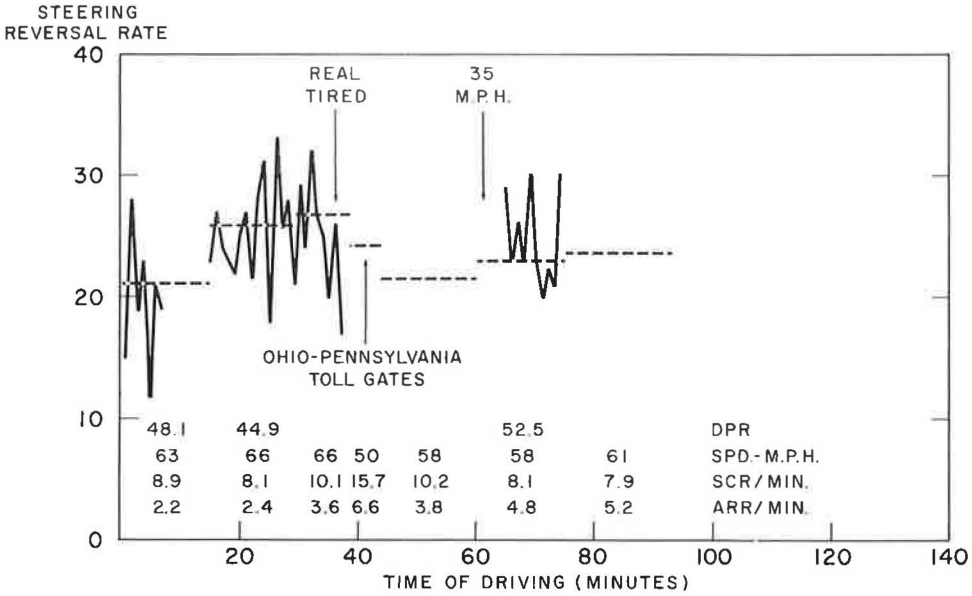


Figure 6. Driver B, 2nd lap; weather: partly cloudy. Signs of fatigue before toll gates.

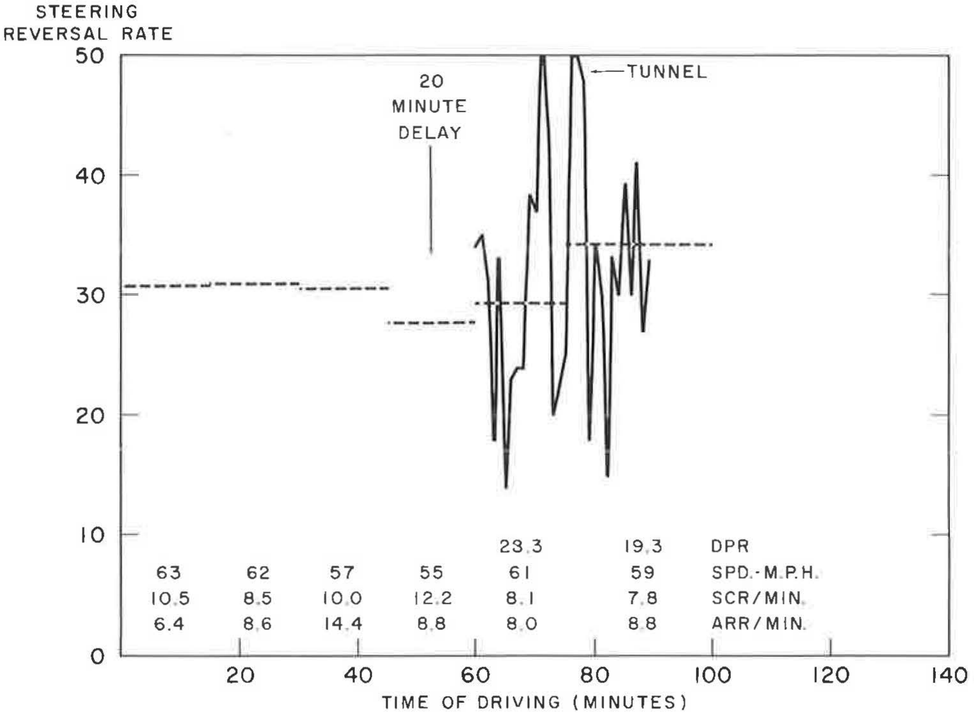


Figure 7. Driver A, 3rd lap; weather: clear. Extreme tension shown, particularly in tunnels and let down immediately after.

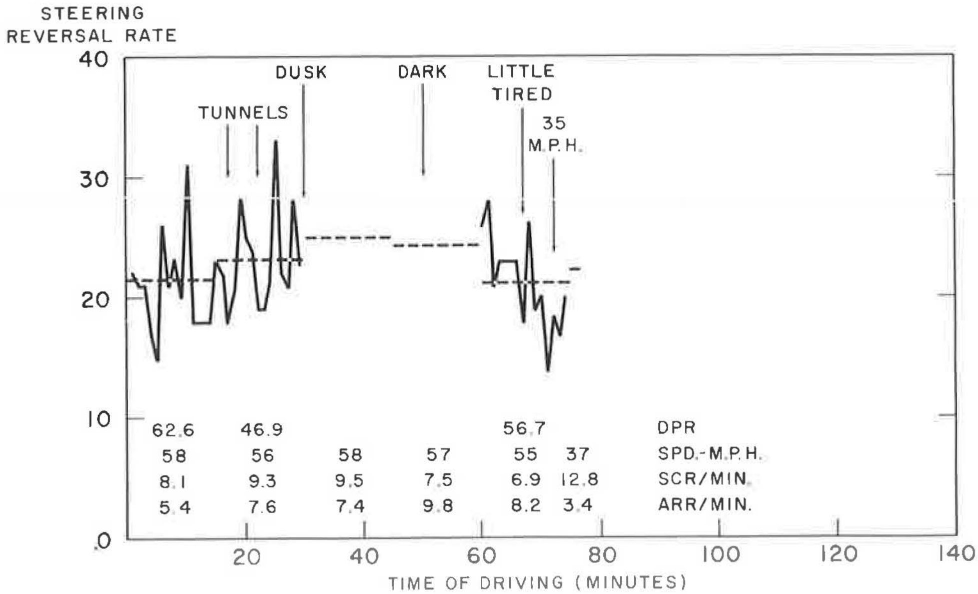


Figure 8. Driver B, 3rd lap; weather: clear. Slight increase in tension during first 30 minutes (SRR) and wider tracking tolerance after 60 minutes resulting in lower SRR.

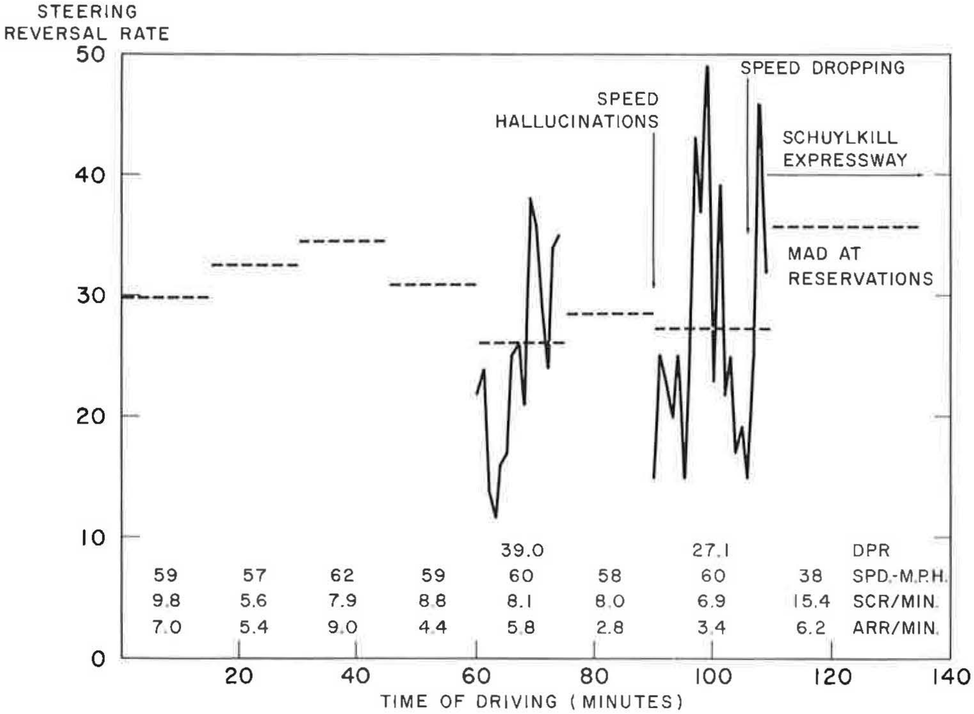


Figure 9. Driver A, 4th lap. Extreme deviation from mean SRR resulting from tension of fatigue.

TRIP LOG RUN NO. 2

Origin: Valley Forge Entrance to Pennsylvania Turnpike — Date: 6-12-62
Destination: Ann Arbor, Michigan — Tuesday

Driver	Time (EDT)	Mileage	Running Time	Miles	Notes
	4:25 PM	5,859.9			Valley Forge, entrance - lap No. 1
B			67	70.1	
	5:32	5,930.0			
			-	-	(1-W) Rest stop between exits 19 and 20
	5:35	5,930.0			
B			52	56.7	
	6:24	5,986.7			
	7:15		-	-	(2-W) Stopped for supper at Blue Mountain
A			135	127.3	Lap No. 1
	9:30	6,114.1			
			-	-	(3-W) New Stanton Plaza - stopped for snack
	9:54	6,114.1			Lap No. 2
B			90	83.7	
	11:24	6,197.8			
			-	-	(4-W) Stopped - Ohio Plaza
	11:45 PM	6,198.0			Lap No. 2
A			94	99.8	
	1:19 AM	6,297.2			
			-	-	(5-W) Stopped for snack at Elyria, Ohio
	1:43		38	39.8	Lap No. 3
B	2:21	6,337.4			
			-	-	(6-W)
	2:25	6,337.4			Lap No. 3
A			31	29.3	Exit 5 - Toledo, Ohio
	2:56	6,366.7			Driver B asleep
			-	-	(7-W) Driver B asleep
	2:56	6,366.7			
A			46	43.5	Detroit-Toledo Expressway
	3:42	6,410.2			
			-	-	(8-W) Change drivers
	3:45	6,410.2			
B			24	17.2	Driver A asleep - Lap No. 4
	4:09	6,427.4			
			-	-	(9-W) Left Driver B in Dearborn, Mich.
	4:10 AM	6,427.4			Lap No. 4
A			40	31.7	Driver A - Solo
	4:50	6,459.1			Ann Arbor, Mich.

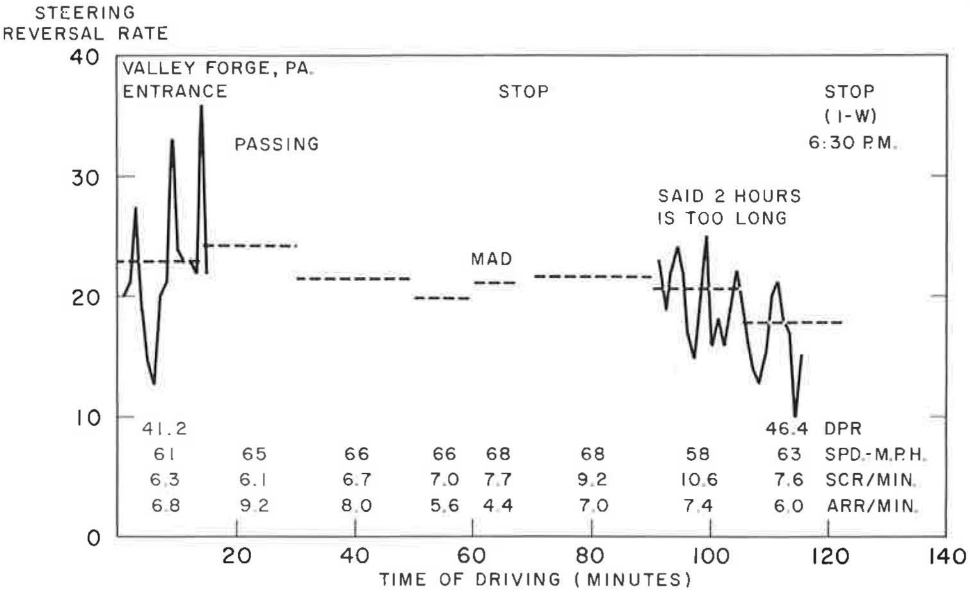


Figure 10. Driver B, 1st lap; weather: rain. Note apparent wider tracking tolerance, causing decrease in SRR.

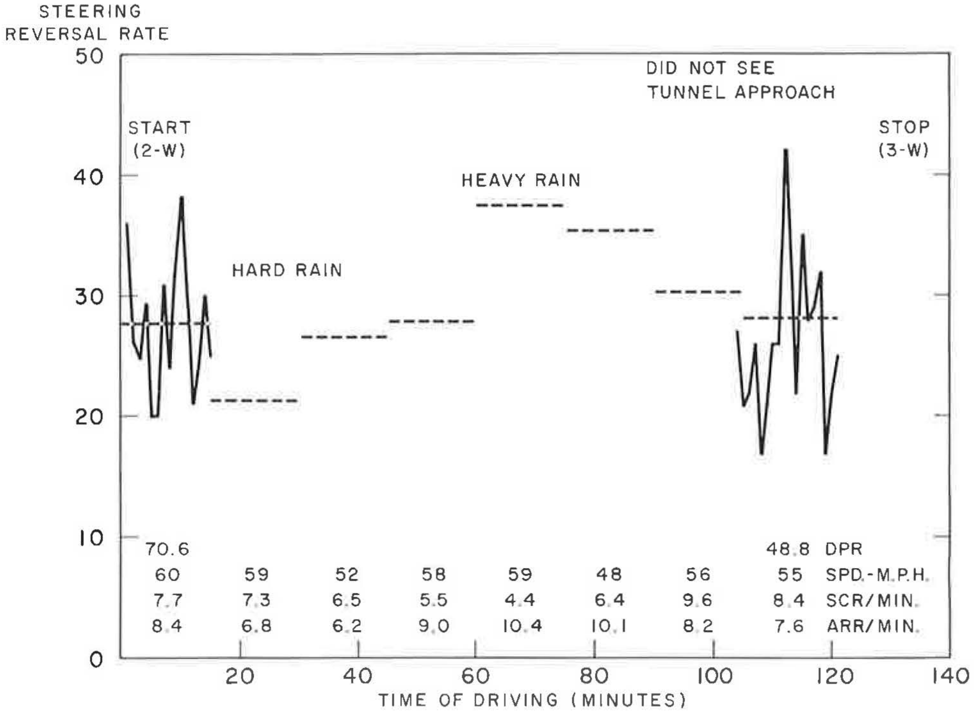


Figure 11. Driver A, 1st lap; weather: rain. Note increase in deviation from mean SRR.

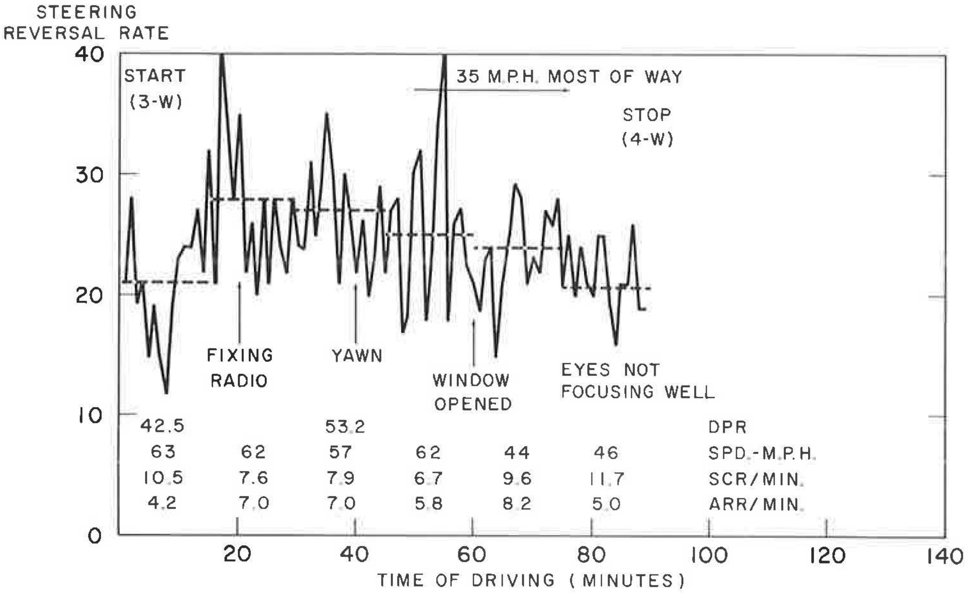


Figure 12. Driver B, 2nd lap; weather: rain and mist. Note apparent cyclic variation in deviation from mean SRR.

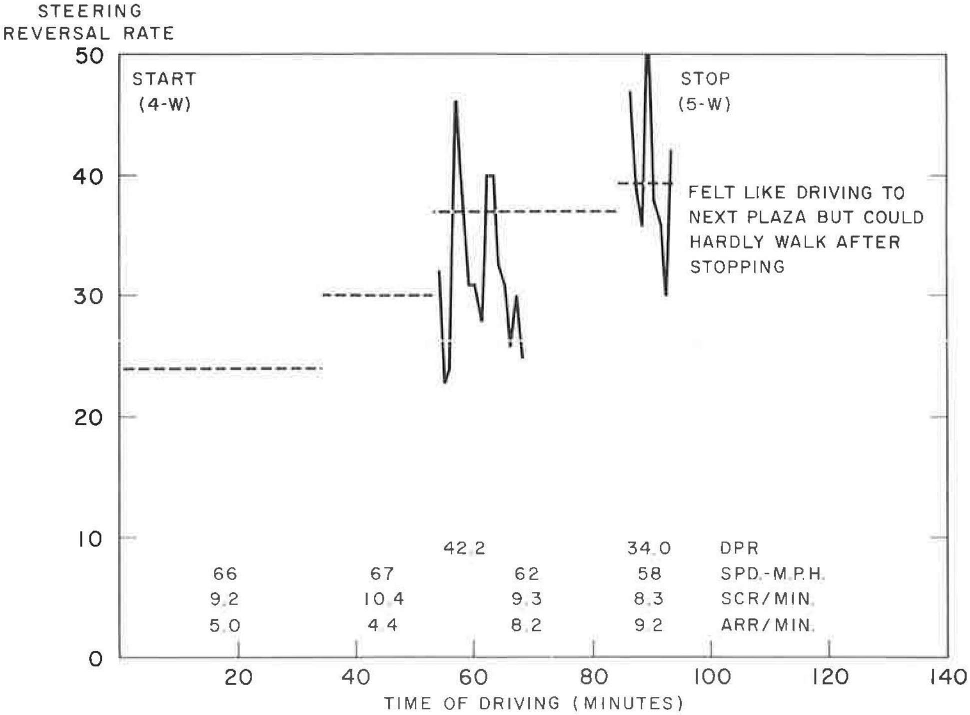


Figure 13. Driver A, 2nd lap; weather: clear. Note apparent increase in nervous tension; driver B dozing at times resulting in irregular time of recording data.

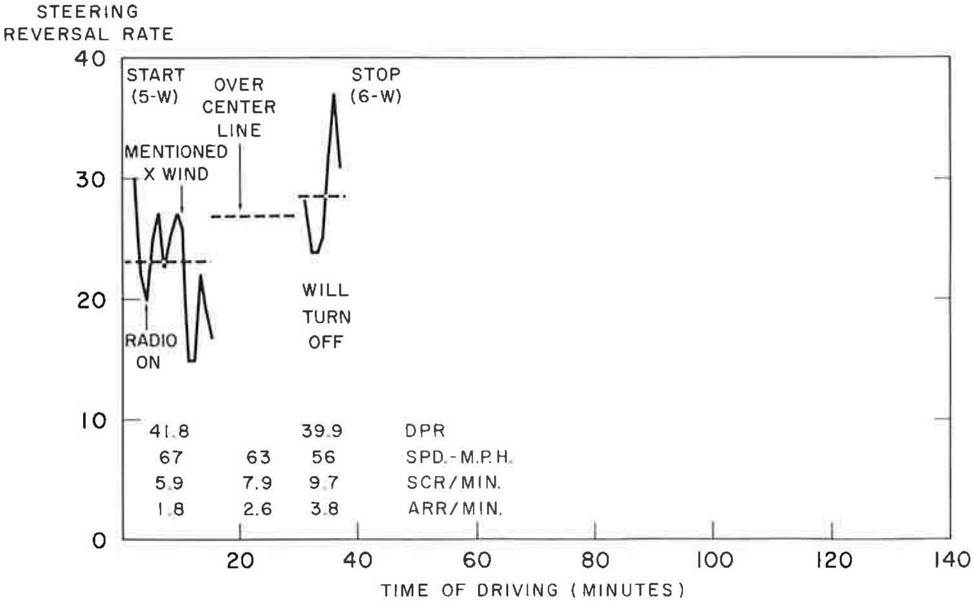


Figure 14. Driver B, 3rd lap; weather: clear. Note increase in tension and drop in average speed.

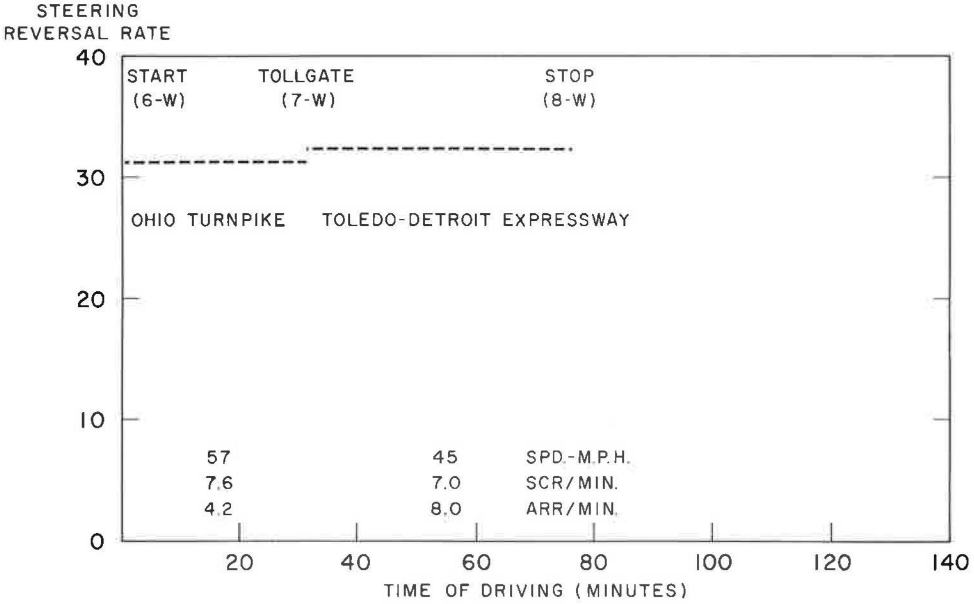


Figure 15. Driver A, 3rd lap; weather: clear. Note drop in speed.

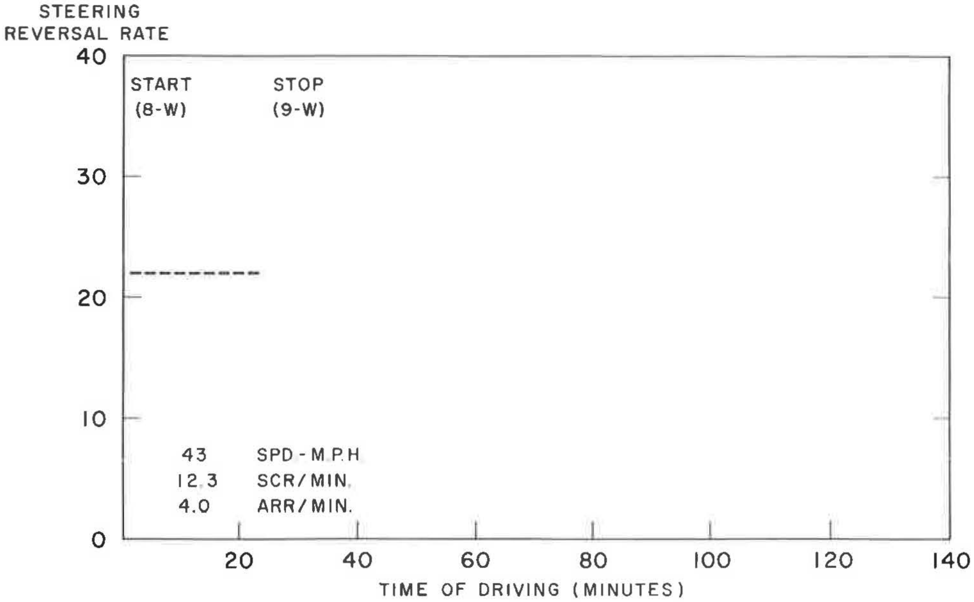


Figure 16. Driver B, 4th lap; Toledo Expressway and residential driving in Dearborn— several traffic lights. Driver A asleep on back seat.

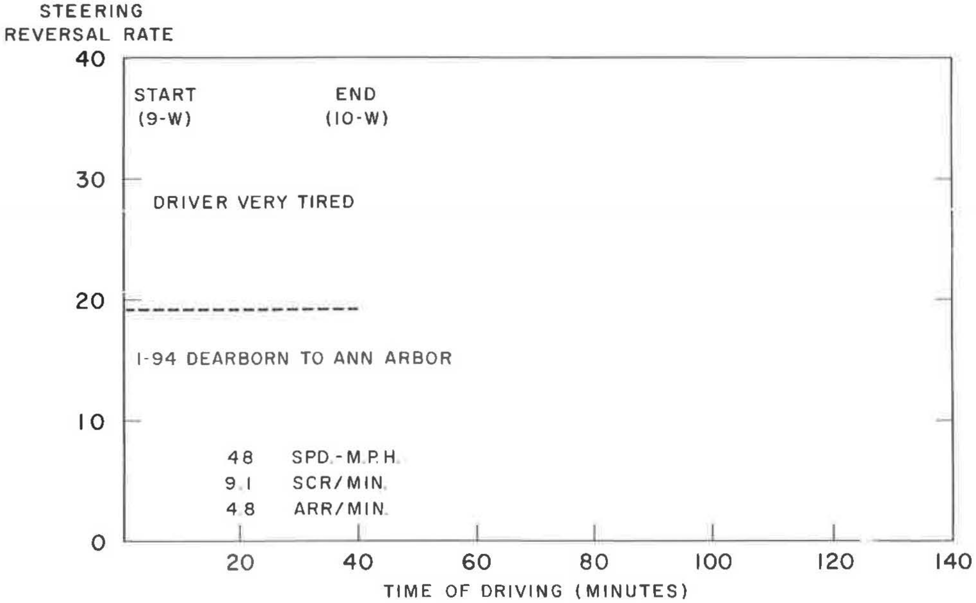


Figure 17. Driver A, 4th lap. Note drop in speed and SRR; some readings as low as 9 seen by driver.

PRELIMINARY TESTS ON STEERING WHEEL REVERSALS, JANUARY 1962

The original drivometer was designed by Greenshields for traffic flow studies. The steering wheel reversal sending unit had an adjustment which permitted a wheel turn tolerance of several inches before the signal was initiated. This tolerance was satisfactory for traffic flow studies in urban and residential streets but tests at rural highway speeds indicated that normal tracking movements of the steering wheel were not being recorded.

The author conducted experiments to determine the fineness of adjustment necessary to include all tracking maneuvers at high road speeds. During these tests it became apparent that the fine steering wheel reversal measurements were related to driver emotions as well as to traffic and environmental factors. It also was discovered that each driver has a basic steering wheel reversal rate, which seems to be the stabilizing signal (feedback) to the driver for a speed control of his vehicle.

Nearly a year of tests followed to evaluate the various effects of psychological factors, to improve the design equipment and finally, to develop the modified drivometer that has been used in this pilot study on fatigue.

Figures 18 through 29 are representative of nearly 100 test runs made with several drivers leading up to the first two hour test to study fatigue.

Both steering wheel reversal rates (SRR) and accelerator reversal rates (ARR) were measured in the pre-tests but it was quickly found that (SRR) were primarily sensitive to driver characteristics and (ARR) were predominantly related to environment. For this reason, only (SRR) are plotted in the attached curves.

The equipment used in these tests was shown elsewhere (3, Fig. 7). It was not as sensitive as the latest drivometer used in the main study reported herein, and for this reason, the rates are generally lower. Also, the timer was set on a 50-sec interval in the preliminary tests compared to the 60-sec interval now used.

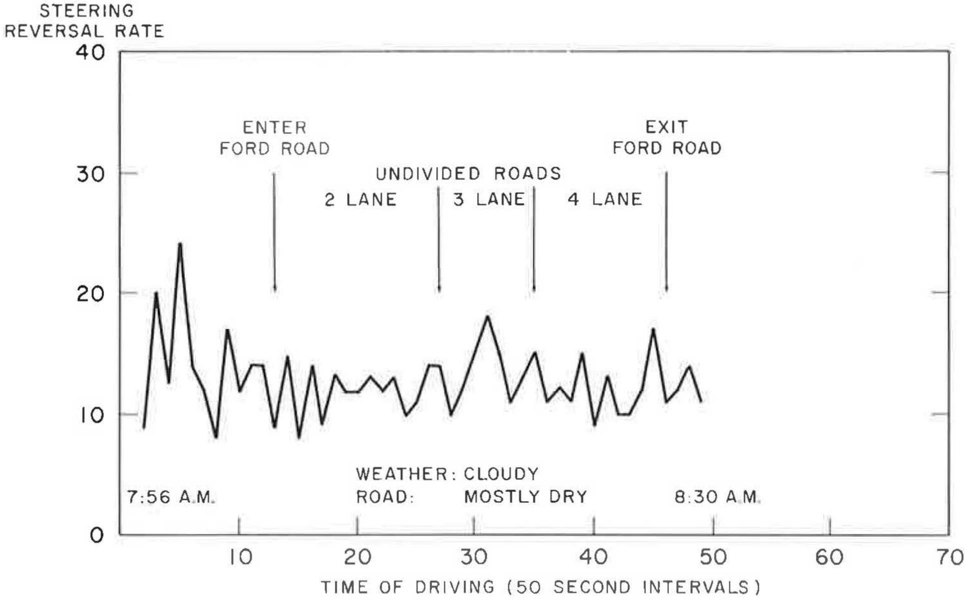


Figure 18. Ann Arbor to Dearborn via Ford Road, 1-4-62. Modified speed to try to maintain constant steering reversals.

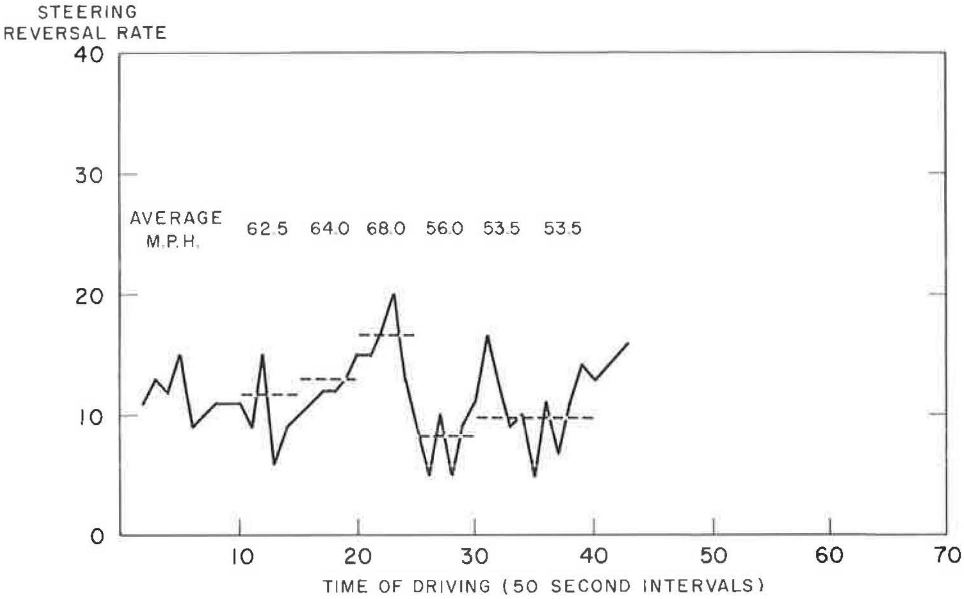


Figure 19. Ann Arbor to Dearborn via Expressway, 1-19-62. Test was a demonstration of the equipment; note sensitivity of steering reversals to speed.

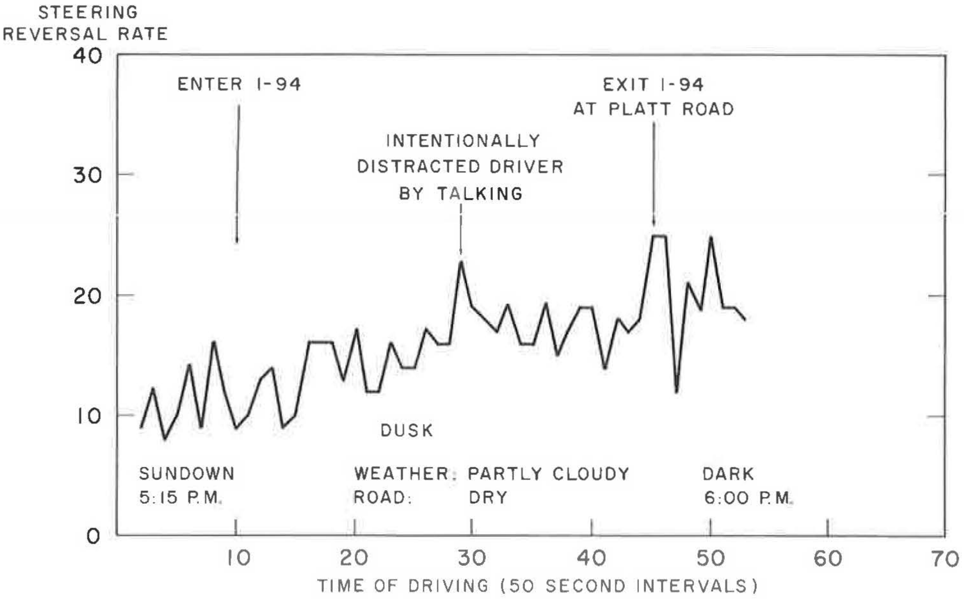


Figure 20. Dearborn to Ann Arbor via Expressway, 1-15-62. Increasing rate may be fault of driver tension or because of decrease in visibility.

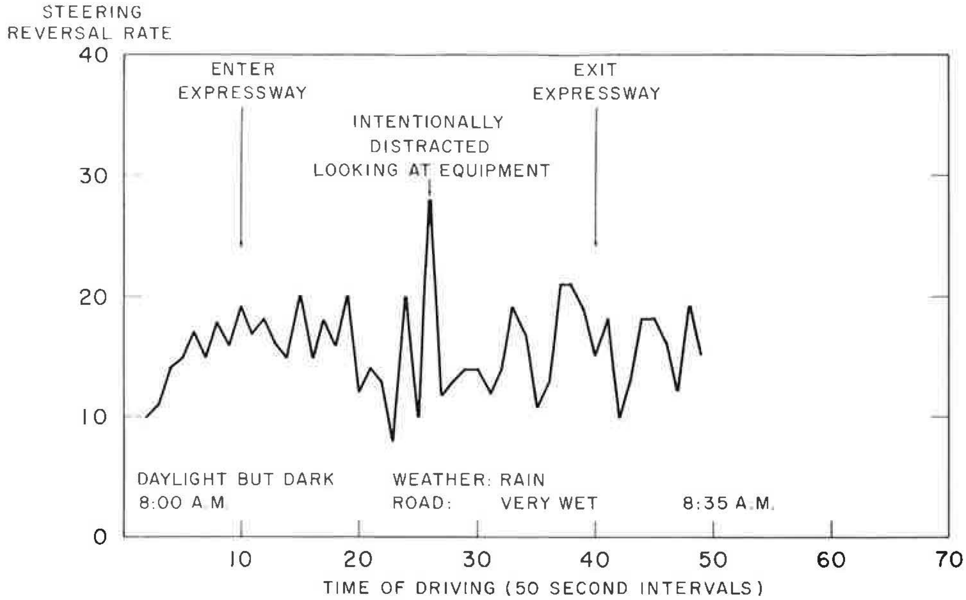


Figure 21. Ann Arbor to Dearborn via Expressway, 1-15-62. Note constant steering reversal rate but increase in deviation from mean.

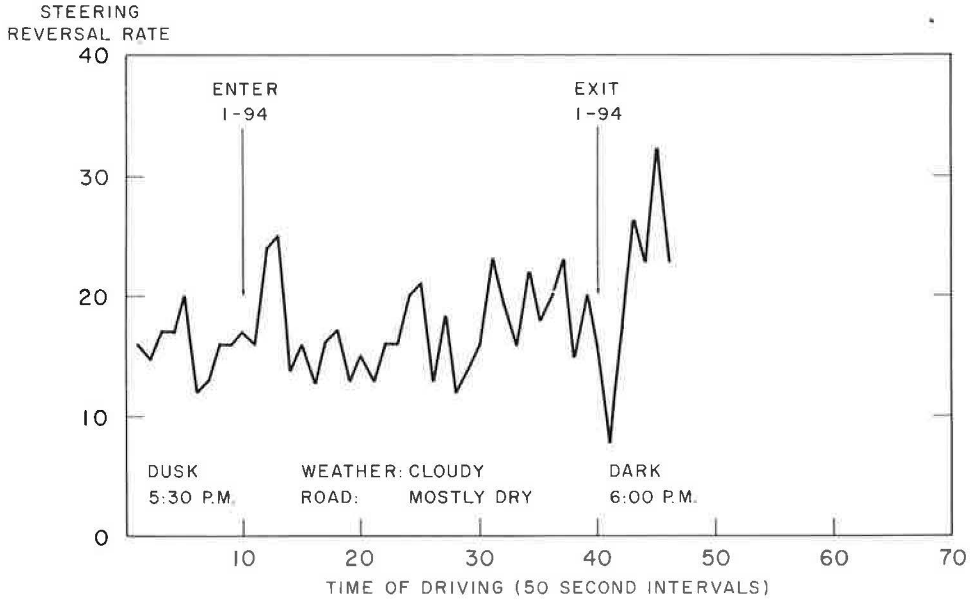


Figure 22. Dearborn to Ann Arbor via Expressway, 1-4-62. Rate increase between the 30th and 40th intervals probably the result of decreasing visibility without decreasing of speed.

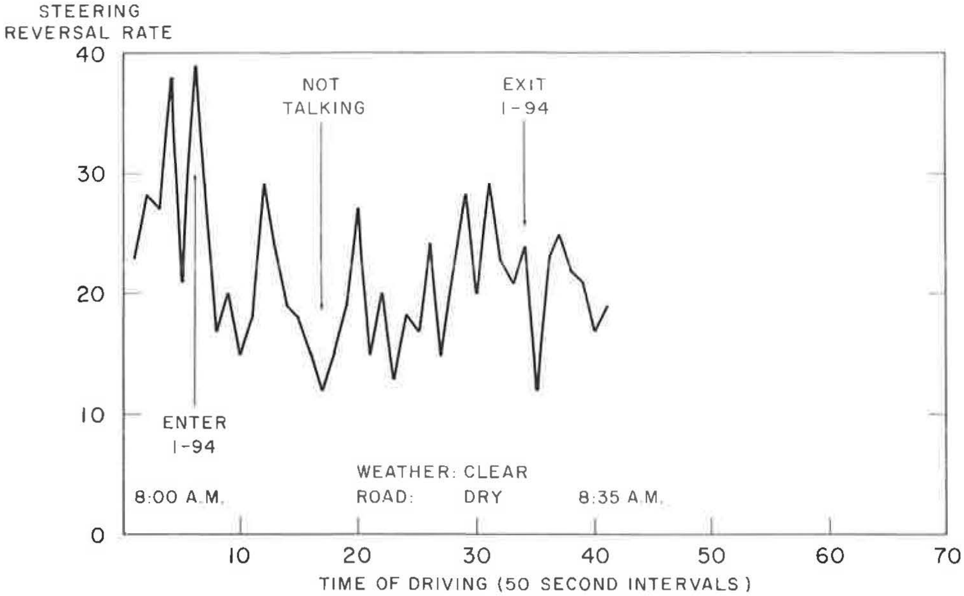


Figure 23. Ann Arbor to Dearborn via Expressway, 1-16-62. Driver very upset about accident which occurred the night before; probably caused the large deviations from mean.

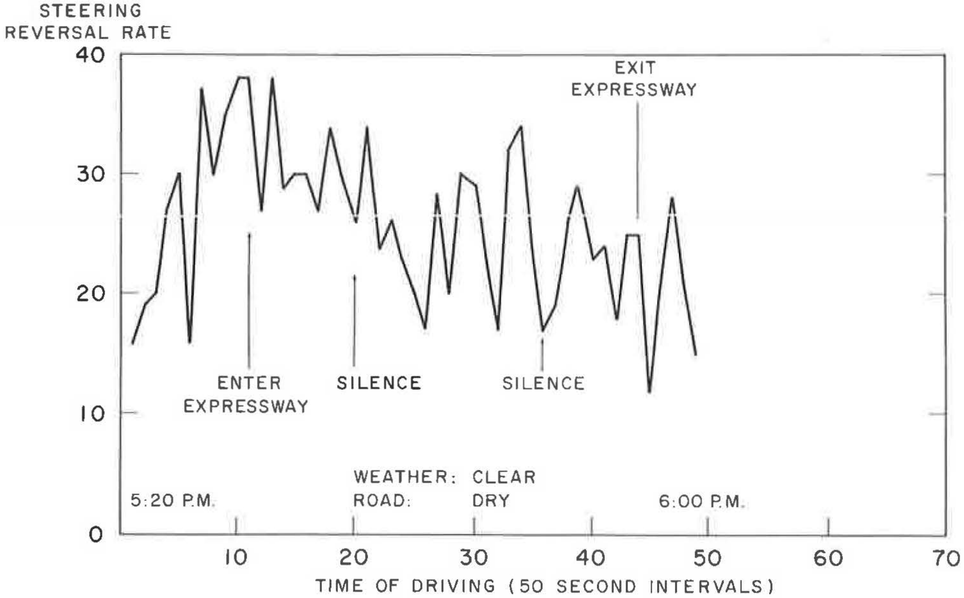


Figure 24. Dearborn to Ann Arbor via Expressway, 1-16-62. Driver shows nervousness when driving resulting in high rate and large deviations.

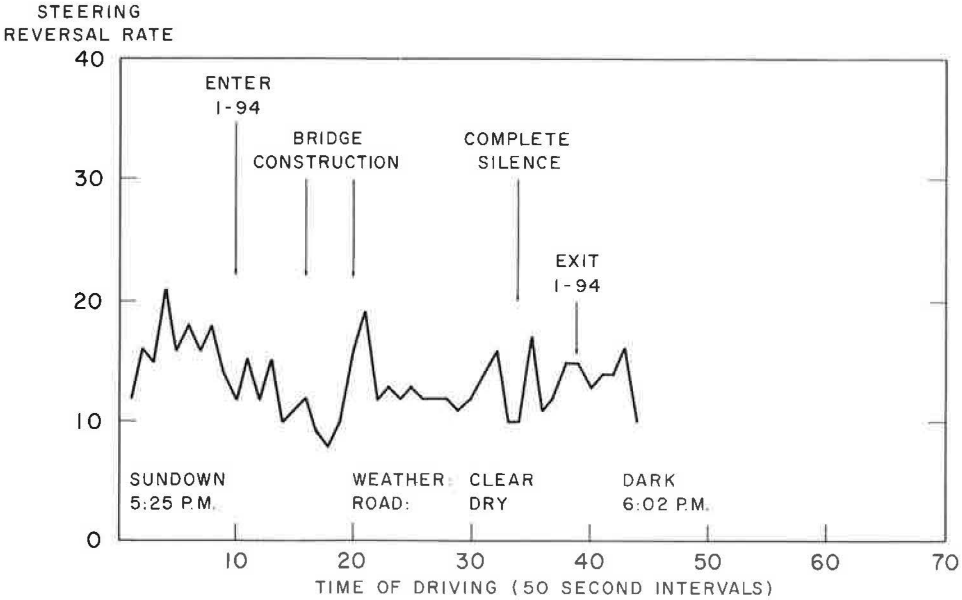


Figure 25. Dearborn to Ann Arbor via Expressway, 1-17-62. Driver was calm, consistent driver and was influenced very little by traffic conditions.

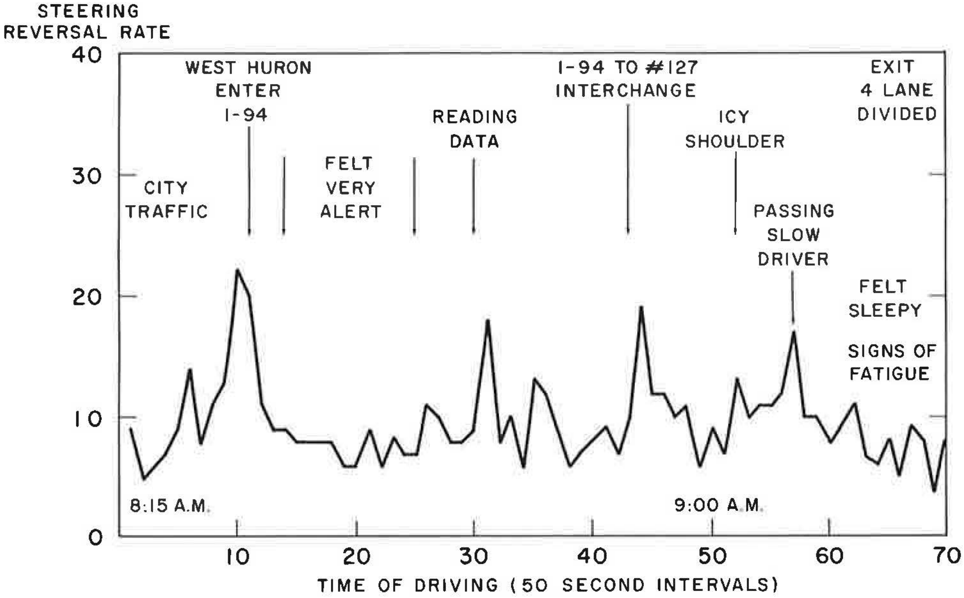


Figure 26. Ann Arbor to Lansing, 1-18-62. Test run was incidental to the primary objective of driving to a meeting. The driver took data while driving thus causing some distractions.

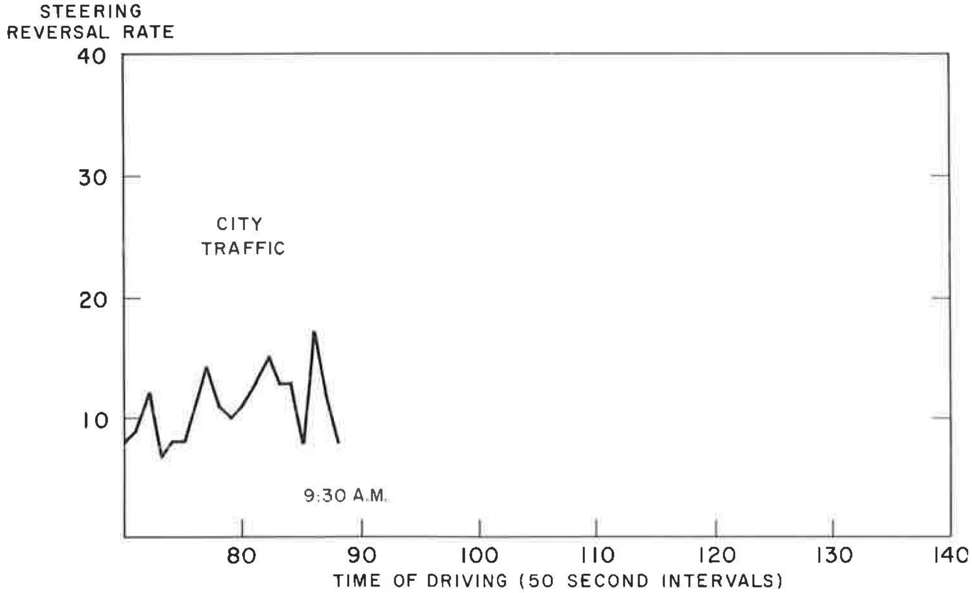


Figure 27. Conclusion of Ann Arbor to Lansing Test Run, 1-18-62. First signs of serious decrease in steering reversal rate caused by acceptance of wider tracking tolerance between the 60th and 70th interval.

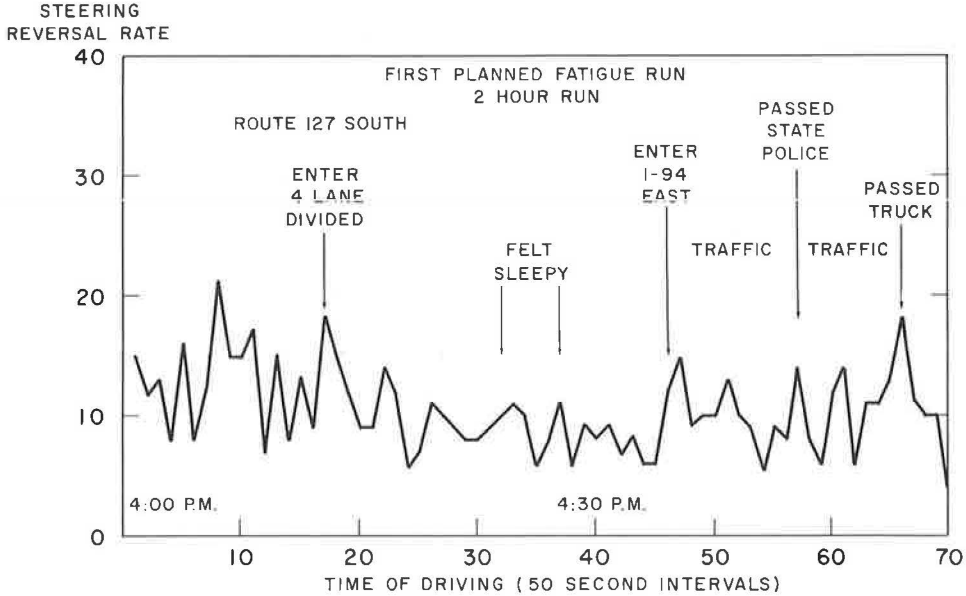


Figure 28. Lansing to Metropolitan Airport to Ann Arbor, 1-18-62. First planned fatigue run shows gradual decrease in steering reversal rate to the 80th interval.

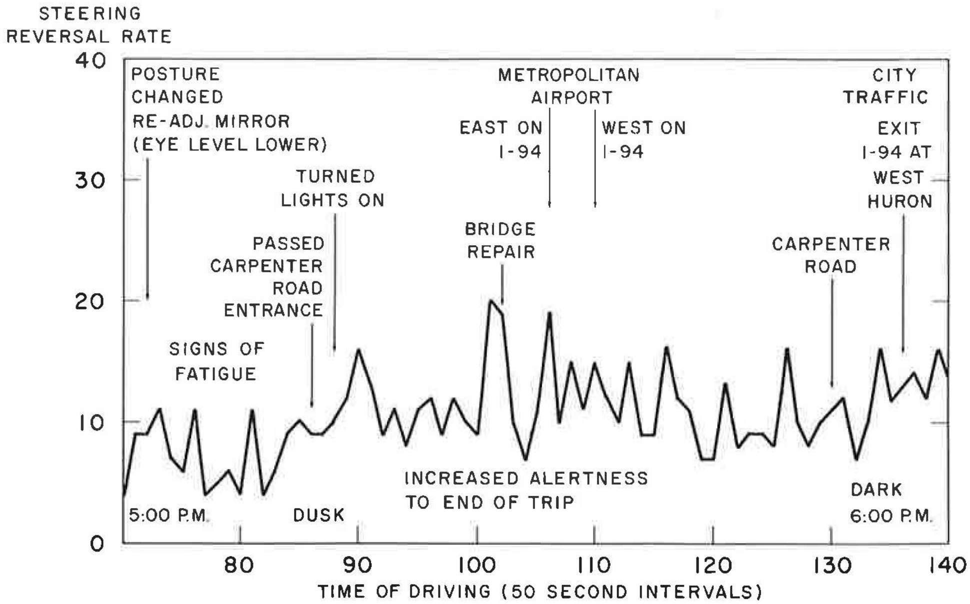


Figure 29. Conclusion of Lansing to Metropolitan Airport to Ann Arbor Test Run, 1-18-62. Driver regained alertness after 80th interval although deviations were generally greater than during first part of run.

Investigation of an Intervehicle Spacing Display

ROBERT L. BIERLEY, Research Laboratories, General Motors Corporation, Warren, Michigan

Unstable spacing between automobiles tends to affect efficient traffic flow adversely. Two experiments were undertaken to test the effect of two types of driver information displays (meters) on vehicle spacing. The first meter showed the driver the actual distance between his car and the car ahead. The second meter showed the driver the algebraic sum of the distance between the two cars and their relative velocity. The latter display increased spacing stability. No marketable device has been designed.

Actual spacing data were compared with theoretical curves obtained from standard car-following laws. A reasonable approximation was obtained.

• TRAFFIC SAFETY and highway capacity are two prime concerns of the traffic engineer. Unfortunately, safety and maximum highway capacity are diametrically opposed in purpose. To achieve maximum highway capacity, vehicles would have to be traveling bumper to bumper, a condition that would obviously be quite dangerous. Conversely, to achieve optimum safety the spacing would be too great to satisfy any reasonable highway capacity requirement. A large number of light signal systems have been proposed to aid the driver following another car. The conventional stop light is the simplest device of this type but it provides only limited information. One solution to this problem would be to automate the driving task fully so that optimum safety and maximum capacity requirements could be maintained. A more economically feasible solution to the problem would be to see if any additional spacing information given to the driver would improve his following performance. This experiment was performed to establish the effect on spacing control of more information about vehicle spacing and relative speed.

Standard car-following laws were used to predict experimental results for display and nondisplay car-following situations.

PROCEDURE

A 1961 Chevrolet was equipped with a car-follower apparatus. The car follower (1) is a device that measures relative speed and distance between two cars. It consists of a reel, attached to the front bumper of a car, holding over 200 ft of piano wire. The wire is fastened to the lead vehicle and a direct current tachometer generator measures the reel-rotating speed which is proportional to the relative speed between the connected vehicles. The number of turns of wire unwound from the reel, as measured by a 10-turn Helipot, indicates the distance between the two cars. A picture and front view drawing of the car follower are shown in Figures 1 and 2. A strain gage accelerometer was mounted in the back seat of the following car. Relative speed, spacing, acceleration, and speed of the following car were all automatically recorded by an oscillograph recorder. The spacing display was mounted on the left side of the front hood of the following car so as not to interfere with vision and yet placed so that only accommodation changes would be necessary when looking at the lead car or the display. A photograph of the indicator mounted on the car is shown in Figure 3.

To test the effectiveness of the spacing display, driver performance was measured with and without additional information. Two identical experiments were performed.

Paper sponsored by Committee on Road User Characteristics.

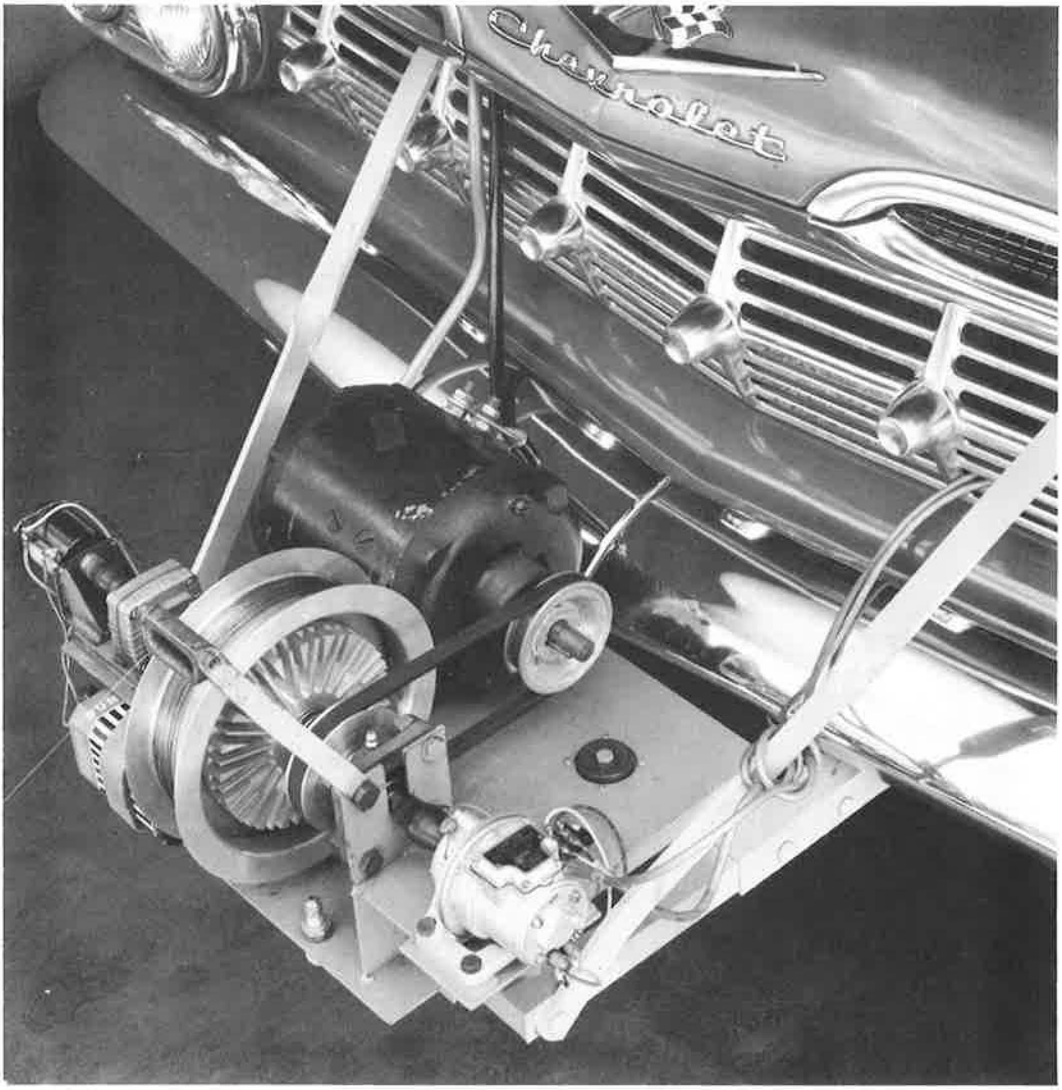


Figure 1. Car-follower apparatus.

The display used in the first experiment was simply a meter which indicated spacing between the two cars from 0 to 160 ft. In the second experiment, the same meter was used with the relative speed between the two cars algebraically added to the relative spacing signal. Full scale for the meter was 0 to 160 ft and ± 6 mph. This produced more exaggerated changes in the meter pointer in response to changes in relative spacing between the two vehicles. This is normally called first-order or velocity-aided information. Figure 4 shows representation of the two displays.

For the spacing display, the output is 0 at a spacing of 80 ft and the pointer moves up the scale as the distance decreases (Fig. 5). The display is analogous to a speedometer indicator that the driver is asked to keep in the center. When it moves up scale, he must reduce speed and vice versa.

In the case of the aided display, the velocity is added in the proper sense to provide anticipatory information. In these experiments the gains were set to produce full-scale positive deflection (from zero center) with $X_1 = 0$ or $X_1 = 6$ mph; i.e., $K_1 = 0.0125$ ft and $K_1K_2 = 0.1667$ per mph.

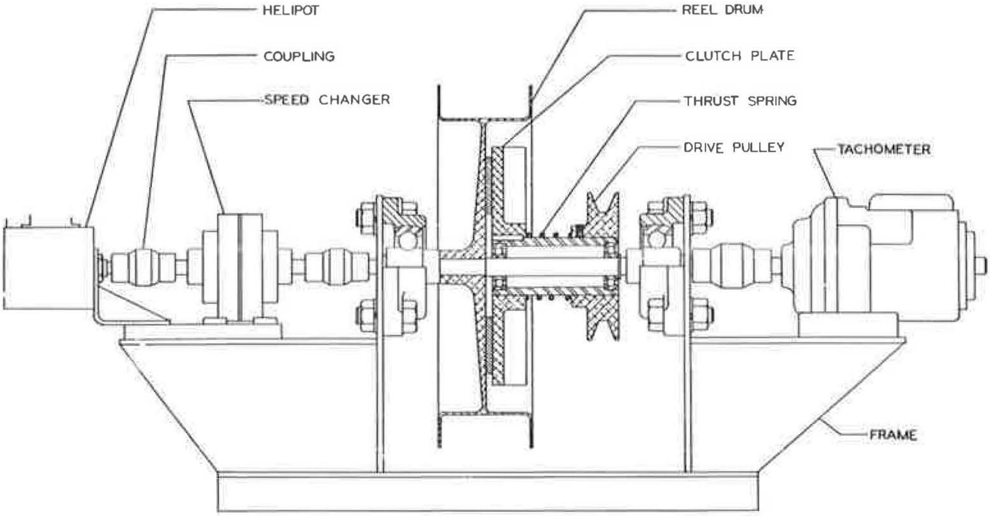
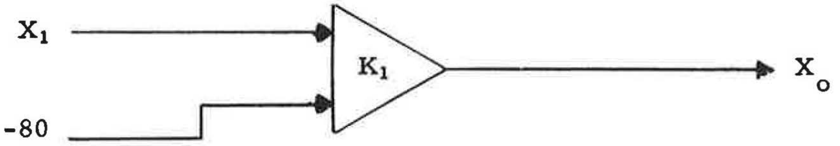


Figure 2. Front view drawing of car-follower apparatus.

Figure 3. Indicator mounted on car.

Zero-Order or Spacing Display

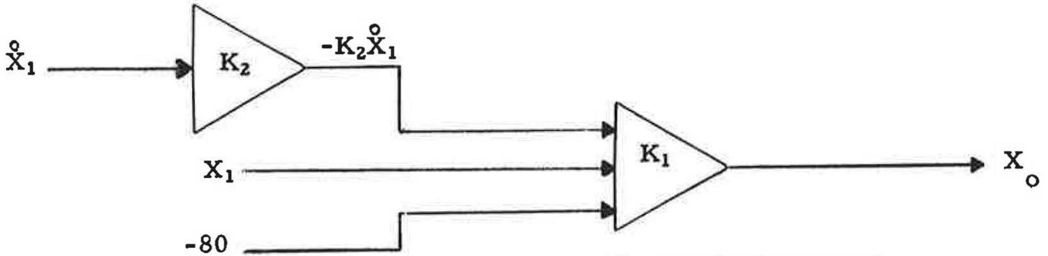


X_1 = intervehicle spacing

X_o = output displacement of zero-centered meter

$X_o = K_1\ (80 - X_1)$

First-Order or Velocity-Aided Spacing Display



X_1 = relative speed

$X_o = K_1\ (80 - X_1 + K_2\mathring{X}_1)$

Figure 4. Representation of the two displays.

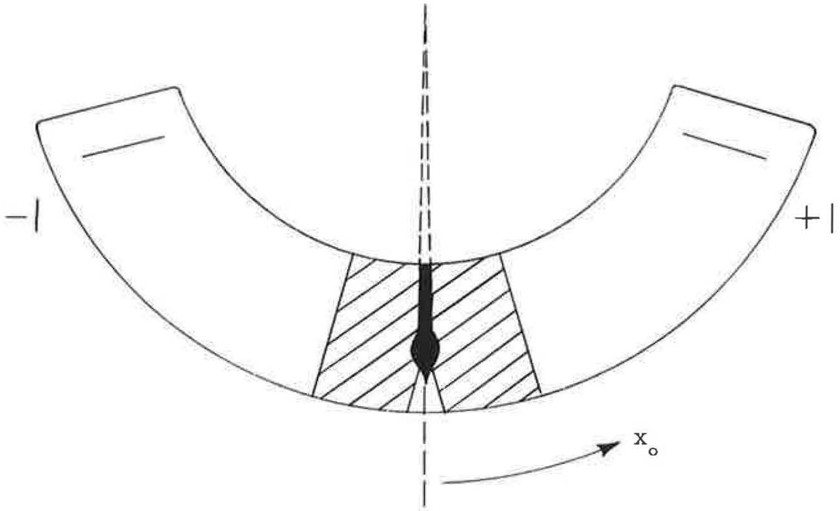
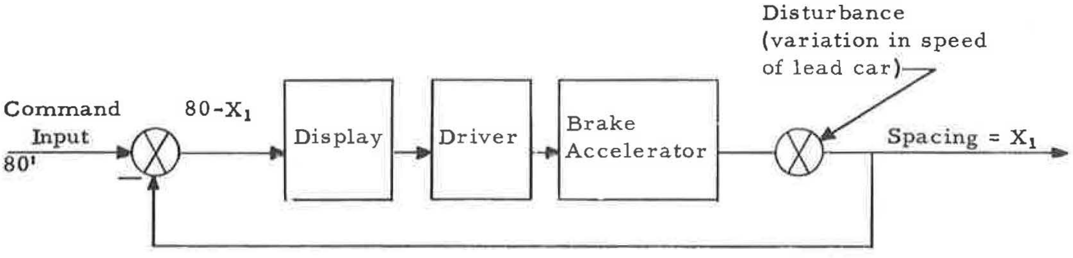


Figure 5. Display face.



$E = 80 - X_1$

Figure 6. Compensatory display.

The prime advantage of aiding is that the display gives the appropriate derivative terms to provide the driver adequate warning of approaching spacing error. Experimental evidence indicates that a compensatory display should be used in preference to a pursuit display when the system is quickened or aided (2, 3). Both displays are of a compensatory nature in that the driver is provided the error signal and attempts to keep the pointer in the center of the red zone. Any change from the center of the red zone is interpreted as error (E). Figure 6 shows the form of the compensatory display.

The test track at the General Motors Technical Center was used for both experiments. The test track is 1 mi in length and one trip down the straightaway is defined as a trial. Drivers were given two practice trials with the meter to familiarize themselves with its operation. Three variations in lead car behavior were used: constant speed trials (in which the lead vehicle maintained a speed of 45 mph), acceleration trials, and deceleration trials. Both the acceleration and deceleration trials were started at 45 mph and then the lead vehicle at some random point on the test track accelerated or decelerated at 3 ft per sq sec until a speed change of 10 mph had occurred. The lead vehicle then maintained the new speed until the end of the trial. The brake lights of the lead vehicle were disconnected so that they would not influence the driver's judgment of relative speed change. A balanced design has been incorporated to eliminate possible experimental bias. The actual order of presentation is given in Table 1.

One-half the drivers received the preceding order of presentation, and the other half received the conditions ND and SD interchanged. The drivers were told that they were to keep the pointer of the meter in the center of the red zone, which was 80 ft. They were told to treat the display as additional information and to use it as often or as little as they needed to maintain the 80-ft spacing. During the nondisplay trials, the drivers were spaced at 80 ft before records were taken and then the display was turned off. Twelve drivers were used in each experiment. The lead car driver was the same for both experiments as was the lead vehicle.

RESULTS

It was hypothesized that a spacing display should improve driver-following performance. Specifically, it was believed that reaction time to changes in lead vehicle be-

TABLE 1

ORDER OF PRESENTATION[a]

Trial No.	1	2	3	4	5	6	7	8	9	10	11	12
Direction	N	S	N	S	N	S	N	S	N	S	N	S
Condition	NDA	SDB	SDC	NDC	NDB	SDA	SDA	NDB	NDC	SDC	SDB	NDA

[a] ND = no display; SD = spacing display; N = north; S = south; A = constant speed; B = acceleration; C = deceleration.

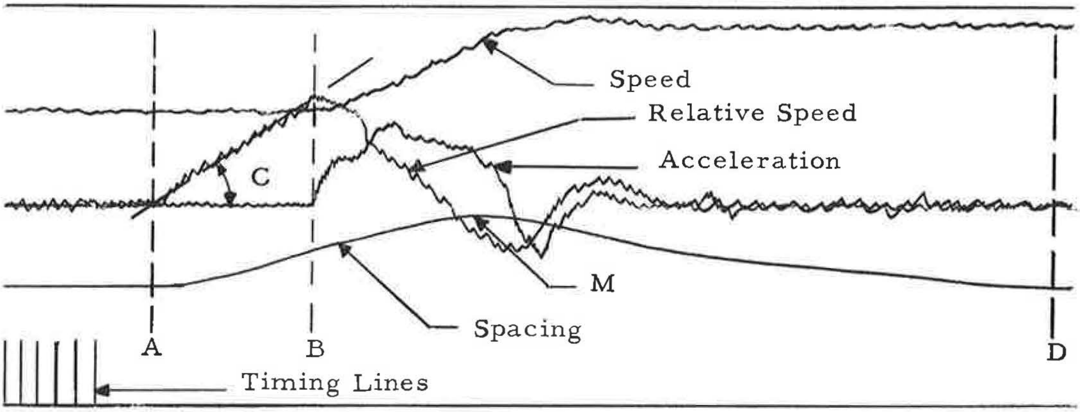


Figure 7. Typical oscillograph record.

havior should decrease, and that maximum spacing change should be reduced. Furthermore, not only should the average spacing error be reduced but the variability in spacing should also be less. A typical oscillograph record of an acceleration trial is shown in Figure 7.

At point A the lead car accelerated at the rate C, which is the slope of the relative speed curve. (Slope of the relative speed curve is only the first car acceleration if the following car speed is constant.) At point B the following car accelerates in response to the lead vehicle. The reaction time or lag time is the time elapsed from A to B. An initial spacing reading is taken at point A and the amount of maximum spacing change in relation to initial spacing is measured at M. Fifteen data points were sampled at equal intervals from A to D which was 20 sec for the acceleration and deceleration trials and the middle 40 sec of the constant speed trials. From some preliminary pilot data it was determined sampling more frequently did not give any additional information.

Experiment Using Spacing Display

It was hoped that the average initial spacing and average acceleration and deceleration rates for display and nondisplay trials would not differ so that unbiased comparisons could be made. Average initial spacing was compared for display and nondisplay trials over all test conditions with no statistically significant difference noted (Table 2). No statistically significant differences were noted for acceleration and deceleration rates for both display and nondisplay trials (Table 3).

An analysis of variance (4, 5) yielded no significant difference in reaction time between display and nondisplay trials for either deceleration or acceleration conditions. Furthermore, no differences were found to exist between acceleration and deceleration conditions (Table 4).

TABLE 2

AVERAGE INITIAL SPACING OVER ALL TEST CONDITIONS

Type of Trial	Spacing (ft)			
	Constant Speed	On Acceleration	On Deceleration	Combined
Display	84.9	87.8	84.0	85.5
Nondisplay	86.4	88.8	87.8	87.6

Similarly, another analysis of variance revealed no significant differences in average maximum spacing change for display vs nondisplay trials (Table 5). There was, however, a significant decrease in average absolute spacing error collapsed across all conditions for the display vs nondisplay trials, $P < 0.025$. Initial spacing was used as the base for determining absolute spacing error (Table 6).

As hypothesized, there was an over-all reduction in the spacing variability for the display trials of 25 percent, with the greatest improvement under the constant speed condition. The three curves (Figs. 8, 9, and 10) show the average absolute spacing error with respect to time for display and nondisplay trials. Virtually no improvement was made during the deceleration trials. The acceleration curves show no differences up to the 6- or 7-sec mark. This would be expected because there was no difference in mean reaction time, average maximum spacing change, and mean acceleration rate for the display and nondisplay trials. However, the "intensity" of the correction for the display trials seems to be much greater than that for the nondisplay trials, resulting in a wide separation at the end of the 20-sec time period. The curves for constant speed show an increase in spacing error with time for both the nondisplay and display trials. However, the error is approximately twice as great for the nondisplay trials at the end of the 40-sec time interval.

It is concluded, then, that the spacing display significantly reduced the average absolute spacing error, with an even greater reduction in the error variability. However, it did not affect the reaction time or the maximum spacing change. In other words, under the best conditions, the drivers were just as sensitive to changes in the lead vehicle without the display as with the display.

TABLE 3

AVERAGE ACCELERATION AND DECELERATION OVER ALL TEST CONDITIONS

Type of Trial	Average Rate (ft/sec^2)	
	Acceleration	Deceleration
Display	2.96	3.23
Nondisplay	2.96	3.06

TABLE 4

AVERAGE REACTION TIME

Type of Trial	Avg. Reaction Time (sec)		
	Accel.	Decel.	Combined
Display	1.58	1.59	1.58
Nondisplay	1.72	1.59	1.65

TABLE 5

AVERAGE MAXIMUM SPACING CHANGE

Type of Trial	Average Maximum Spacing Change (ft)			
	For Constant Speed	On Acceleration	On Deceleration	Combined
Display	11.4	30.9	20.6	21.0
Nondisplay	14.6	34.0	19.8	22.8

TABLE 6

AVERAGE SPACING ERROR

Type of Trial	Average Spacing Error (ft)			
	For Constant Speed	For Acceleration	For Deceleration	Combined
Display	5.1	15.6	9.8	10.2
Nondisplay	7.6	19.9	10.0	12.5

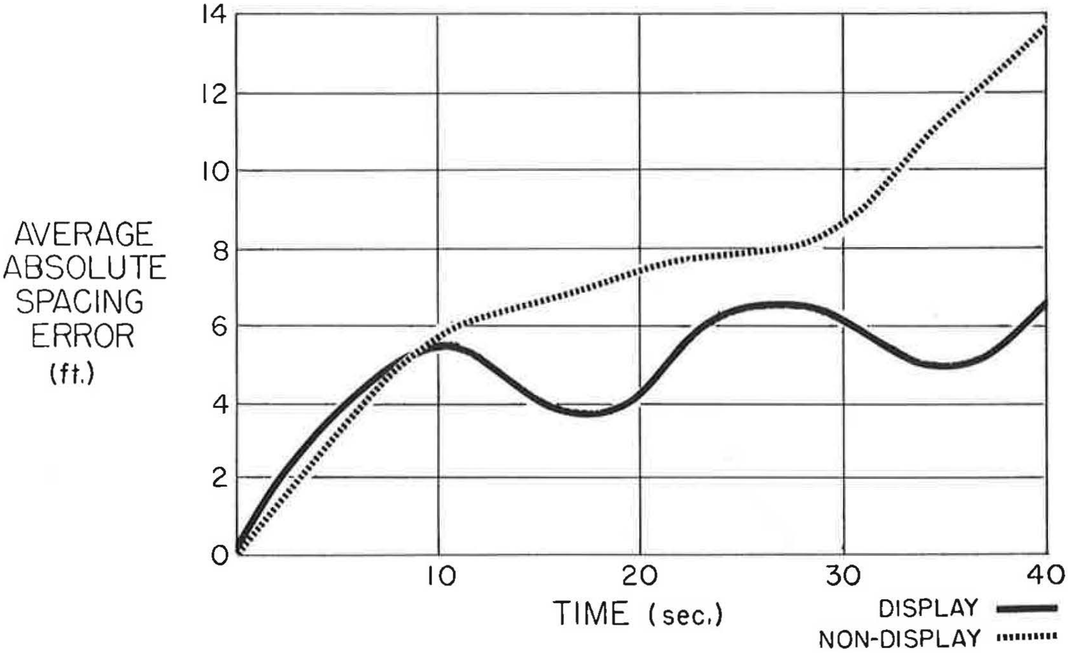


Figure 8. Average absolute spacing error vs time for display and nondisplay trials at constant speed.

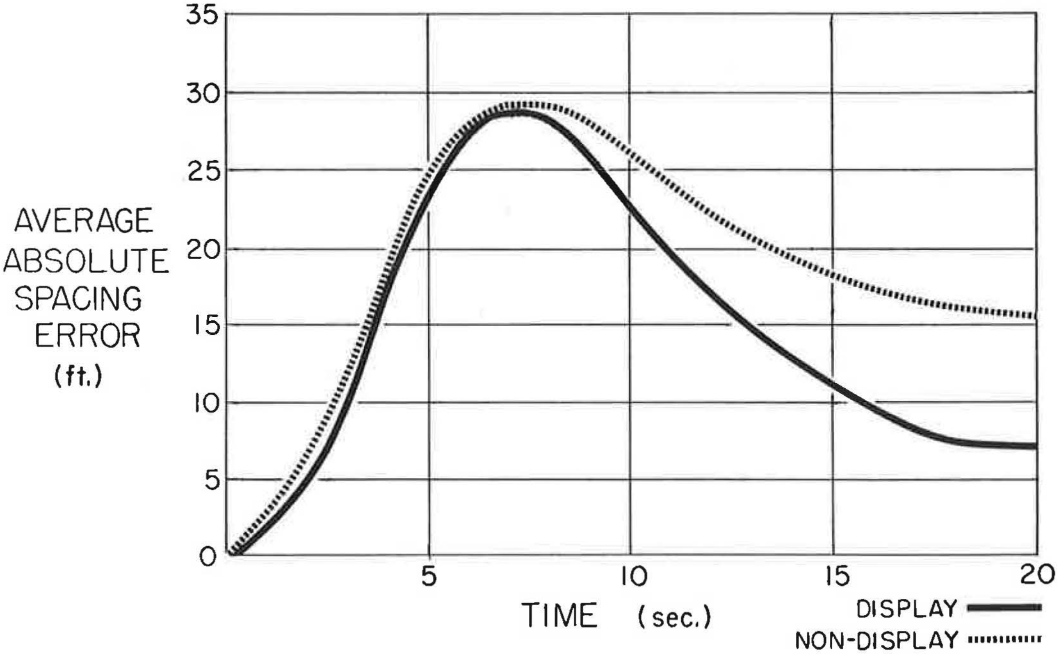


Figure 9. Average absolute spacing error vs time for display and nondisplay trials at acceleration.

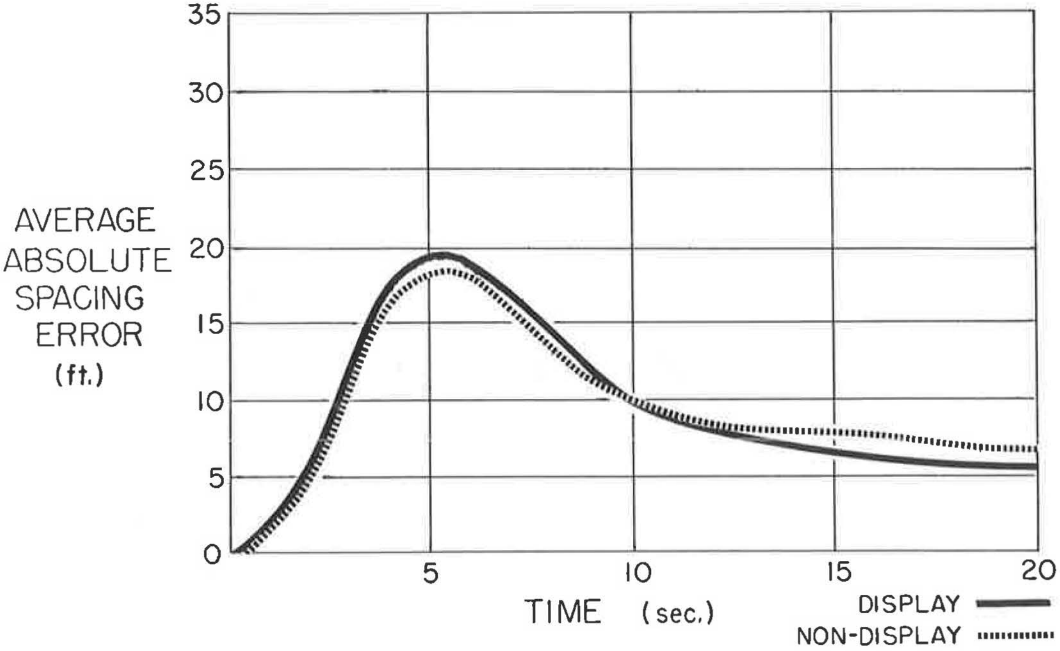


Figure 10. Average absolute spacing error vs time for display and nondisplay trials at decelerations.

Experiment Using Velocity-Aided Spacing Display

Again, it was determined that no significant differences existed between average initial spacing for the display and nondisplay trials (Table 7). The average acceleration and deceleration rates did not differ and compared favorably with the average values obtained in the first experiment (Table 8).

An analysis of variance was performed on the reaction time data and the average reaction time for the display trials was found to be significantly less than for the nondisplay trials, $P < 0.005$ (Table 9). The interaction between displays and conditions was significant at the 0.05 level of confidence. This means that the display had a greater effect on reaction time for acceleration trials than it did for deceleration trials. Again, no significant differences were noted between the acceleration and deceleration conditions.

The average maximum spacing change was significantly reduced ($P < 0.005$) for the display trials as would be expected by the decrease in reaction time. The nondisplay results are nearly the same as those of Table 5, further verifying the consistency of the tests (Table 10). Again, as with the spacing display, a significant decrease in

TABLE 7

AVERAGE INITIAL SPACING

Type of Trial	Average Initial Spacing (ft)			
	Constant Speed	Acceleration	Deceleration	Combined
Display	81.0	82.1	80.5	81.2
Nondisplay	81.0	86.9	81.3	83.1

average spacing error for the display trials ($P < 0.025$) was found to exist. Once again, the nondisplay results (Table 11) may be compared with Table 6.

An even greater reduction in spacing variability for the display trials was shown for the velocity-aided spacing display, 47.5 as compared with 25 percent for the position display. Decreases in variability of 71.5, 60 and 25 percent were observed for the constant speed, acceleration, and deceleration conditions, respectively. The three average absolute spacing error curves with the velocity-aided spacing display are shown in Figures 11, 12, and 13. For the acceleration condition the peak for the display trials is significantly less than for the nondisplay trials. This is true to a somewhat lesser degree in the deceleration trials. During the constant speed condition, spacing error again increases with time for the nondisplay trials, while leveling off for the display trials.

TABLE 8

AVERAGE ACCELERATION RATE

Type of Trial	Avg. Accel. Rate (ft/sec^2)	
	Acceleration	Deceleration
Display	3.09	2.96
Nondisplay	2.85	2.98

TABLE 9

AVERAGE REACTION TIME

Type of Trial	Avg. Reaction Time (sec)		
	Accel.	Decel.	Combined
Display	1.11	1.34	1.23
Nondisplay	1.68	1.68	1.68

One interesting result of both experiments was the qualitative way the drivers reacted to inputs of the lead vehicle. The response time was virtually independent of the different acceleration and deceleration rates. Although the average acceleration and deceleration rates were approximately 3 ft per sq sec, rates ranging from 2 to 4 ft per sq sec were experienced. The correlation between acceleration rate and response time was essentially zero. This result agrees with previous research which found response time relatively independent of the slope of the ramp input (6). Undershooting (under-correcting) by the drivers was more common during deceleration than acceleration conditions. During the deceleration condition, the driver would remove his foot from the accelerator pedal and, after seeing that the car in front was slowing down at a more rapid rate than expected, then apply the brake. This may be due to the normal cue of the brake lights not being available. In about 30 percent of the acceleration

TABLE 10

AVERAGE MAXIMUM SPACING CHANGE

Type of Trial	Average Maximum Spacing Change (ft)			
	Constant Speed	Acceleration	Deceleration	Combined
Display	7.0	26.3	19.9	17.7
Nondisplay	14.8	32.5	23.0	23.4

TABLE 11

AVERAGE SPACING ERROR

Type of Trial	Average Spacing Error (ft)			
	Constant Speed	Acceleration	Deceleration	Combined
Display	4.0	15.0	9.1	9.4
Nondisplay	7.1	18.8	11.2	12.4

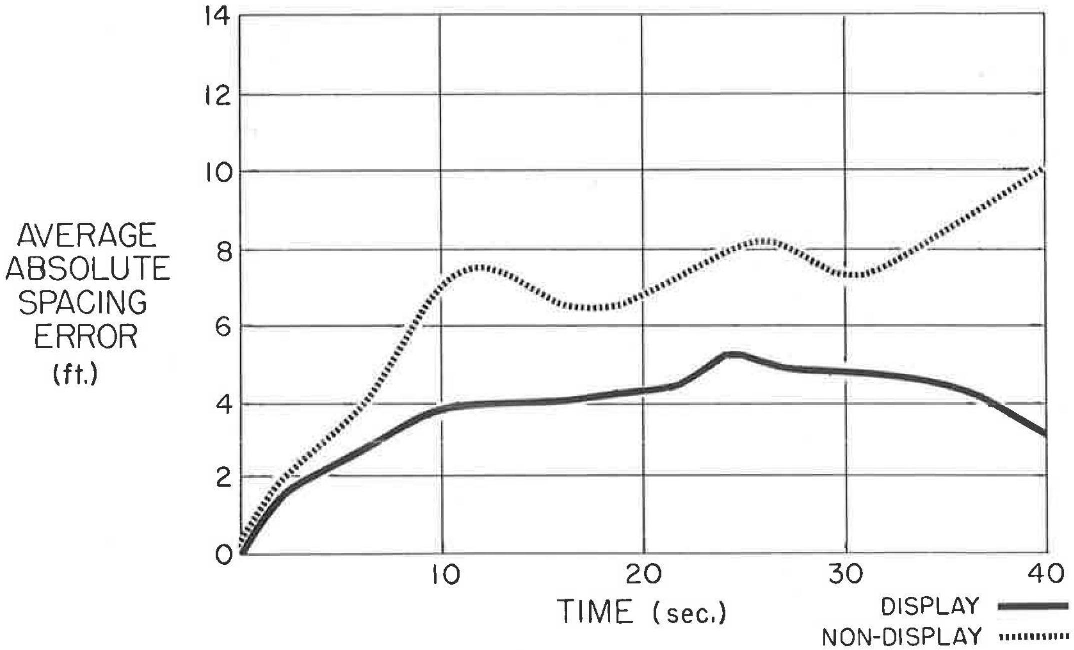


Figure 11. Average absolute spacing error curve with velocity-aided spacing display, for constant speed.

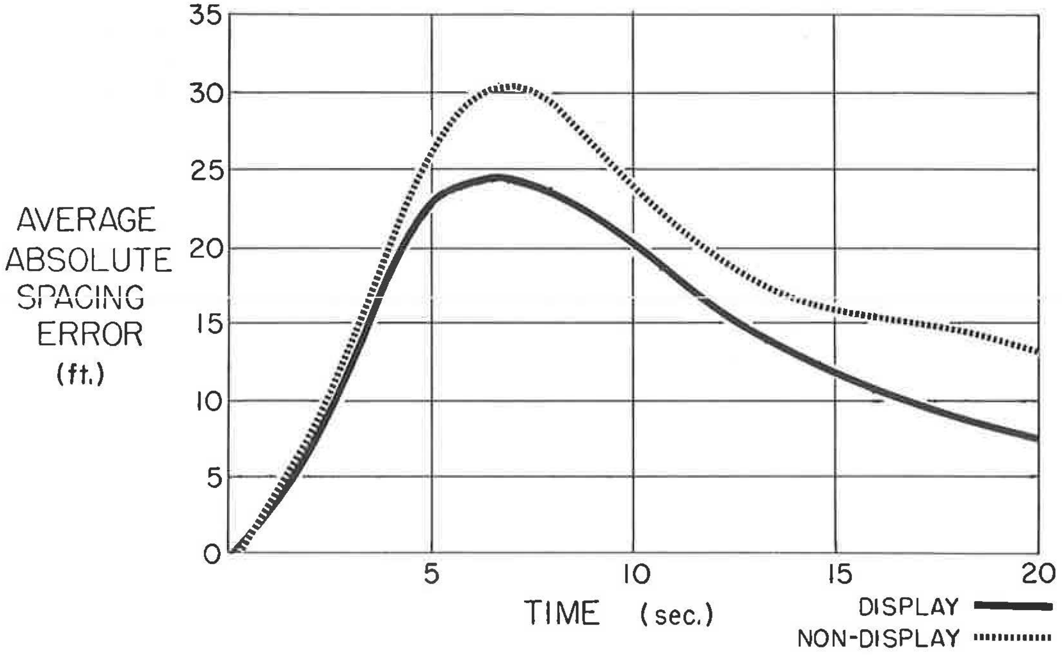


Figure 12. Average absolute spacing error curve with velocity-aided spacing display, for acceleration.

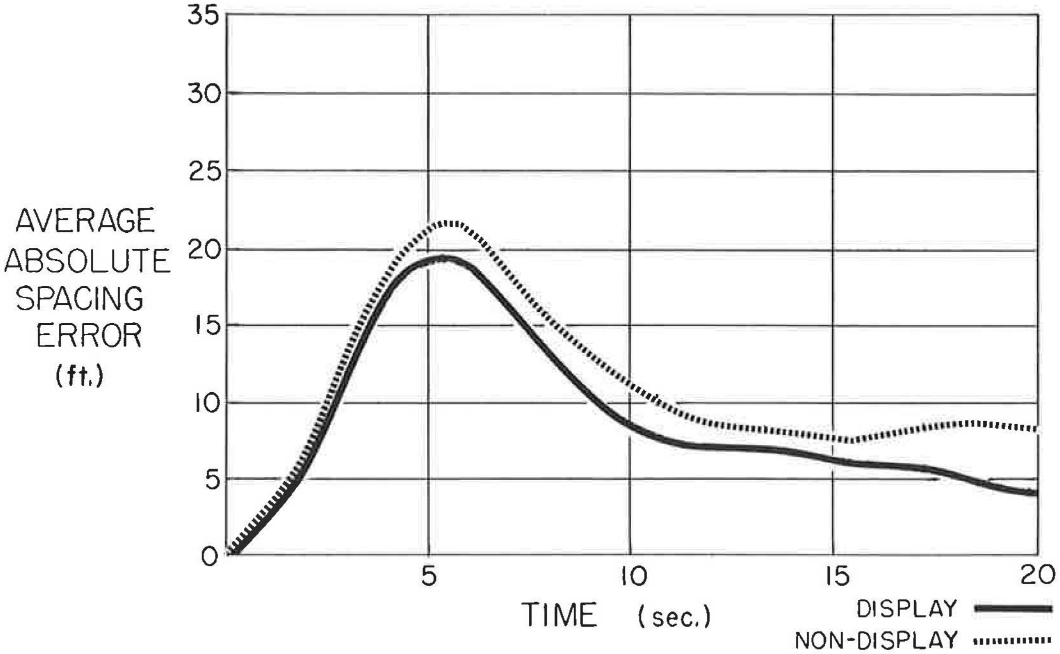


Figure 13. Average absolute spacing error curve with velocity-aided spacing display, for deceleration.

trials drivers made an initial correction and then had to correct harder. This second correction also took place to a lesser degree after initial braking. The percentage of second corrections was significantly reduced for the velocity-aided display trials.

Because both experiments were identical, with the exception of the type of displays used, the nondisplay group's performance should be quite homogeneous. Tests for homogeneity of variance between the two groups of drivers were performed on reaction time, maximum spacing, and average spacing data. The values of F obtained were all nonsignificant. The two groups' variances are said to be homogeneous; that is, they are both assumed to be estimates of the same population variance.

SUMMARY AND CONCLUSIONS

By changing the position display into a velocity-aided spacing display, following performance was significantly improved. Not only was there a greater reduction in the average spacing error variance, but significant decreases in maximum absolute spacing change were observed. Also, driver reaction time was reduced markedly. By analyzing the reaction time data a little further, the total reaction time is found to be made up of a number of different reaction times, such as detection time (the time it takes a driver to notice a change in lead vehicle behavior), decision time (the time involved in deciding whether to step on the gas or to use the brake), and simple response time (time elapsed from the decision until the actual response is initiated). There are some relatively accurate estimates of these reaction times from previous research (7); for example, decision time for a two-choice situation is usually between 0.25 and 0.30 sec; simple response time is normally between 0.19 and 0.26 sec (an additional 0.19 sec is involved in moving the foot from the gas pedal to brake (8). Therefore,

$$\text{Total Reaction Time} = \text{Detection Time} + 0.225 + 0.275 = \text{D.T.} + 0.50$$

and for deceleration,

$$\text{Total Reaction Time} = \text{Detection Time} + 0.225 + 0.275 + 0.19 = \text{D.T.} + 0.69$$

TABLE 12

DETECTION TIME

Type of Time	Type of Rate	Detection Time (sec)	
		Velocity-Aided Display	Nondisplay
Total response	Acc.	1.11	1.68
	Dec.	1.34	1.68
Detection	Acc.	0.61	1.18
	Dec.	0.65	0.99

Detection time is the only place where an immediate improvement in driver response can be made with indicators of the type used here. The improvement made by the velocity-aided display is shown in Table 12 (assuming the preceding average decision and response times).

The reduction in detection time for the acceleration condition was 48 percent, whereas the detection time for deceleration was reduced by 34 percent.

The particular experiments described have attempted to see if driver-following performance could be improved, even under the best possible conditions. The driver was given a specific task (to maintain an 80-ft spacing) and was told to perform as well as he could. It was felt that if an improvement in performance could be realized when the driver was performing optimally that any device that could be developed would be worth even more for the normal driving situations. Because the veloctiy-aided spacing display improved following behavior significantly, it is feasible to assume that a device similar to it would be a great help in limited-access highway driving situations. Although the display used in the present experiment was of a visual nature, this does not mean it is the best possible means of displaying spacing information. No attempt was made in the current test to establish optimum values of the constants K_1 and K_2. Further research is necessary to establish the effectiveness of different displays. Because the visual channel is quite overloaded, an obvious alternative would be a display that utilizes one of the other sense modalities, such as audition. Finally, some practical means of determining spacing and relative speed must be found.

THEORETICAL IMPLICATIONS

A number of theories have been proposed concerning single-lane traffic following in which the driver responds to stimuli from cars in front or behind him (9, 10, 11, 12). These follow-the-leader theories can be represented by a differential-difference equation:

$$\text{Driver Response} = \text{sensitivity} \times \text{stimulus} \qquad (1)$$

The driver response to some stimulus can be either acceleration or braking. Previous research has been quite successful in establishing a high correlation between the acceleration response of a driver and the relative speed between the following and lead vehicles (10). The equation describing the following vehicle's acceleration is

$$\ddot{X}_F\,(t + T) = \lambda\,[\,\dot{X}_L\,(t) - \dot{X}_F\,(t)\,] \qquad (2)$$

in which

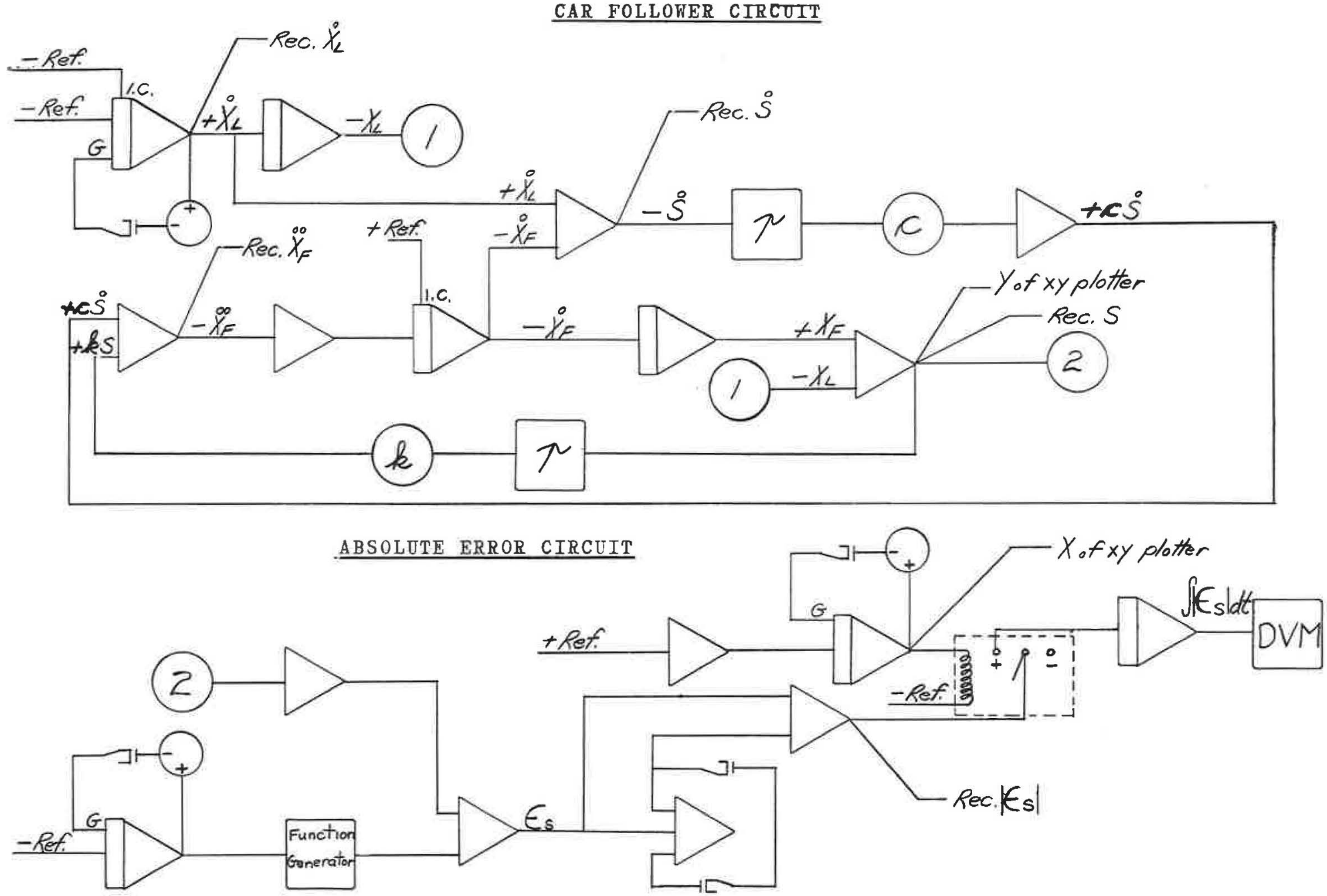
$\dot{X}_L$ = speed of lead vehicle;

$\dot{X}_F$ = speed of following vehicle;

λ = sensitivity; and

T = reaction time of the driver-car system.

It has been shown that if λ is a constant a fairly good approximation to the actual data



CAR FOLLOWER CIRCUIT

ABSOLUTE ERROR CIRCUIT

Figure 14. Circuits for car-following law and measurement of absolute error.

can be obtained by the car-following law (Eq. 2). An even better approximation to the data can be made by assuming that λ is inversely proportional to the spacing (11, 12).

Because the initial spacing was relatively constant in the present experiment, Eq. 2 was chosen with λ being a constant to describe the driver's response. It is believed that the driver is using two types of information in responding to changes in the lead vehicle. Not only does the driver react to relative speed differences but he corrects for changes in relative spacing:

$$\ddot{X}_F (t + T) = c\,[\dot{X}_L (t) - \dot{X}_F (t)] + k\,[X_L (t) - X_F (t)] \tag{3}$$

in which

X_L, X_F = positions of the two cars at time t; and

c, k = sensitivity constants for relative speed and relative spacing, respectively.

If $\dot{S}$ and S represent the relative speed and relative spacing terms in Eq. 3, then

$$\ddot{X}_F (t + T) = c\,(\dot{S}) + k\,(S) \tag{4}$$

An analog simulation of Eq. 4 was made and compared with the actual spacing data in the present experiment. Two circuits (one for the car-following law and the other for measuring absolute error) are shown in Figure 14. The absolute error circuit compares the theoretical relative spacing from the car-following law with the actual relative spacing data obtained in the experiment. The experimental data are reproduced by using an XY plotter as a function generator. The absolute error $|E_S|$ is cumulated and is displayed in digital form on a digital voltmeter. The initial conditions for the simulation were the same as the actual experiment. In other words, the simulated initial speed of the lead and following vehicles was 45 mph or 66 ft per sec. The lead vehicle accelerated or decelerated at the average rate of 3 ft per sq sec until a 10-mph or 14.7-ft per sec change was reached. The time delays used for the simulation were the same as those in Table 9. Each simulation lasted 20 sec. Values of c and k were varied until the $|E_S|$ was a minimum. The values of c and k which produced the best fit to the experimental data are given in Table 13, in addition to the average error between theoretical and actual relative spacing curves. A change of approximately ± 5 percent in the c and k values does not significantly affect the average error ($|E_S|$).

The values of c were greater for deceleration than acceleration; however, the k values remained fairly constant. Values of c and k were greater for the display curves of acceleration and deceleration than for the nondisplay curves. In other words, the velocity-aided spacing display increased the driver's sensitivity to changes in relative speed and spacing. Figures 15 through 18 show the agreement between the theoretical and actual relative spacing curves.

The value of c is analogous to the damping factor in a physical mass-spring-damper

TABLE 13

AVERAGE ERROR[a]

Type of Trial	Type of Rate	Average Error		
		c	k	$\bar{E}_S$(ft)
Display	Accel.	0.530	0.020	0.74
	Decel.	0.760	0.032	1.08
Nondisplay	Accel.	0.470	0.014	1.02
	Decel.	0.710	0.014	1.73

[a] $(\bar{E}_s) = \dfrac{\int_0^T |E_s|\,dt}{T}$

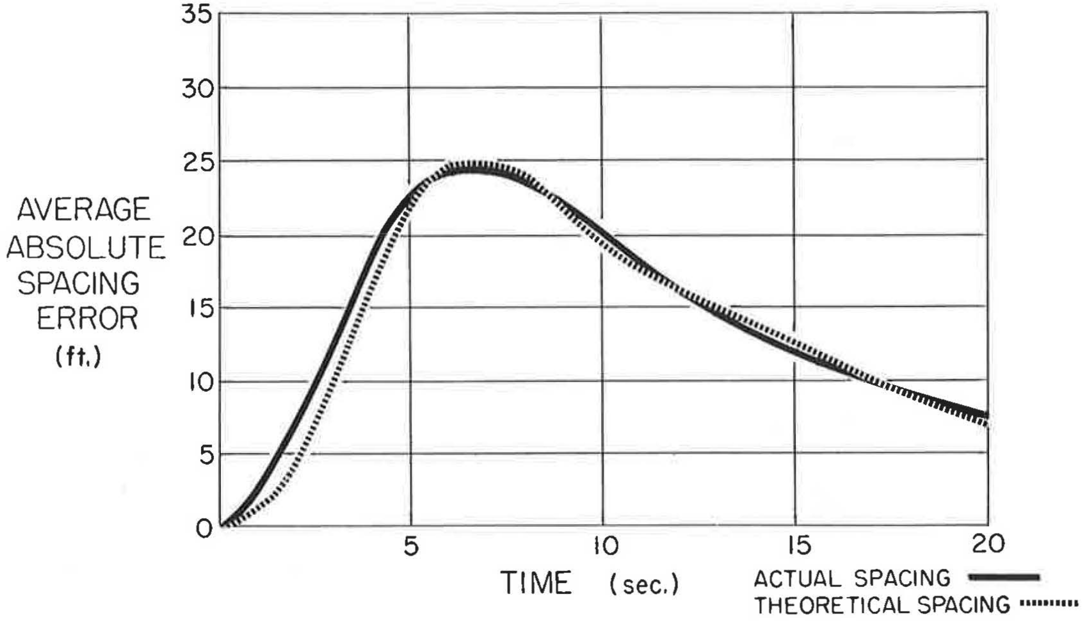


Figure 15. Agreement between theoretical and actual relative spacing curves for acceleration in display trials.

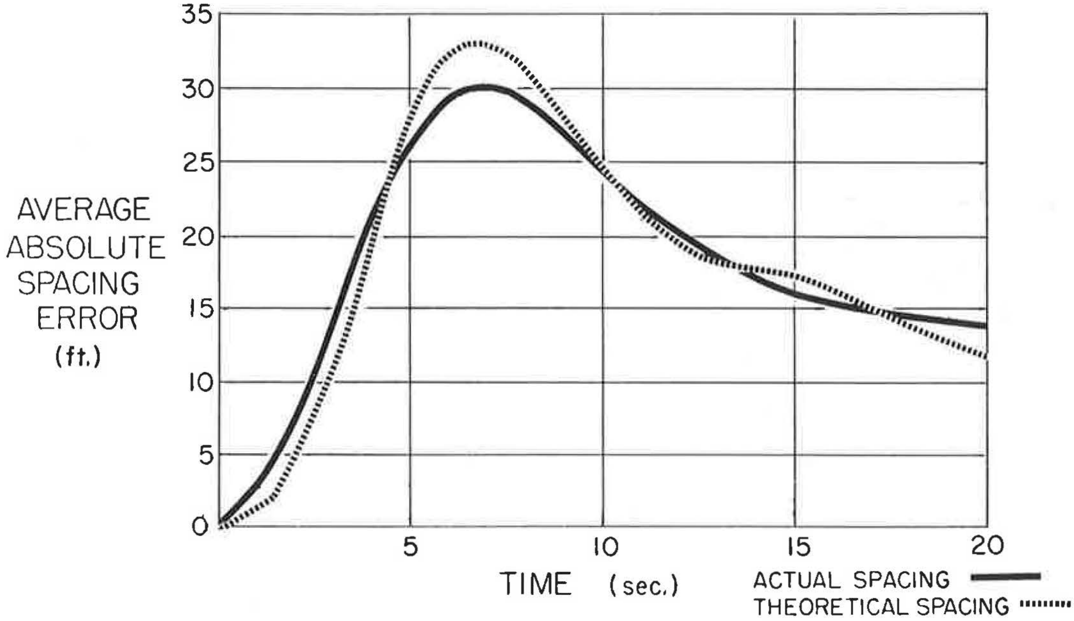


Figure 16. Agreement between theoretical and actual relative spacing curves for acceleration in nondisplay trials.

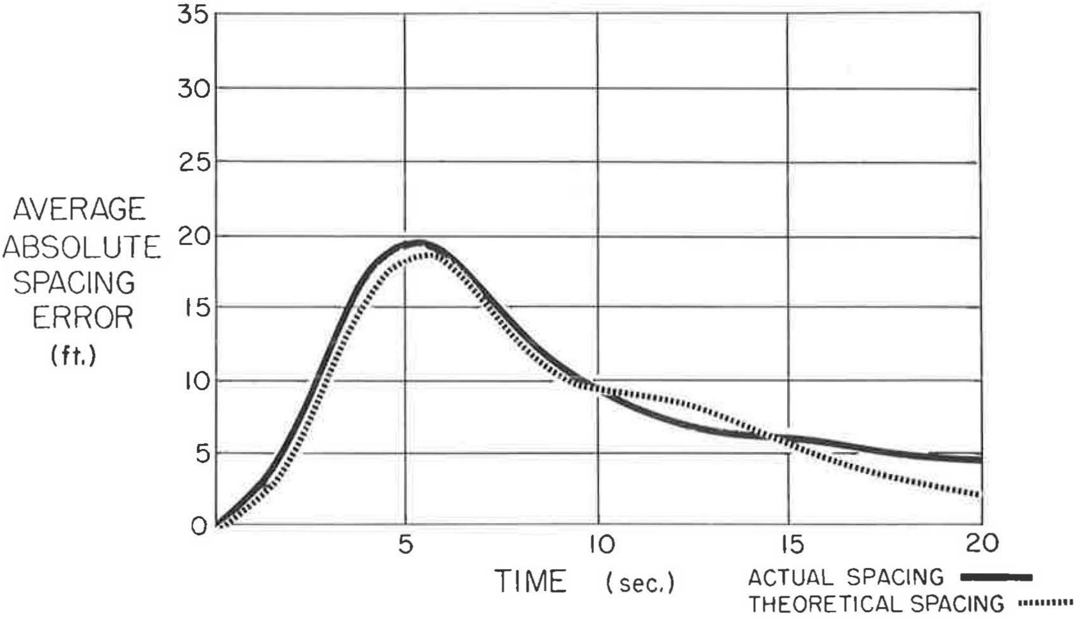


Figure 17. Agreement between theoretical and actual relative spacing curves for deceleration in display trials.

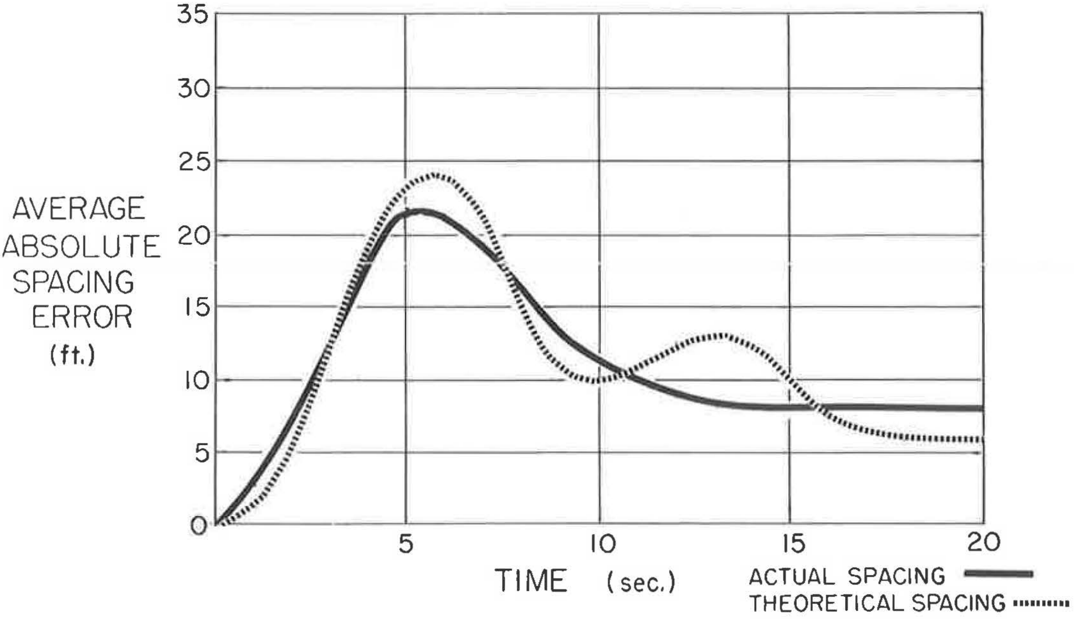


Figure 18. Agreement between theoretical and actual relative spacing curves for deceleration in nondisplay trials.

system and limits the relative velocity between the two cars, whereas the k term is analogous to the spring constant and determines the rate of recovery to initial spacing. Further research will attempt to determine the amount of change in c and k for various initial spacings, relative speeds, and reaction times. Also, the values of c and k for individual drivers rather than average group performance will be obtained.

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Vision at Levels of Night Road Illumination

VIII. Literature 1962

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•CONTRIBUTIONS from the vision literature of interest to the Night Visibility Committee are selected, and as in previous years (82), no attempt is made for complete coverage. Of general interest are Fletcher (46), a new edition of Weston (99), the Duke-Elder series (41), a new set by Davson (34), and a review by Blair (23). Sneller (91) has written a small volume for the beginning driver with one chapter on rules for night driving. The reports of the National Committee in France summarize much of what is known about seeing at night driving luminances (18, 66, 67). Waldram's analyses are summarized (96) and there is an interesting attempt to evaluate the Smith-Cummings-Sherman driving-seeing system (20). The evaluations vary with the ratings of the individual judges, and there is an interesting discussion of accidents of professional drivers.

ILLUMINATION

Rex (81) appeals again for more light on highways, for at least as much as used in some European countries. DeBoer (35) states the essentials of road lighting and recommends 0.6 fL as a compromise between the desirable and reasonable cost. Connolly (32) summarizes some of the recent work on automobile lighting, including the new amber turning lights. Increased fixed lighting does reduce accidents (59). Harrington and Johnson (54) describe an improved instrument for measuring pavement reflectance.

Glare fatigue is explained in a British medical journal (1) as due to fatigue from the eyelid and associated muscles trying to hold the lid partially closed to reduce the dazzle. Meyer (73) discusses glare and the scattering of light within the eye. New measurements of the wavelength transmissions of the ocular media are available (103). A median of 10 to 20 ft reduces glare from low beams but must be 70 ft or more to reduce discomfort from high beams (62). Lighting arrangements for the reduction of glare are discussed by Foote and Kaercher (47). Hofer (56) advocates an aluminum glare screen. Contrast and seeing with poor lighting are discussed by Aulhorn (19). Finch (43) recommends flat luminaires to delineate the road edge.

The pupil regulates the light entering the eye and because of its own thickness shuts off light from wide angles (61). Weale (98) shows the role of the crystalline lens in the aging eye. The smaller pupil and increased lens absorption may account for the poorer vision of old age rather than changes in dark adaptation. From 2.5 to 3 times more light is needed for older people (97). Weale also suggests that the Stiles-Crawford effect can include the rods of the retina.

Meeting distance vision measured by Johansson (63) in Sweden reveals that symmetrical low-beam headlights are more efficient for seeing an object just off the road than are asymmetrical lights.

Motion pictures of different types of signs have been made on the road and shown to various groups to learn the relative seeability of different designs. This type of analysis by Burg and Hulpert (31) should be extended into night driving conditions. A warning is given against flashing and dazzling repetitive stimuli which cause fatigue, are disturbing, and may even have a hypnotic effect on some drivers (2). This is regarded as especially true at night when more effort is required because of the unusual contrasts. White posts, guardrails, broken lines, or other markers which flicker should be avoided.

Paper sponsored by Special Committee on Night Visibility.

Elstad (42) reports on sign luminances and finds ambient levels of 0.1 fL in the country, 0.4 fL in suburban, and 4 fL in urban regions. High beams give 66 ft and low beams 58 ft visibility distance per inch of height of a standard letter. U.S. signs with place names were judged better than British or continental signs for simple junctions, but the continental diagram signs were preferred for complicated intersections (15).

ACUITY AND CONTRAST

Simmons (89) describes a visibility meter that reduces a 2^0 field to threshold contrast without changing the level of adaptation of the eye. Boynton and Miller (27) consider the following mechanisms for dark adaptation: increase in photo pigment, neutral adaptation of single receptors, increase in retinal summation areas, increase in retinal summation times, and a decrease in the number of coincident quanta. Each shows a different effect on the curve for adaptation. A sudden change of luminance disturbs vision in accordance with the relative levels, and contrast must be increased to avoid loss of seeing.

Luria and Kinney (69) have measured some effects on adaptation from short exposures to increased light, although at much lower levels of illumination than usually prevail on highways. Fry (48) reports a device for measuring transient adaptation. The question of recovery from glaring effects from oncoming automobile lights remains unanswered. Hallet et al. (53) describe the sensitivity of different retinal areas to brief flash stimulation, and the variation that they found questions the validity of some of the intensity-area laws. Roper (84) stresses the need for more information on acuity and contrast as seen at night driving luminances. Marimont (72) proposes a model to explain the apparent greater contrast from increased luminance.

Wolf (101) finds that both central and peripheral flicker fusion decrease with age, and Domey (39) reports improved predictability of age and dark adaptation when flicker measurements are included in the equation. The Biophotometer has been modified by the addition of a fixation control (70).

The size constancy question is being investigated by Anstis (17) through the effects of the position of the eye and movements of shadows on a screen. The problem is related to night driving and further work could be useful. Speaking of perception problems, Bloomer (24) indicates that increasing stress and stimuli can increase vigilance and reduce accidents—a consideration for planning design and education.

Variations of depth of focus of the eye and spherical aberration with pupil size need to be considered when prescribing spectacles and discussing acuity (3, 16). The out-of-focus blurring of retinal images and two-point contrast thresholds are measured by Ogle (77).

DYNAMIC AND SPACE VISION

Fiorentini (45) has summarized the dynamic characteristics of the vision process. Brownstein and White (28) show that at a forward acceleration of 1g, about twice as much contrast is needed for seeing from 1 to 0.03 fL. Vision does not black out during movement of the eyes (95). Latour (65) demonstrates wide variations in thresholds for perceiving flashes of light from eye movements. Vertical stripes must be brighter to be seen by the laterally moving eye, and horizontal stripes are seen under these circumstances better than vertical stripes. Vibrations of 3 to 4 cps adversely affect reading dial instruments. Vibration rates from 2 to 7 cps should be minimized, and at frequencies of 5 cps, higher contrasts are required for seeing (40). Low frequency vibrations are reported to decrease contrast thresholds and high frequency movements to increase thresholds (64). The frequency response of compensating eye movements fixating a static target is higher than the frequency response of pursuit movements by still subjects fixating a moving target. This is believed due to otolithic stimuli added to the visual sensation (52).

A uniform visual field free from cues fails to maintain the focusing mechanism of the eye. The restricted fields at night increase nearsightedness of some eyes. Heath (55) has measured night myopia with both objective and subjective methods for periods of 4 hr and finds the myopia due to a general breakdown of the focusing mechanism; as large fluctuations (0.75 Diopter), changes in level (1D) and drifts (1.5D) occur continuously and irregularly. Fincham (44) reports that accommodation and convergence relations also breakdown under similar conditions of view. Both researches question the correcting of vision for night myopia. However, an individual may have a mean focusing amplitude and correcting for this amount of myopia does help those drivers. The French (18) report recommends that glasses large enough to cover the peripheral fields be used when correcting night myopia.

COLOR

The French (18, 67) study also recommends adding shape differences to color differences to make signals less misunderstandable. Undue amounts of noise affect the visual fields and the color fields are first affected according to Benkö (22).

R.G. Fry (50) states that yellow glasses are scarcely useful for motorists because of the small amount of blue and blue-gray contrast on roads. Verriest et al. (94) discuss the visual loss from withdrawal of the short wavelength light by use of colored glasses. This may explain why wearing yellow glasses during the day does not help night driving vision. A Russian experiment with colored asphalt roads is reported (93). So far, no results seem to have been reported from this use of colors under adverse conditions of dense fog, heavy rain, or snow on moonless nights.

Davids (33) tells how color-deficient men see a green traffic light as white, ask why the amber is so like the red light, why not change the red to a scary blue seen by all men, why there is a program to replace easy-to-see black-on-yellow signs with less visible white on red and why some car makers now use rear lights which look as big as front lights. Fortunately only a few men are so handicapped, yet these pleas should be considered when color-coding roads and signs. Breckenridge (29) considers U.S. signal lights and standardization. Huber (57) discusses the use of colors on the ramps of the experimentally color-coded exchange in Minnesota.

DRUGS

Sloan (90) has revised and indexed his previous paper on drug effects on vision, and a summary (4) of the possible effects of drugs on driving is now available. Dix (38) has re-examined the question of improving dark adaptation with large amounts of vitamin A and finds that there is little improvement. On the other hand, Masci (73) reports improved ability to perceive targets after small doses of caffeine. Long treatments with chloroquine can result in degeneration of the retina (79). The uncontrolled use of many drugs could very well lead to visual distrubances that could trigger an accident. Many of the commonly-used stimulants are followed by irritability, fatigue, and decreased ability to concentrate, and many of the various sedatives and tranquilizers can also produce drowsiness and mental confusion. Unless large amounts have been taken, it may not be obvious that the individual in an accident was suffering from an undue amount of the drug. Nevertheless, here is a field that should be more thoroughly studied. (Also pertinent are 104 and 105.)

Alcohol decreases eye movement frequency, more so when the subject is being vibrated (52). Schmidt (85) states that clinically-identified alcoholic drivers are involved in proportionally more accidents than the general driving public. Accidents involving the drinking driver are partly a problem of alcoholism, rather than the effects of alcohol on the casual drinker.

VISION AND TESTING

Long (68 A) discusses, the intangibles of driving seeing and particularly the danger of complying with only a minimum of legal standards. Whether the driver with a visual deficiency is dangerous may well depend on how well he can compensate for that deficiency. Others offer useful comments in the general field (9, 16, 36, 78). The physical impairments of the problem drivers are tabulated by Sneller (92). Bateman (21) discusses the aspects of binocular vision and accident proneness. Some colors are, he believes, more useful in locking stereovision than others, and diplopia must be avoided by proper correction of phoria at distance to provide fused binocular vision.

As might be expected, the new British law makes a £50 fine a possibility when glasses are required and not worn by drivers. At any time a driver can be checked as to whether he can read a British auto license at 75 yd. Much of the comment has concerned the fact that, though some drivers could read part of a driving license, they might not be able to read a six-letter plate (5) and as the illumination is not specified, the visibility could be determined by the more or less light available. Not all number combinations provide equal acuity targets (3, 5 through 11). Others criticize that, though this law is a good start, other tests (fields, phorias, color, etc.) may be as important as reading a license plate at 75 yd. Weale is quoted (7): "Eyes ought to be tested under the conditions under which they are alleged to have failed."

A program for testing driver's vision is given by Humphriss (58). The medical viewpoint on screening vision procedures is given by Lippmann (68). The need for carrying a second pair of glasses by those whose sight is inadequate without glasses is again stressed (10, 11). Nearsighted individuals should have full correction (102).

Contact lenses have limitations for air crew personnel (37) and some of the limitations apply also to automobile driving. Tinted contact lenses, other than the very palest shades, should not be worn when driving at night (83). Blyford (25) describes a contact lens photoelectric, eye movement recorder.

Schober (86) states that the average night driving luminance in Germany is 0.1 fL; the variable-focus French "Verilux" lens must be adjusted carefully to avoid difficulties in seeing while driving and that this lens is not too satisfactory after strong presbyopia has developed. Bryan's (30) "Nite-Site" antiglare lens and its proper use is described. Vision specialists have an opportunity in some cases and an obligation in others to provide proper occupational glasses for motorists, which should be lightweight, have small nonobscuring frames large enough for adequate peripheral view, with good nonslip ear pieces, fit comfortably (even with vibration), and come with a strong case for protection when not worn. Metal frames are recommended (8, 10, 11, 16). For night driving, the curves of the lenses should be selected for best vision and least distortion, and be antireflective-coated when reflections of lights are annoying or obscure vision.

Curved windshields are criticized (12), and vision in rear view mirrors has been investigated (60, 76). Convex mirrors are used more in Great Britain than in the United States, and difficulties from their use are cited, particularly for older people who cannot accommodate enough to see the image from the convex mirror. Distances of mirrors from the eyes of the driver and the relative positioning are reported, and for useful aid the mirror should be within 30° of the forward road view. When convex mirrors are used, curvatures of about 27 in. and a field of view of 15° are recommended; although a larger mirror with a field of 30° would be better. Problems of seeing when backing are discussed by Gernet (51). The proposed California project to test static and dynamic visual acuity, field size, glare resistance, and recovery should give useful information (13, 14).

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A Hypereffective Visual Signal for Night Driving Warning Device

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•THE ENHANCEMENT of retinal sensitivity described in this report was first observed in electroretinographic studies of frogs. However, in the interest of brevity, only human perception is discussed here.

There are many studies of flicker reported in literature, but they are almost all concerned with the upper frequency terminus of the visual perception; that is, they are concerned with a rate of iteration so fast that the iterative stimulus seems to be a steady light—that is, at the critical flicker frequency (1, 2, 3). The present study is also concerned with iterative stimulation, but at very slow frequencies, near 5 per second, instead of near 50 per second.

At very slow rates, the stimulus can be perceived as going on and off. If the stimulus is modified to be brighter and dimmer, instead of on and off, a brightness contrast can be found which is so low that the change in the stimulus cannot be seen. This is a visual threshold, and, of course, must be estimated by the usual psychometric procedure. However, at these slow rates, another and new variable can be introduced, the duty-cycle, or fraction of time within a single brighter-dimmer-brighter cycle in which the brightness occurs. This duty cycle is called "temporal contrast." Just as brightness contrast, $\Delta B/B$, varies from 0 to 100 percent, so temporal contrast, $\Delta T/T$, also varies from 0 to 100 percent. In presenting slow iterative stimuli, therefore, there are two contrast parameters—luminance and time. These two parameters can be independently superimposed on the rate of iteration or repetition.

The interaction of these two parameters of visual perception were measured, and the preliminary results of these measurements are presented. The stimulus apparatus consists of a glow-modulator tube, of a type originally developed for telephonic transmission of pictures (Sylvania, operated at 2,000 cps and less than 25 mA). The activating voltage of this tube permits independent control of frequency, duration, and brightness of the light pulses. The light was presented to the human subject in Maxwellian view as a featureless circle about 30° in diameter, through an effective 2-mm pupil. The tube was maintained at a constant background brightness of 8 ft-candles, and brighter flashes were then introduced in groups of five at controlled rates, as shown in Figure 1.

In the present experiment, these rates were 2½, 5, and 10 per second. The temporal contrast, or duty cycle, of these groups of flashes was varied between 5 and 20 percent. The brightness contrast was varied near the threshold between 1 and 5 percent. The subject sounded a buzzer if he saw the flashes after a warning ready signal. Brightness contrast thresholds were estimated at the 50 percent level of probability of seeing. Visual sensitivity, or stimulus effectiveness is shown as the ordinate, with varying temporal contrast on the abscissa. The data are presented logarithmically.

The lowest ordinate indicates the greatest effectiveness of the stimulation. In this series, and at this adaptation level, a brightness contrast threshold of just over 1 percent is found, with 10 percent temporal contrast, in this subject, when the stimulus is presented at a rate of 5 per second. The slower presentation rate of 2½ per second raises the threshold; that is, is less effective as a stimulus. The faster rate of 10 per

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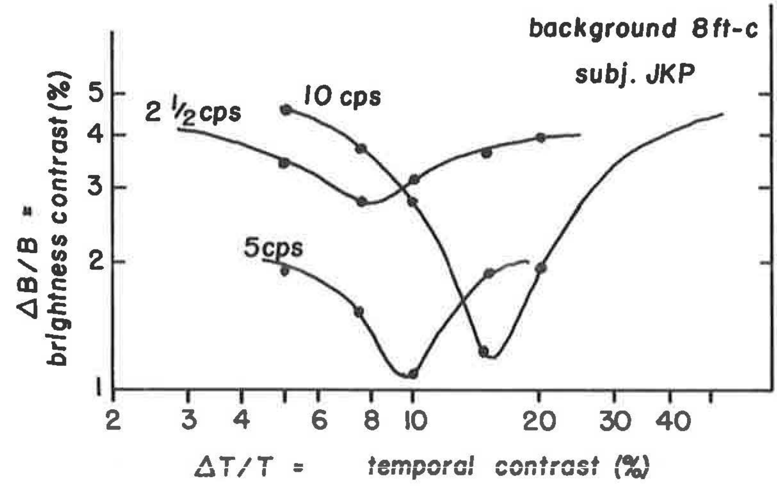

Figure 1. Relation between brightness contrast and temporal contrast (duty-cycle) at very slow flicker rates, showing sharp decrease in brightness contrast at threshold for specific temporal contrasts, at moderate brightness levels comparable to headlight road illumination.

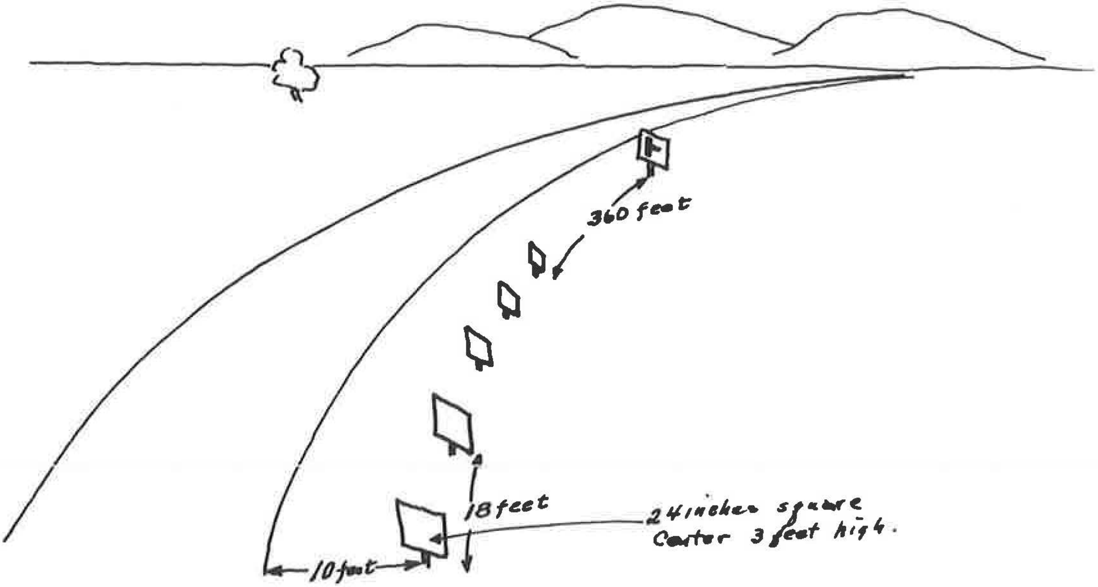

Figure 2. Presentation of hypereffective stimuli by directive retroreflective panels (rather than diffusely retroreflective panels), or by specularly reflective mirrors (dimensions shown approximated for speed of about 60 mph).

second is also less effective. There does exist, therefore, a combination of brightness and temporal contrasts, and rate of stimulus, which is a hypereffective visual stimulus.

Observation establishes a new and rather unusual fact. The rate and duration of a flashing stimulus can be modified or chosen to create a visual stimulus far in excess of the effectiveness that would usually be expected. This phenomenon is admittedly greatly unexplored. A whole new family of contrast thresholds has been uncovered. However, immediate application of this enhanced effectiveness is quite possible and practical. A visual warning device that presents groups of short light flashes above the background ered the preceding criteria if he has contemplated using simulation as a methodology for pursuing his research.

If an interest in the functional properties of the driver and the system in which he operates is assumed, a course that demands a concise and rigorous definition of the properties of the man-machine system is followed. In driving, one is confronted with a dynamic system characterized by complex equations. Man is a creature whose output is stochastic. Therefore, modeling the system becomes a tremendous challenge if an attempt is made to define the system in its entirety.

The dilemma may be resolved if the researcher is willing not to study the system in its entirety. A programatic approach that permits exploration of certain aspects of the driving situation and their interactions, and that requires that all assumptions be made explicit is known as part-task simulation.

Given the inherent complexity of the driving task, the alternate path (i.e., full-scale simulation) faces two difficult problems. First, by increasing the number of variables both explicitly defined by the research and implicitly involved by the nature of the driving field, the number of observations that must be made increases exponentially. Likewise, the variety and number of experimental controls required to obtain reliable data must be increased. Second, the human has a tremendous facility for adaptation. He selects, masks, and filters information in such a manner that it is difficult to obtain reliable data in highly complex and unstructured (unprogramed) experiments.

Therefore, the dilemma is that to oversimplify the research is to lose the reality of the driving task, whereas oversimulating makes theoretical research extremely difficult, if not impossible, because of its complexity. A choice has to be made and the one made here is the former. That is, to start from the existing body of theory on how the human operates under limited and sometimes ideal conditions and eventually to synthesize driving. Part-task simulation is performed piece by piece as the research dictates in order ultimately to approach the psychological and physiological reality of the highway. From this viewpoint, research on driver behavior is performed which hopefully leads to an understanding of the underlying behavioral processes that define driving.

METHODS

As suggested previously, the starting point of any synthesis of driving should be fairly close to the laboratory, and not too far from a single variant operation. There are several branches which such a research program may take. Figure 1 shows a representation of the type of research plan that dictates the steps to which specific inquiries should be subjected. The initial requirement is a logical analysis of the driving task out of which several alternative paths of research may evolve. The procedure generally involves several steps:

1. Selecting an operation or set of operations that appear to be involved in driving. Braking, steering, and sign legibility are examples.
2. Devising or using an existing model of operational performance based on rational analysis and empirical laboratory studies. Braking, for example, has been hypothesized to be in response to a discernible rate of closure, dependent on detection of the acceleration of the angle subtended at the eye by a leading vehicular form. It has also been hypothesized that the margin of closure is dependent on a risk-taking criterion employed by the driver. Such models lead to explicit and testable hypotheses. Theoretical studies along these dimensions have been conducted in laboratory settings.
3. Performing a study that includes system dynamics like those found in current automobiles. These dynamics should reside on a continuum, one end of which is predictable from laboratory studies.
4. Answering questions on whether the anchor ends of the continua are supported, whether, in the specific studies conducted, the outcomes match those already found in the areas where empirical research has already been conducted, and whether the vehicle dynamics react in the expected manner.
5. Taking the research effort to the field to validate the models in controlled tests. Inconsistencies and unexpected results must be fed back to earlier stages of the theory-building. Other permutations than the one detailed may issue from the logical analysis of the driving subtasks explored.

Part-Task Simulation in Driving Research

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•A CONSIDERABLE AMOUNT of energy has been devoted to discussions of simulation techniques, methods, and design. From a purely engineering standpoint, the development of system simulators is a complex and challenging exercise. However, the nature of their designs depends primarily on the uses to which they are to be put and on the knowledge of the performance of the system to be simulated. In driver simulation, it is evident that the emphasis has been on training drivers. The inability to specify the human performance variables has led to designs of varying complexity, using face validity as a criterion.

Simulators for research on the surface appear to be rather rare. Yet, this is something of an optical illusion, for much of what goes on in the laboratory employs simulation, although unrecognizable relative to a face validity criterion. Any attempt to study natural phenomena under controlled conditions in the laboratory involves simulation in one form or another. What normally determines its characteristics are the objectives of the research, the pre-existing knowledge of the phenomenon in question, and a concern for the interaction processes. In this context, simulation is a research strategy or methodology required for the conduct of research on certain classes of problems.

From the standpoint of this paper, the interest in simulation arises solely from a desire to subject certain aspects of driving to study under laboratory conditions. Because of the nature of these studies, the apparatus required is very simple and it perhaps should not be dignified by the name simulation. It is toward this particular class of research strategy that the present paper is directed.

PART-TASK SIMULATION

Simulation as a methodology has existed for many centuries. Any plan, physical mock-up, or mathematical abstraction of reality must be considered a type of simulation. It is the degree to which reality is to be represented that determines the type of simulation that the experimenter uses to study a specific phenomenon.

A number of considerations are involved in the researcher's selection of a point on this continuum of simulation. First, the intent of the researcher may be primarily to describe a phenomenon. Typically, such an orienting philosophy has preceded the major scientific disciplines and has been characteristic of their infancy. The researcher may be concerned with the functional aspects of a phenomenon with a desire to understand the process by which a phenomenon occurs. The latter approach typifies the sophisticated sciences such as physics and the emergence of new scientific disciplines such as biophysics.

Second, the lack of available functional mathematical equations defining the static and dynamic states of phenomena likewise determines the tendency toward a full-scale representation of reality. Third, when immediate application is desired, the tendency appears to be one that permits a large body of implicit assumptions to be made and a heavy reliance on intuition as to what constitutes the major aspects of the phenomena in question. Fourth, there is an emotive aspect which determines how one simulates a particular aspect of the real world. The researcher may find closure more likely in a simplified but coherent modeling of specific aspects of reality or he may be distressed by an apparent lack of closure in anything short of what looks and feels like the real world. The scientist or engineer concerned with driving behavior has probably consid-

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Paper sponsored by Special Committee on Driving Simulation.

Tinted Contact Lenses—A Handicap for Night Driving

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•THE DANGER of wearing tinted contact lenses when driving at night is the same as from other materials which prevent light reaching the sensitive retina of the eye. A typical set of commercial tinted, contact lenses gave the following transmissions (measured with a photocell corrected to the standard observer):

Property	Clear	Green	Blue	Brown	Gray	Amber	Pink
Transmittance (%)	91	78	84	71	76	90	-
Thickness (mm)	0.17	0.18	0.16	0.18	0.165	0.16	-
Another set[1] (computed to 0.20 mm) range, shades 1 to 3 (%)	-	84-93	64-93	71-89	58-92	-	91-93

[1] From (1).

The windshield can transmit 92 percent of the light reaching it when it is clean, although some of the safety glasses absorb light in addition to the 8 percent reflection losses. A transmission of 70 percent usually is the minimum legally acceptable. Spectacles, unless antireflection-coated, also decrease the light for seeing by some 8 percent lost from surface reflections. Therefore, nearly one-fifth of the light can be lost from the eye by a clean windshield and spectacle lenses, or untinted contact lenses.

Yellow (Noviol C) and similar lenses transmitting 85 percent of the light have been considered dangerous, as the seeing distance with them can be less than the stopping distance. On this basis, only the palest tints of contact lenses may be worn without corresponding loss of seeing, unless the lighting is increased correspondingly. The night luminances are rarely high enough to compensate for the absorption by tinted contact lenses.

Pinhole contact lenses (2) are occasionally prescribed for special purposes. Although they are not apt to be worn by anyone driving at night, practitioners should be aware of and warn the user of the reduction of night vision by such lenses.

Tinted contact lenses, absorbing more than 10 percent of light, can be a source of danger when worn at night, and it is recommended that no tinted or pinhole pupil contact lenses be worn when driving at night.

ACKNOWLEDGMENT

Appreciation for B. Grolman's aid is gratefully acknowledged.

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Paper presented at January 1963 meeting of Special Committee on Night Visibility.

luminance at rates of several per second could be expected to be more certain of visual response than a steady stimulus of equal contrast. This could be applied to a nighttime highway warning device, prepared from retroreflective materials. A group of such patches, set just off the shoulder of the roadway, could serve as a warning that directive instruction for the vehicle operator is to be expected.

It is quite easy to suggest experimental specifications for such a warning system, as shown in Figure 2. If it is assumed that the retroreflective material is to be presented as a set of panels 10 ft from the shoulder that there is a vehicle speed of 62 mph, or about 90 ft per sec, and that 10 percent temporal contrast at 5 cps is required, each cycle will therefore need 18 ft, and each panel must be 22 in. long. The panel can be square, about 2 ft per side. The panel should be set 3 ft above the road, at an angle to reflect the headlamp illumination, 2 ft above the road, back to the driver's position, about 4 ft above the road, when the driver is about 2 sec away from the device, or about 180 ft. The retroreflective material should be sharply, rather than diffusely, effective, or it could be specularly reflective mirrors. About 4 sec, or 360 ft, beyond the warning, the instruction sign should be placed. Naturally, such a proposed scheme as this will require road testing. Experimental verification of its application does not require great expense.

ACKNOWLEDGMENT

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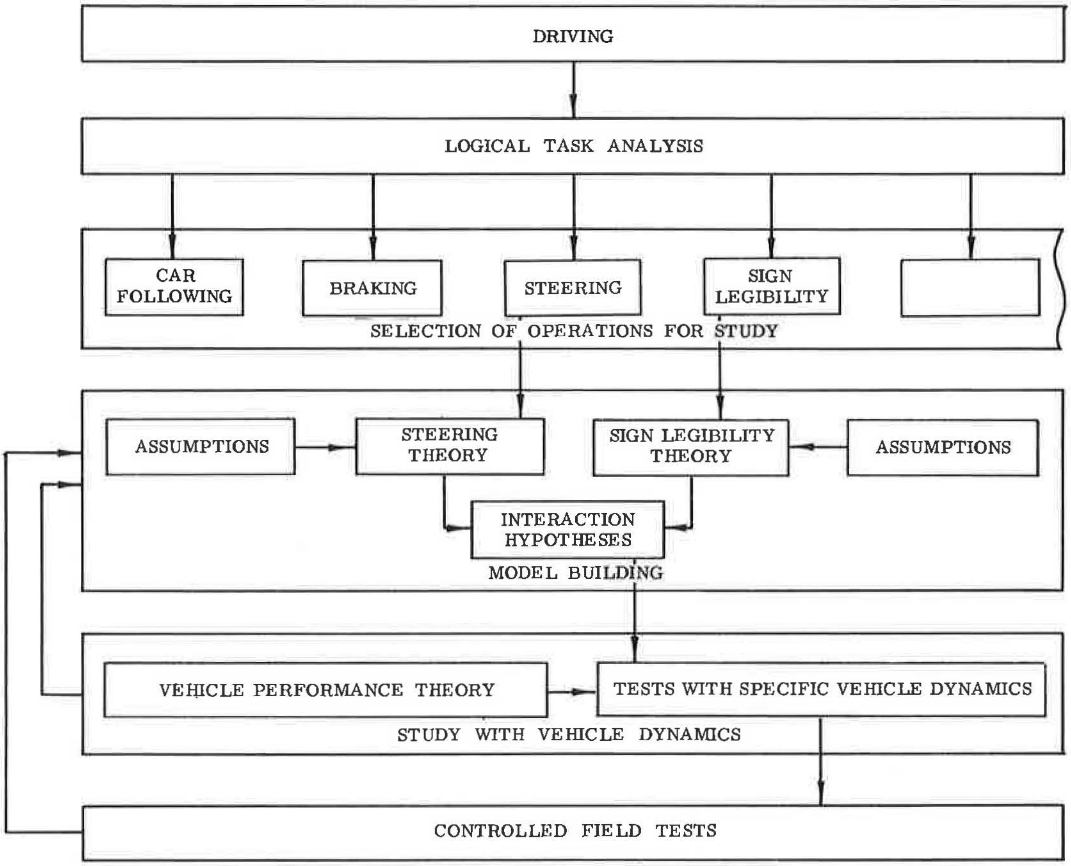

Figure 1. Programatic driving research.

The success of a program of research using the part-task approach demands that assumptions made in the modeling be explicit. If the guidance situation, for example, is to be simulated, some rather important assumptions must be made about how the driver is able to tell whether he is maintaining his position on a specific course. This is evidently some feedback mechanism or concept which should provide an explanation for the translation of these perceptual cues to psychomotor responses, such as turning the steering wheel. Some researchers have begged the question or deemed it unresolvable at this point in time. Others have made assumptions as to the nature of the feedback. Some researchers (1) have assumed that the driver pursues his course; he attempts to null the difference between his vehicle and the roadway course. Others (2) have postulated that the driver assumes a relatively stable hypothetical reference between lanes or a physical lane marking and attempts to compensate the difference between this stable reference and the vehicle.

The literature (3, 4, 5) of tracking in laboratory situations is voluminous. Neither of these assumed displays has been verified for the roadway situation, but it is with the aid of one or the other or some alternative that steering may be brought into the laboratory and data that are useful in the direct confirmation of hypothesized relationships derived.

BUREAU OF PUBLIC ROADS SIMULATION FACILITY

The Bureau of Public Roads is developing a program of research for which the part-task simulation concept is applicable. The process of what is called time sharing is already under study.

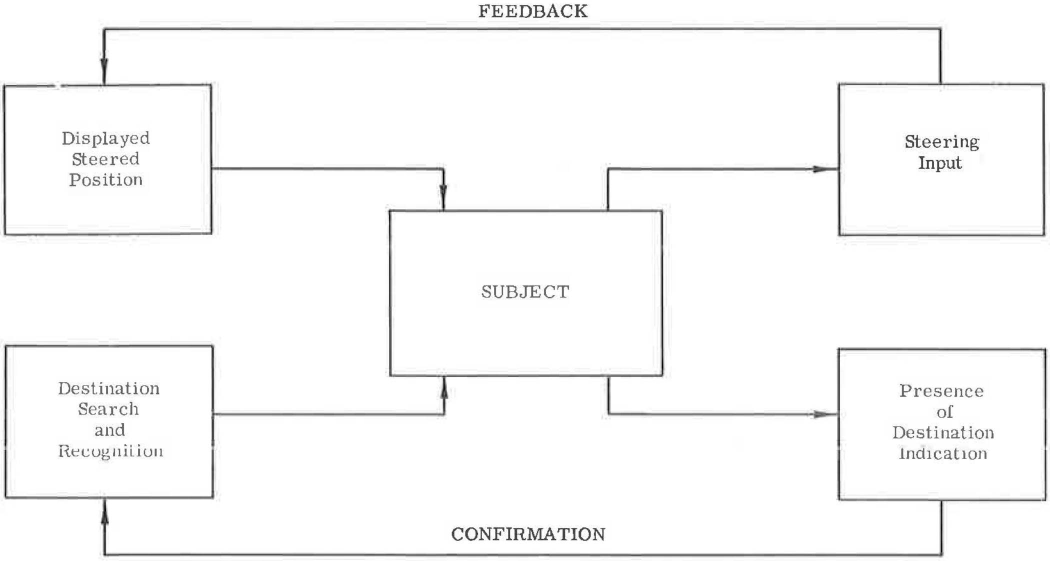

Figure 2. Perception and psychomotor requirements of time-sharing tasks.

Time sharing appears to be of fundamental significance in driving. Logical analysis suggests that the driver is required to carry out two fundamental classes of operation. One is a tracking task related to maintaining vehicle position relative to the roadway. The other involves the searching out and recognition of discrete or fixed elements in the driving environment. Several problems arise relating to the interaction of these two subtasks: What classes of interaction occur? How is performance of one affected by the other? How does increasing complexity influence performance of each operation? Such questions can be answered fairly directly and to a first approximation by simulating the two driving subtasks. Figure 2 shows the perceptual and psychomotor requirements involved in a conceptualization of the time-sharing task.

Formally, time sharing is defined as the process used by the human operator of attending to more than one task by paced or quasi-random sampling of displayed signals. Briggs and Howell (6) have qualified this type of alternation procedure to be applicable to either (a) central time sharing, when stimulation is transformed into a series of psychomotor outputs or stored for future use, or (b) peripheral time sharing, when several sources of available information must be acted on. Concern has been primarily with the latter but not with the exclusion of central processing.

The facility for conducting the time-sharing study defines the operating environment of the human operator. As in most psychological laboratory research, the apparatus may be considered in three logical blocks; the stimulus generation circuitry, the timing instrumentation, and measurement-recording subsystems. These components, in addition to the human operator, define the system in its entirety. Figure 3 shows a block diagram of the system in its entirety along with the timing paradigm.

For the time-sharing study, two stimulus-generating components for the perceptual inputs were employed. One was a low-frequency sine wave oscillator used to provide a tracking signal. The task was a single compensatory type. The error signal consequently was displayed on a CRT display and controlled by handcrank. For the recognition task, a rear projection motion picture tenchique was employed. The stimulus material was a series of signs with different messages from which the subject had to select a key one. Thus, the subject had a continuously varying tracking task and a discrete recognition task.

Timing was achieved by use of a photocell device controlled by the motion picture film, and was employed to control the measurement system. Essentially, there were

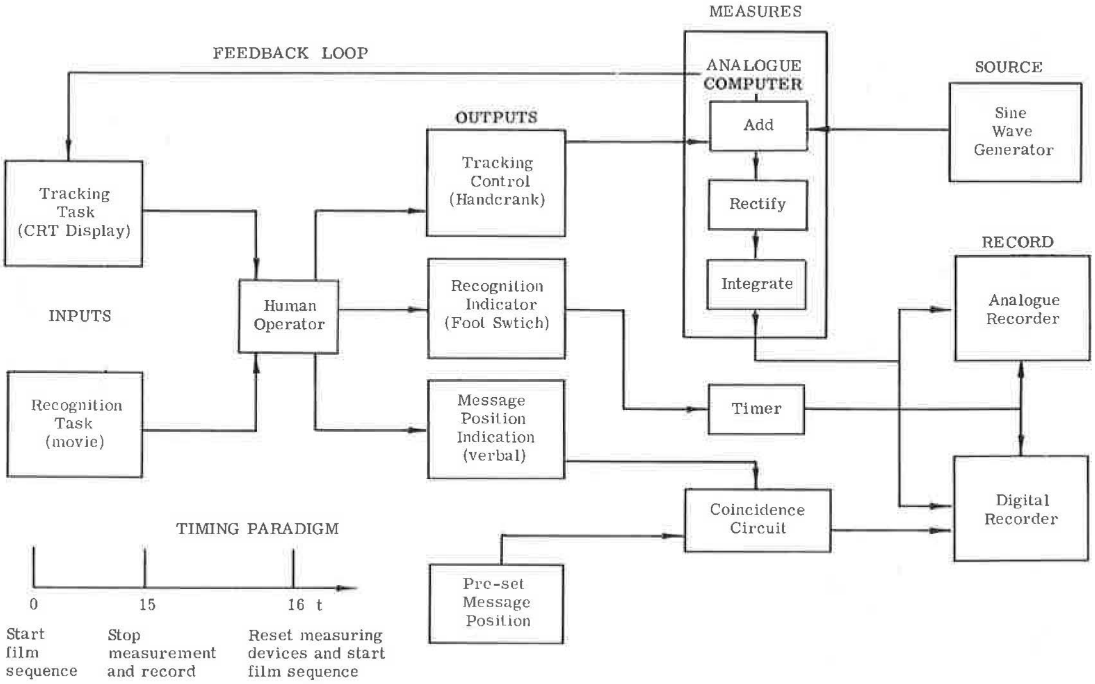

Figure 3. Time-sharing simulation system.

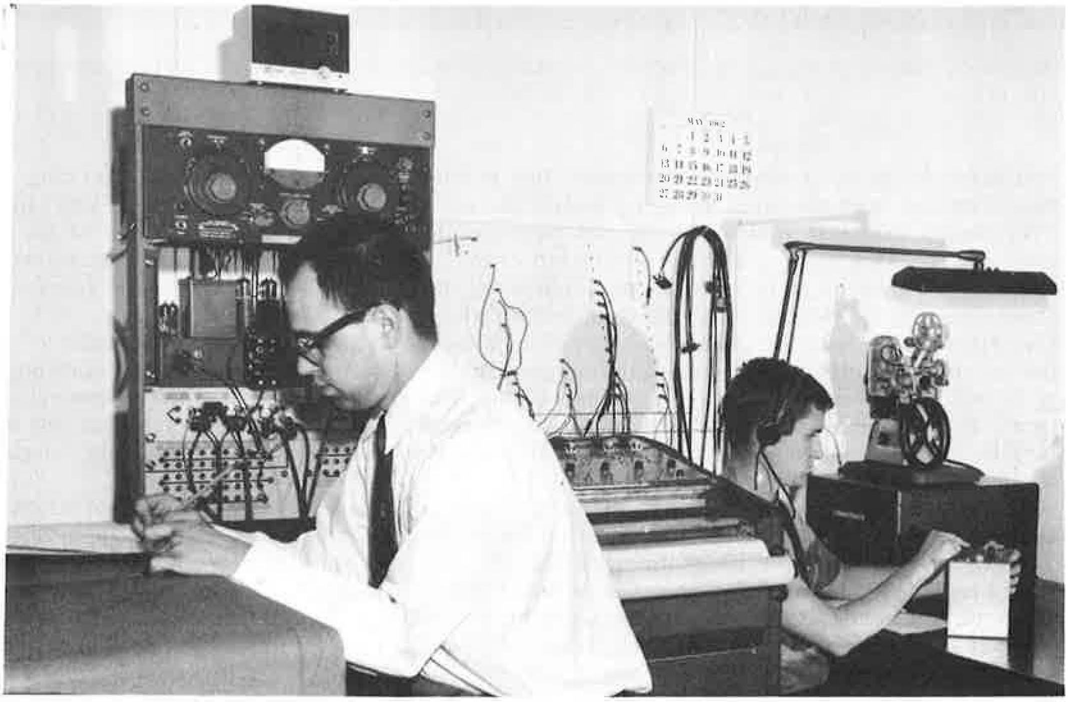

Figure 4. Laboratory apparatus employed in time-sharing study.

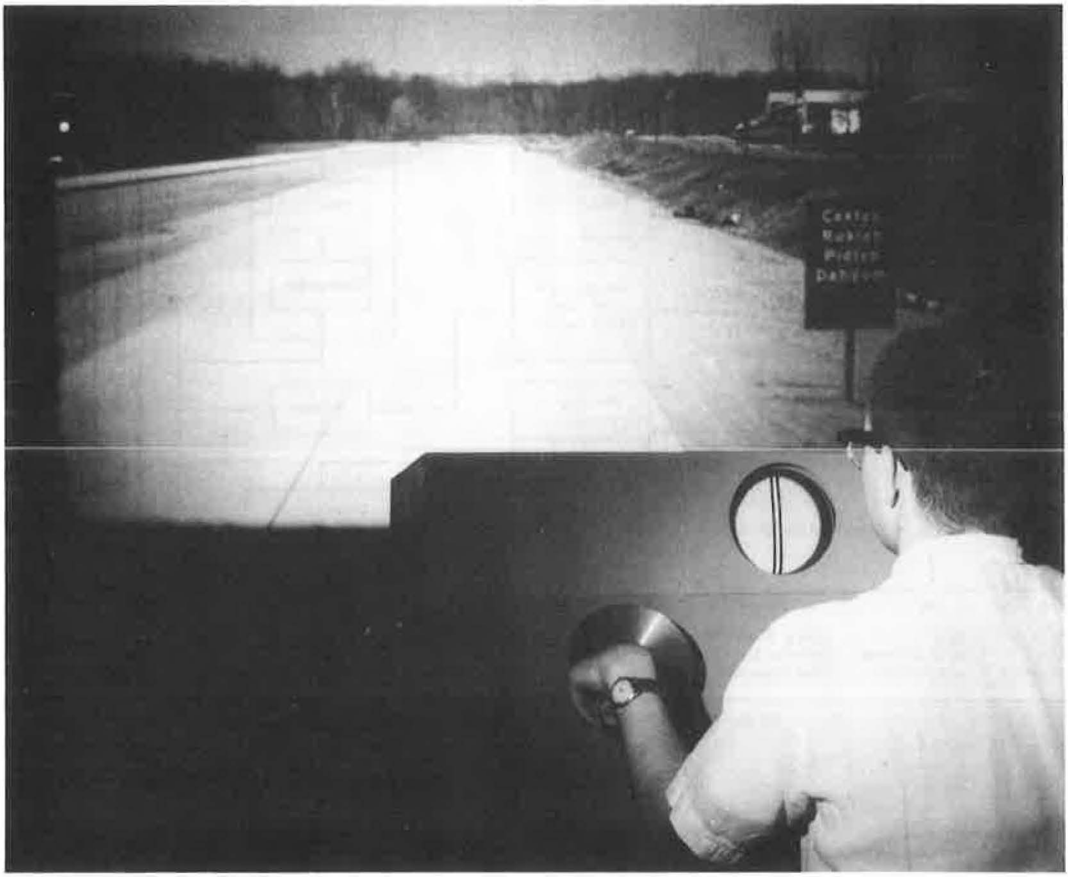

Figure 5. Subject seated at driving console performing tracking and search-and-recognition tasks.

two parts to the response measurement: one related to the measurement of tracking performance, and the other concerned with the recognition task. To measure tracking proficiency, a small analogue computer was used to measure instantaneous tracking, absolute tracking error, and the integrated error. Because the last of these was used as an overall measure of tracking performance, the operation was carried out for a fixed time period during which the subject had to perform the recognition task. For the latter operation, the measures of performance were the response time at which the subject recognized a key message on the sign and the accuracy of that recognition. A digital counter measured time, started by the film sequence and stopped by the subject. A simple coincidence circuit was used to code the correctness of subjects' identification of the message. Figure 4 shows an overview of the stimulus generating, timing, and recording subsystems.

Both digital and analogue recording were employed. Integrated error, recognition time, and accuracy of recognition were coded in digital form and printed out on a digital recorder. The analogue recorder continuously recorded the sine wave input, the subject's tracking, the tracking error, and the cumulative error. Also recorded was an indication of recognition. Hence, with digital records, data for statistical analyses were immediately available; with the analogue record, data for microanalysis of the time-sharing process were available.

The facility described obviously looks little like an automobile. The operator is seated at a console (Fig. 5). He is confronted with a simple compensatory task and the task of searching out key messages on signs along the simulated roadway. It is in the operations that most of the similarity to driving lies, certainly not in the appearance.

The system output provides the raw data by which the model of time sharing may be implemented. Not only may a set of restricted hypotheses be tested within a specific and limited model but also, where additional data are collected (particularly continuous data), a number of ad hoc hypotheses may be tested. Confirmation or rejection of specific hypotheses permits model building. Ad hoc information permits expansion of the inquiry and eventually a more general prediction of behavior.

For purposes of this discussion, the experimental design and results are not reported here. The signficant factors to be examined in this section are the system's output and the specific aims of the research, as a means to illustrate the type of research developed by the part-task simulation method.

For development of the time-sharing study, a system has been synthesized that has as its input a tracking function and a search and recognition task. Expectations as to the response to each are rather clear-cut. The interactions of the two supply unique information about the time sharing of the two tasks. Specifically, the output of the system yields measures of tracking performance and dynamic legibility under conditions systematically varied to permit an analysis of performance across each task.

The model of time sharing devised has dealt with the relative decrement of one task while another maintains dominance. There are, of course, other measures which permit inference of these relations.

ADVANTAGES OF PART-TASK SIMULATION

A part-task facility of the type described here has certain inherent characteristics relative to research in driving. Essentially, it provides a laboratory facility organized around a set of fundamental building blocks. These elements allow a great flexibility in the kinds and classes of research that can be carried out. It is adaptable and modifiable to changing requirements and insights that come through the research process.

Also, because of the simplicity and elementary nature of the laboratory, rather rigorous planning of research is mandatory. The user must define in detail and in advance exactly what he is going to do and how he is going to do it. Because this is not really a "driving simulator," the researcher is never allowed the luxury of studying "just driving." Further, the researcher is never under the illusion that research performed using the facility is a complete analogue of the real driving world. It is obvious that the research can, at most, say something about a very few specific human processes that are perceived to be important in driving. It is always evident with this kind of research that validation in the real system will be required for any of the results obtained in the laboratory facility.

Another feature of laboratory research of this type is that it represents a direct way to develop and test models of driving behavior separate from the host of other variables that confound research done on the highway. By abstracting certain aspects of driving performance in this fashion, it is possible, to a first approximation at least, to uncover and examine in detail the specific behavioral processes determining observed performance. To develop a general model of driving, a synthesis will be required of several such behavioral processes. It is in "teasing out" of these underlying processes that the present facility holds its greatest promise. It has been developed for radical modification, allowing a breadth of research, and hence can serve as several different part-task simulators to meet research requirements.

A very practical advantage of this type of facility is that the researcher can get on with the business of doing research very rapidly. The speed with which studies can be programed and carried out is quite high, allowing pursuit of what appear to be promising lines of research or the dropping of others as the situation demands. It is easier, therefore, to coordinate the laboratory studies with the test track and field studies that are also going on. If something is uncovered in a field study, it can be very quickly brought in and set up in the laboratory to be examined in depth as required.

CONCLUSIONS

The part-task facility discussed in this report is actually less a simulator than a laboratory for the analysis of the driving task. It is designed as a means for directly testing conceptual and experimental models of driving processes. Its ultimate objective is to determine the nature and functional characteristics of certain of these driving processes and to delimit classes of interaction phenomena that arise in driving.

From one viewpoint of driving simulators, this facility should not be considered a simulator. It is, in reality, a laboratory for the conduct of behavioral research using dynamic stimulus material. It is only in the use of this kind of stimulus material that the facility may be considered in any way as a simulation of driving. Consequently, if the research carried out in this laboratory is to be related directly to driving, it must ultimately be validated by actual, controlled field studies. Thus, the research program of which this facility is a part is conceived as one part of a closed loop in which research progresses from the laboratory to the test track to the field situation and back again. With this research approach, a highly flexible laboratory facility is necessary. It needs to be one that allows freedom for a large range of behavioral studies capable of examining a host of performance dimensions. The present part-task facility is aimed precisely to fill those areas of research needs.

ACKNOWLEDGMENT

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Use of Stress in Part-Task Driving Simulators—A Preliminary Study

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To evaluate the feasibility of using stress in driving simulator research, drivers were subjected to continuous glare while performing a series of tasks in an instrumented vehicle on a specially designed test track. The tasks included keeping within a 7-ft lane at 20 mph, maintaining a constant headway and estimating time to coincidence with an approaching or overtaking vehicle. Methodological problems in driver research were examined.

•THE IMPORTANCE of simulation in highway research is well accepted. There has been considerable recent interest in both full-scale and part-task simulators. A goal of the full-scale approach is complete fidelity in representing the visual, auditory, and kinesthetic stimuli to which the driver is exposed. This is a research and engineering feat of great magnitude, and successful full-scale simulators are still in the future. The part-task approach promises more immediate and economically feasible research on highway problems. Individual elements of the driving task, such as steering, accelerating, road following, or passing, are simulated. Only those visual, auditory, and kinesthetic stimuli necessary for the performance of the part-task are provided. This paper examines the methodological problems involved in defining the requirements for such part-task simulators.

A part-task research simulator will have as its function the determination of the effects of contemplated highway, vehicle, or driver alterations on safe, efficient transportation. It will be developed to simulate particular parts of the driving task which might be affected by such changes or experimental variables. Many meaningful variables, however, will have no effect in simulation studies, due to the ability of the driver to perform adequately under a wide range of conditions.

One method for magnifying the effect of an experimental highway or vehicular variable on a driving part-task is subjecting the driver to one or more psychological or physiological stressors. If the effects of various stressors on the part-task have previously been determined and these effects do not interact with the experimental variable, it should be possible to select a stressor that will degrade performance on the part-task of interest to a point where the effect of the experimental variable is more apparent.

Many studies may be found in the psychological and ergonomic literature dealing with the effects of stress on driving and related types of performance. Typical results of such studies are briefly summarized:

1. Carbon monoxide.—Prolonged exposure to carbon monoxide concentrations of 45 percent or greater have been found to impair performance on psychomotor tasks (1). Increasing concentrations of carbon monoxide have been found to decrease sensitivity to brightness differences under low illumination (2).

2. Fatigue and wakefulness.—Many studies have found performance decrements attributable to fatigue and wakefulness (3, 4, 5, 6). In a study of the effects of rest

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pauses on driving efficiency, Lauer and Suhr (7) found reaction time, experimenter evaluation of driving, side-to-side sway, and lateral placement of the automobile to be adversely affected by lack of rest pauses.

3. Glare.—Glare has been found to increase errors in a tracking task (8), raise the threshold for detection of a target in the vicinity of the glare source (9), and cause difficulty in fixation (10). The effects of glare are difficult to interpret in most studies, as glare may act both as a distracting stimulus, preventing the subject from devoting sufficient attention to his task, and as a veiling luminance, directly interfering with the visual portion of the task.

4. Information overload.—The information-handling ability of the driver was studied by Brown and Poulton (11) and Christner (12) by requiring the driver to perform a supplementary task: detecting the digit that was changed in successive auditory series of digits. Brown and Poulton found an increase in errors as vehicular and pedestrian traffic increased. Christner did not find the digit scan task to be a sensitive indicator of driver information-handling load.

5. Noise.—Noise has generally been studied as a distracting stimulus and has been found to impair performance in psychomotor tasks (13, 14), visual vigilance (15), decision making (16), and time estimation (17). Impairment generally occurs at noise levels above 90 db and is most serious at the higher frequencies. Noise tends to increase performance time and estimations of time intervals.

6. Heat and cold.—Heat has been found to cause decrements in a wide range of tasks, including manual dexterity, tracking and vigilance (18). Bursill (19) found a funneling of attention toward the center of the visual field with increased heat. Cold has less effect on performance in general, although it has been found to impair kinesthetic sensitivity (18).

7. Vibration.—Vibration has been found to cause decrements in ability to maintain a constant foot pressure and in compensatory tracking (20). Other effects are found for specific combinations of frequency and amplitude.

Although these studies suggest possible effects of each of the stressors examined on driving part-tasks, specific quantitative relationships between the intensity of each stress and decrements in performance on each part-task are lacking. This lack could be filled by direct experimental investigations. The feasibility of performing such studies, using an actual vehicle and a special test course, is investigated in the following experiment.

This study is concerned with the effects of glare on the performance of four driving part-tasks: road following, vehicle following, judgment of time to coincidence with an approaching vehicle, and judgment of time to coincidence with an overtaking vehicle. Because it is entirely a methodological exploration, conclusions about the effects of glare on driving would be inappropriate.

APPARATUS

A test course consisting of two white lines 7 ft apart was painted on unused airport ramps (Fig. 1). The course is 0.8 mi long and consists of four straight sections, two 100-ft radius curves, three 170-ft radius curves, one more gradual curve and one very tight curve (the U-turn). The total driving distance from the beginning of the course, around the U-turn and back to the starting point, is 1.6 mi.

A 1955 Buick was used as the test vehicle. Lights were installed on the front of the vehicle to serve as a target for photographic measurement of intervehicular distance (Fig. 2). The rear tires were illuminated to facilitate observation of road-following performance. Controls were provided to enable the experimenter, seated at the right in the front seat, to apply the brakes or prevent use of the accelerator.

A spotlight was mounted on the hood of the test vehicle, directly in front of the driver and at a distance of 84 in. from his eyes. The spotlight intensities used were 3.0, 4.5, and 5.8 v, producing glare levels of 0.09, 0.37 and 9.0 ft-candles at the eye, with the eye in the center of the beam. The light was left off for a fourth, no-glare condition. The spotlight was powered by a 12-v storage battery. Voltage to the spotlight was controlled by a rheostat and monitored with a voltmeter.

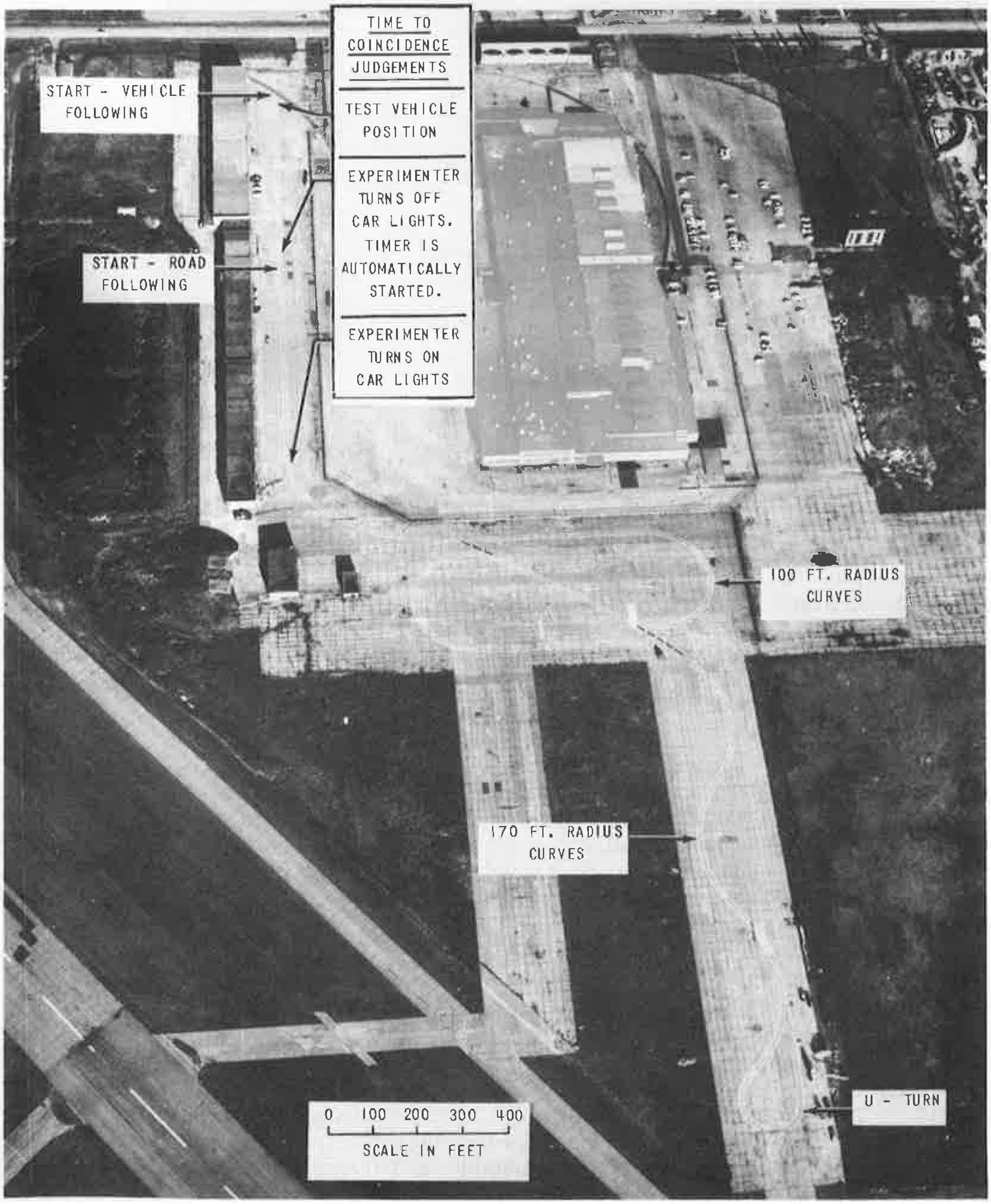

Figure 1. Driver research course.

A second vehicle was used to precede, follow, or drive toward the test vehicle for the various performance measures. For road following, an experimenter in the second vehicle used a two-way radio to record the positions of the test vehicle. For the vehicle-following runs, a motion picture camera was operated from a rear-facing seat in the preceding vehicle, a station wagon. For the time-to-coincidence runs, a standard electric timer was started by the pressure of the tires of the experimenter's vehicle on a hose laid across the test track, and stopped by a button in the test vehicle.

Figure 2. Test vehicle.

PROCEDURE

All experimental runs were made after dark. The subjects, four volunteer Laboratory employees, were run on successive nights. The subject reported about an hour before dark, practiced driving around the course six times, and then rested until the experimental runs were begun. The orders in which the four part-tasks were run and in which the four glare levels were presented were counterbalanced across subjects. The glare levels are designated 1 (no spotlight), 2 (3.0 v), 3 (4.5 v), and 4 (5.8 v).

Vehicle Following

The subject's car was positioned 64 ft behind the experimenter's car at the beginning of the test track. The subject was instructed to follow the experimenter's car, maintaining a constant distance. A shorter route across the track which eliminated the 100-ft radius curves was used, as shown by the dashed lines in Figure 1. The vehicles drove to the end of the course, turned, and returned to the starting point for each run. The distance maintained by the test vehicle was recorded by the photographic method described.

Road Following

The test vehicle started 272 ft from the beginning of the course. The subject was instructed to drive around the course, keeping between the two white lines. If he touched or crossed over one of the white lines, or returned to the correct position, an experimenter in a vehicle following the test vehicle recorded the word "on," "over," or "off." The spacing between these words, as later displayed on an oscillograph, was used to measure the time during which the subject's tires were between the lines, a tire was touching a line, or a tire was outside the painted lane.

Time to Coincidence—Approaching Vehicle

The subject's car was parked at the beginning of the test track, facing the track, but just outside the two white lines. The lines were at the subject's left. The experimenter's vehicle proceeded along the track from a point just beyond the first curve with its lights off. When it reached the straightaway, the experimenter driving the car turned his headlights on and drove 420 ft, crossing a hose which was laid across the track 272 ft from the subject's car. The pressure of his tires on the hose rang a bell which signaled him to extinguish his lights. The pressure on the hose also started the timer. The subject, who wore ear defenders, was instructed to close his eyes when the headlights of the approaching vehicle were extinguished. He was then to imagine the vehicle

TABLE 1

EFFECTS OF GLARE ON PART-TASK PERFORMANCE

Part Task	Glare Level			
	1	2	3	4
Road following[1] (%)	31	27	36	41
Vehicle following[2] (ft)	14	16	16	18
Coincidence[3] (sec):				
Approaching	1.0	1.0	1.6	0.9
Overtaking	1.1	2.1	1.2	1.4

[1] Time at least one tire was not within painted lane.
[2] Standard deviation of intervehicular separation.
[3] RMS error.

continuing to approach (it actually turned off) and press a button when he thought it would reach him. This button stopped the timer, and the time elapsed was recorded.

This part-task was begun with four practice runs, two at 25 mph and two at 35 mph. The subject was given immediate knowledge of his deviation in seconds from the correct time. At each glare level two runs were made at 25 mph and two at 35 mph in varying orders.

Time to Coincidence—Overtaking Vehicle

The procedure was the same as that used for the approaching vehicle runs, except for the position of the test vehicle. The test vehicle was between the two white lines, facing away from the approaching experimenter's vehicle. The subject observed the experimenter's vehicle through his rear-view mirror.

RESULTS

In general, there was little observable effect of the glare source used on performance on the four driving part-tasks. The results are presented to illustrate the type of data that can be collected in such studies.

Table 1 gives the performance scores obtained on the four part-tasks. Although the differences obtained were quite small, it appears that glare produced the greatest effect on road following, a lesser effect on vehicle following, and no discernible effect on time-to-coincidence judgments. If these results were obtained in a study employing a larger number of subjects and higher glare levels, or perhaps intermittent glare, it would be possible to classify the four part-tasks studied according to their relative resistance to the effects of glare.

ANALYSIS

The preceding sections illustrate the type of study that would be performed to develop a taxonomy of stressors and their effects on driving part-tasks. In the experiment performed, the effects of the stressor employed were not as striking as would be desired for actual research in this area. The study does bring out a number of methodological considerations which may be applied to further research on the effects of stress on driving part-tasks:

1. A program of extensive pretesting and apparatus modification should be carried out to insure that the intensities of the stressors used in the final study are appropriate for breaking down the driving part-tasks of interest.
2. The subject should be thoroughly trained in performing each part-task under stress, before the final measurements of his performance are taken. Learning to per-

form a specific part-task and adaptation to a given stress follows various patterns for different subjects. It is, consequently, not reasonable to counterbalance learning and adaptation effects across subjects. The effects must be eliminated before the start of the experiment proper.

3. Due to these large individual differences, it is essential that a sufficient sample of drivers be studied. Ten would be a minimum.

4. Intra-individual differences are also large in studies of this kind. It is recommended that each subject/condition combination be replicated at least once.

If these considerations are given sufficient attention, experimental determinations of the effects of stress on driving part-tasks should be a feasible and fruitful approach. Data collected by this method could be used to select the part-tasks to be simulated and the types and levels of stress to be included in each part-task simulator.

ACKNOWLEDGMENT

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Applications of the Automobile Simulator

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An automobile simulator has been used in driver behavior studies. It is shown that these studies would have been difficult or even impossible if attempted on the actual highway. The simulator and the various applications of the simulator to driver behavior studies are described.

•DRIVER BEHAVIOR studies can either be conducted on the highway or on an automobile simulator in a laboratory. Many problems develop if highway studies are attempted. Control of traffic and measurement of variables are the major complications that arise. These problems become non-existent if an automobile simulator is used and the possibility of a real accident is eliminated. However a simulator is an approximation, and consequently, results of simulator studies will also be approximate.

DESCRIPTION OF SIMULATOR

The simulator used was a two-car type (1). One vehicle was driven by the subject and the other was controlled by an analog computer. The driven vehicle was a full scale mock-up of an automobile while the lead vehicle was a small toy. This toy together with the scaled down road and roadway scenery was viewed by a TV camera. The image was presented to the driver of the rear vehicle by a TV monitor mounted on the hood of his automobile. Figure 1 shows the simulator; Figure 2 is a block diagram.

ADVANTAGES AND LIMITATIONS

The most serious limitation of the present simulator is that the driver senses no acceleration forces. Other limitations are that the maximum distance between the two automobiles is limited, the roadway is straight and level with no intersections, and passing is not possible although the driver can swing out into the left lane.

This simulator uses an analog computer as an integral component. With the computer it is possible to program the lead automobile for many different types of driving experiments. In studying driver models it is a simple matter to replace the driver with his analog on the computer and test the validity of the driver model.

APPLICATIONS

Direct

The simulator was directly used to good advantage in driver behavior studies. In one investigation the driver was trying to follow the lead vehicle (traveling at a constant velocity) at a constant headway. Headway is defined as the distance between the front bumper of the rear vehicle and the front bumper of the lead vehicle. As would be expected, the driver was not able to follow at a constant headway but instead deviated randomly about a mean headway. Many models have been proposed for this car-following situation.

Barbosa (2), in studying Herman's equation of car following (as well as many others) with the aid of the automobile simulator, was able to show that these equations gave only

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an approximate fit under limited variations of the variables. Under the restraint of these limitations, he found that a large class of functions would give the same approximate fit. In his attempts to devise a more general model, Barbosa considered constant acceleration levels of varying amplitudes and sense, and was able to propose a decision point model. Later studies justified his model and led to what is now called the action point model.

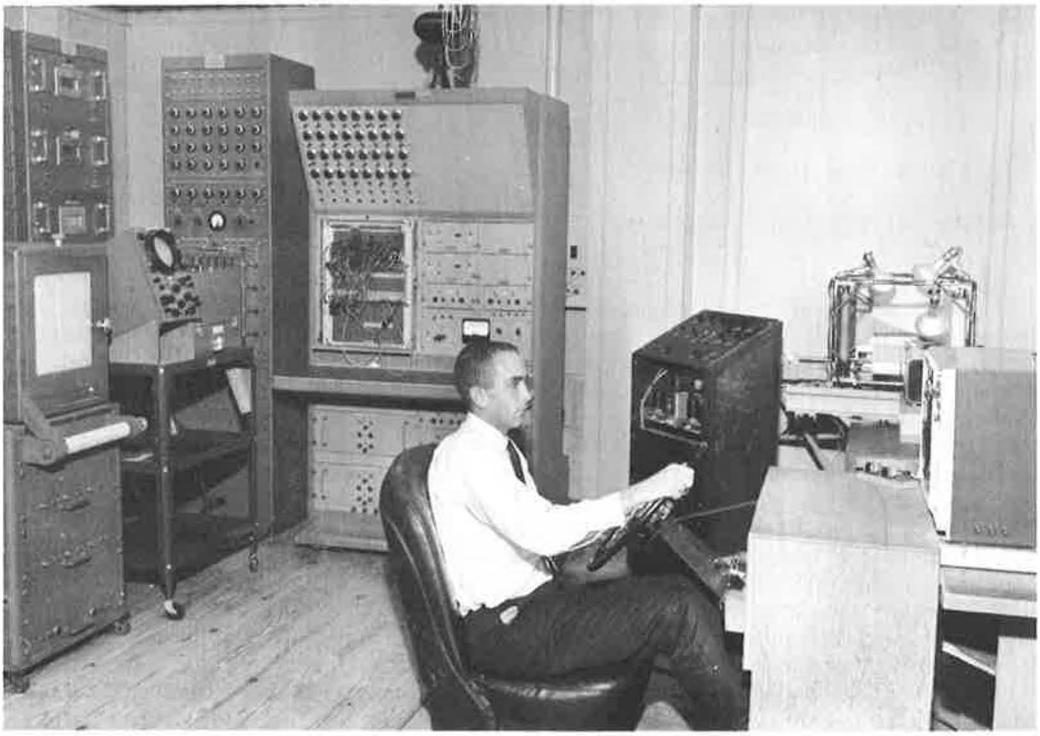

Figure 1. The complete simulator.

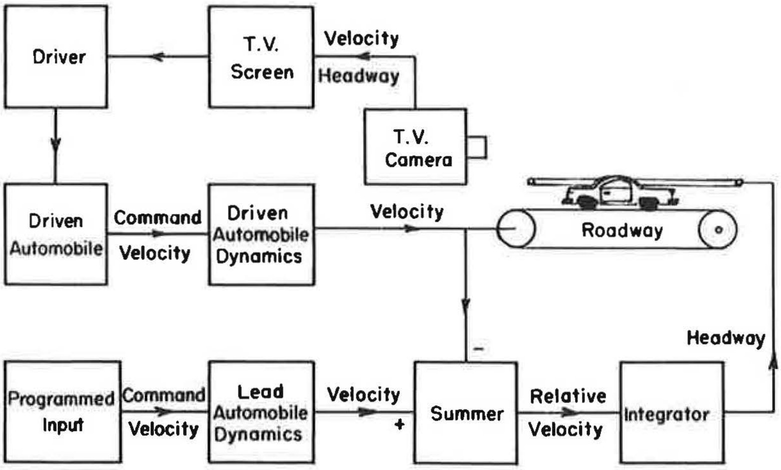

Figure 2. Block diagram of simulator.

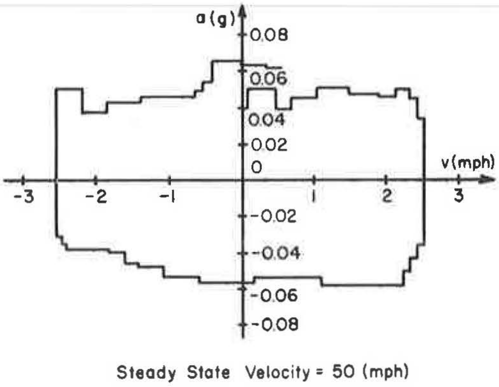

Figure 3. Typical a-v trajectory.

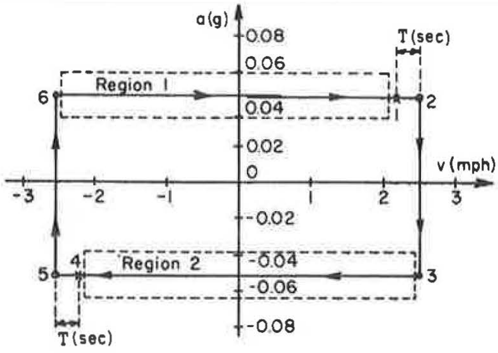

Figure 4. Expected response of decision point model.

The justification of the action point model is evident if the trajectory shown in Figure 3 is analyzed. This trajectory is typical of that obtained if the driver's acceleration is plotted against the relative velocity existing between the driver's vehicle and the vehicle being followed. The trajectory shown in Figure 4 is the response expected from the action point model and it is evident that this is just a smoothed version of the actual trajectory, that is, the small variations in the positive and negative acceleration levels have been averaged out. In Region 1, the driver is accelerating at a constant value of 0. 05 g. At point 1, the driver makes a decision to decelerate at a rate of 0. 05 g. This point is called a decision point. After an undetermined delay of T seconds the driver takes action at point 2 and instantly decelerates to a value of 0. 05 g at point 3. Point 2 is termed the action point. In Region 2, the vehicle slows down with a constant deceleration of 0. 05 g. At point 4, the driver makes a decision to change his acceleration and then acts on his decision at point 5. The driver is now back in Region 1 and has completed one cycle in the trajectory.

This particular model is quite simple and appears to give a more reasonable explanation of the car-following situation for a wider variety of conditions. The action point model is under active study and the exact nature of this model will be the subject of a future report in which the dependence of the action points on the independent variables will be made clear by considering the means of the variables as well as the variances of these means.

Another direct application of the simulator was in a preliminary study of the effect of large changes in lead car velocity on the driver. This preliminary study has shown that the action point model can again be used to explain the behavior of the driver. In the experimentation for this study the lead car velocity had to be abruptly changed and the resultant transient variables of the driven car measured. No difficulty was encountered with the simulator in making these measurements.

Indirect

Indirect applications of the simulator were made in visual thresholds studies. The lead vehicle was made to undergo changes in range, velocity, and acceleration and the corresponding visual thresholds of the driver in the rear vehicle were measured. In these studies, the velocity threshold has received most consideration. A statistical study of this threshold has been partially completed. Results of the complete study will be the subject of a future report. Preliminary investigations of the range and acceleration thresholds have also been made. The threshold studies demanded a multitude of precise measurements under varying conditions and these were readily obtainable from the simulator.

CONCLUSIONS

Through the use of an automobile simulator, a new model of the driver has been found. This action point model is radically different from any other model that has been proposed for the human driver. Preliminary studies have shown that this model in its most general form is probably the most complete model so far developed.

The simulator has also made visual threshold studies possible. Present studies on the velocity threshold indicate that fundamental contributions to pyschophysics will result. It is thought that these fundamental contributions will have immediate applications in highway design (both conventional and electronic), traffic flow, and virtually every area where a human is concerned with the velocity of an object that he is watching.

ACKNOWLEDGMENTS

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Human Thresholds Related to Simulation of Inertia Forces

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• FOR THE PURPOSE of this report it was appropriate to review the simulator laboratory development at U. C. L. A. and then describe a series of tests conducted on the moving-base simulator.

The Institute of Transportation and Traffic Engineering at U. C. L. A. has been greatly interested for about 12 years in the research potential of a driving simulation laboratory. The Institute's first motion picture for playback to a driver seated in a vehicle mock-up was produced nearly five years ago. Shortly after that, with help from an Automotive Safety Foundation grant, the driver could sit in a real running vehicle operating on the rollers of a chassis dynamometer while he responded to the motion picture films.

Results of this work were reported in HRB Bull. 261. Briefly, it was possible to say that drivers responded differently to straight-road scenes than to winding-road scenes. Both speed and steering wheel movements reflected this difference in the expected direction, namely, slower speed and more wheel movements during the curving-road trip. Evidence and arguments were presented relating to the need for simulating inertial forces and the feasibility of one method of producing these forces of acceleration and centrifugation.

During the past three years with the help of a grant from the U. S. Public Health Service, four types of activity have been under way at the Institute:

1. Improvement of the visual display and feedback fidelity. A 160° wide-angle motion picture system was demonstrated at the first National Symposium on Driving Simulation in February 1960.
2. Development of data recording and processing techniques which now directly provide computer analysis capability without need of human chart reading and keypunching.
3. Conduct of research on driver behavior. Reactions to "wrong-way" driving, driving after staying awake all night, and left-hand off ramps behavior are currently under study. The initial phase of a study of blood sugar and driving fatigue is nearly complete and a pilot run of drunken drivers has been made.
4. Construction and testing of inertia forces apparatus.

Each of these four activities could be the subject of a presentation. However, this report shall deal with progress in the inertia forces simulation activity.

The method substitutes gravity for inertia force. A model (Fig. 1) of a proposed device serves to demonstrate the principle involved. It is a movable platform that can pitch, roll, and yaw. If the simulator vehicle and visual display are placed on the platform, the inertia force that a driver feels when slowing his vehicle is simulated by pitching the platform forward. Five, ten, possibly twenty degrees from the horizontal may be needed to produce the appropriate amount of force to match his deceleration rate. As was documented in HRB Bull. 261, pitching in this manner can produce a reasonably close approximation of vehicle deceleration rates as measured by recording accelerometers in the field.

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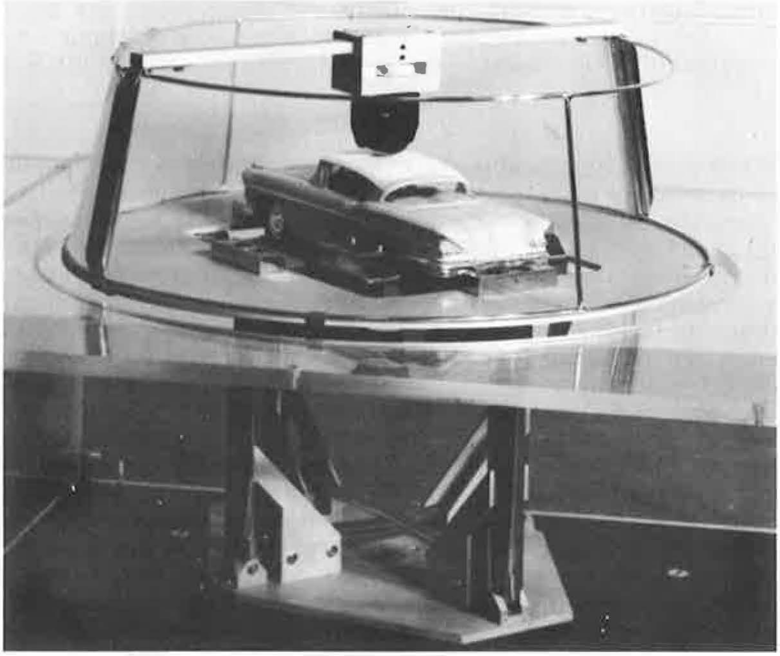

Figure 1. Proposed model which can substitute gravity for inertia force.

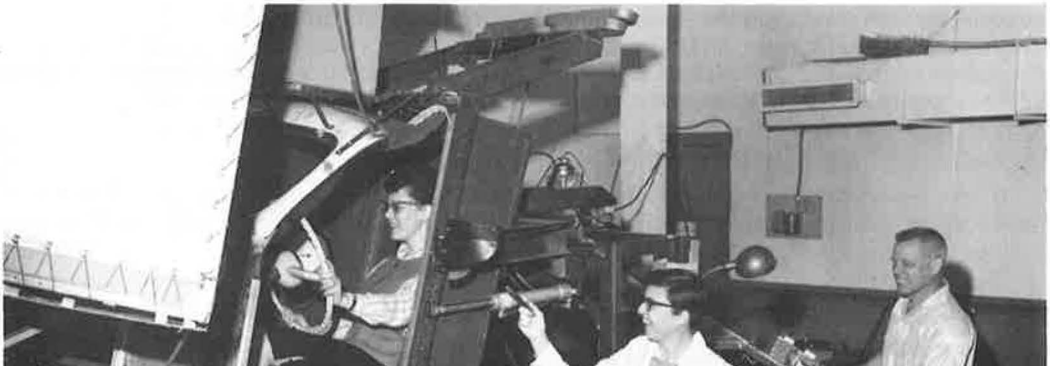

Figure 2. Driver demonstrating one position of the moving-base device.

The proposed device demonstrated one of several possible mechanical systems for producing pitch, roll and yaw. In order to investigate the possibilities of substituting gravity for inertia force, a moving-base device was constructed (Fig. 2). The driver can be pitched about an axis approximately shoulder high and rolled about an axis in the same horizontal plane located directly in line with the center of his body.

PROCEDURE

Using this device, a series of position judgments was obtained from drivers as they sat behind the wheel in the device and were moved to various positions. Two types of procedure were used as follows: (a) movement from an initial position to another position and a judgment requested while the driver remained in the "new" position; and (b) movement from an initial position to a new position and back to a level position and a judgment requested of the new position (the position immediately preceding the return to level).

These tests were performed to determine the accuracy with which drivers could determine the extent to which they had been pitched or rolled. The first procedure (a) relates to the perceived magnitude of the illusory inertial force during its presentation; and the second procedure (b) relates to perceived magnitude of the illusory inertial force after it had been experienced and the driver returned to a normal condition (in terms of inertial forces).

In order to maintain the attention of each driver, a subsidiary task was provided, namely, a vision acuity test. A series of slides projected an image on the projection screen 4 ft in front of the driver. He controlled (with a hand-held button switch) the rate of presentation of these 15 slides and gave an oral judgment as to the position of the checkerboard target in each. (These vision test slides were prepared from the Bausch and Lomb Orthorater test device.)

Whenever the driver heard a buzzer tone he interrupted the vision test and adjusted a pointer located in the cab to what he judged to be the horizontal or the new position angle. This pointer was mechanically linked to one outside the cab from which the experimentor recorded the judgment value to the nearest degree. A second pointer outside the cab displayed the actual angular position of the apparatus.

To eliminate any effects due to order of presentation, the series of angular positions was assigned using a random number table, and the various combinations of initial and new positions each appeared an equal number of times for each subject.

EXPERIMENT PLAN

It was postulated that the variance of measurements on a set of subjects in the experimental environment (moving-base device) for a given attitude of the device, is a relative measure of the disorientation associated with that attitude.

The experimental conditions were as follows:

Pitch 1: Subjects asked where horizontal is while they were in the "new" position.
Pitch 2: Subjects asked what the angle was after they have been brought to zero position.
Roll 1: Same as pitch 1.
Roll 2: Same as pitch 2.

There were 16 position sets for pitch, and 12 for roll; for example, from 0° to 25° was one pitch set and -15° to 25°, another pitch set.

It was assumed that there was no difference in standard deviation of set of threshold responses for P_1 vs P_2 for a given pitch-attitude combination.

The number of subjects was 75. Representative results are given in Table 1.

DISCUSSION AND CONCLUSIONS

The results indicate that drivers (as tested) were not able to clearly distinguish among a variety of angular positions. The coarseness of their position thresholds may explain in part why it has been possible to create an illusion of inertial forces

TABLE 1

REPRESENTATIVE RESULTS[1]

Condition	Position (deg.)		Mean Position Estimate (deg.)	Std. Deviation (deg.)	Coef. of Variation	Judgment	
	Initial	Final				Range (deg.)	No.
Pitch 1	0	25	18.22	16.38	0.9	-25 to 78	178
Pitch 2	0	25	40.07	41.21	1.01	8 to 80	152
Roll 1	0	15	11.77	15.97	1.35	-40 to 45	190
Roll 2	0	15	28.14	27.03	0.95	-46 to 85	112

[1] All tests were performed in counterclockwise direction (minus sign indicates clockwise direction).

(in this device) when drivers have been subjected to a visual display that suggests motion that ordinarily would produce such forces.

It is possible that the moving-base device used in this research provides motion and changing exposure to gravity in such a way that kinesthetic, proprioceptive and pressure senses and the otolith are stimulated in similar manner and degree to that experienced when the driver is exposed to inertial forces in a moving automobile. The inappropriate sensations (in the moving-base device) due to stimulation of the semicircular canals are ignored or "overridden" by the strong suggestion of motion that he is receiving from the visual display (a motion picture of a driving scene).