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Foreword

Solution of highway traffic problems demands a knowledge of the human being and his behavior as a road user, since either as a pedestrian or a driver, he is involved as an essential element. This Record presents eight papers and one abridgment which shed light on the performances of road users.

These reports deal with various road-user characteristics including the relation of individuals' driving records to visual acuity, an automatic system for vehicle control, recording of a driver's visual input, study (by simulation) of wrong-way driving on freeway off-ramps, drivers' attitudes toward alternative highways, changes in driver performance with time in driving, effects of fatigue on performance, and nighttime aspects of relative velocity detection by drivers.

This Record will be of particular interest to researchers and innovators concerned with human factors research, driver improvement, visual aspects of driving, and driver performance. The papers dealing with simulation are a contribution to the ever-increasing technology and application developing in this field. Several of the papers offer insight to traffic and highway engineers concerning drivers' views on choice of highways and traffic device location.

Albert Burg and Ronald Coppin discuss relationships between dynamic and static visual acuity and driving records of individuals. On the basis of comparisons of approximately 2,000 California volunteers, the relationship between dynamic visual acuity and driving record was found to be stronger than that between static (standard) visual acuity and driving record.

Three Ohio State University researchers, Robert Cosgriff, John J. English, and William B. Roeca, Jr., researched aspects of automatic longitudinal control of individual vehicles in the traffic stream. Requirements for such a control system are outlined and pertubation effects on the traffic stream resulting from such control are explored.

Study of information needed by the driver was fostered by the development of a vision aperture device by Donald A. Gordon of the U.S. Bureau of Public Roads. The device was designed to isolate and record the driver's visual input. Essential information consists of the road edges and center-lane marking, and it was found that drivers do not have a common manner of securing the necessary visual information.

Slade Hulbert and J. Beers measured driver response to unexpected "Do Not Enter" signs at the University of California simulation laboratory. Red and white signs produced earlier and more correct responses than conventional black and white signs. Several styles of pavement-marking arrows placed on ramps so that wrong-way drivers approach from the point end were also studied. Driver response seemed to indicate that these arrows are not satisfactory alerting devices.

Richard M. Michaels of the Bureau of Public Roads has described an attitude scale for measuring drivers' feelings toward alternate highways. The research explored relations between driver attitudes and their choices, and examined some subjective factors underlying traffic generation and highway use.

Bruce Greenshields of the University of Michigan measured fatigue effects of drivers over a period of time, using the Drivometer. Some aspects of driver performance adversely and sharply decreased when drivers drove under sleep deprivation conditions. Emotional responses temporarily overcame fatigue, but long-term fatigue effects tended to be overriding.

Howard V. Jones and Norman W. Heimstra's South Dakota University study investigated the ability of drivers to make accurate judgments of time required for passing. It was found that drivers are not capable of making critical passing judgments in an accurate manner.

Truman M. Mast, Jones and Heimstra employed a driving simulator to determine the effects of fatigue on driving performance. The results indicated sensitivity to fatigue varies considerably with the task assigned. The importance of motivation was also demonstrated.

E. P. Todosiev and R. E. Fenton investigated velocity estimation in car-following experiments at night. Using a simulator, they found that night velocity thresholds (velocity threshold is that relative velocity at which a headway can be detected with a 50 percent probability at a given headway for a given presentation time) are smaller than day velocity thresholds.

Contents

Visual Acuity and Driving Record

ALBERT BURG, Institute of Transportation and Traffic Engineering, University of California, Los Angeles; and
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•THE INSTITUTE of Transportation and Traffic Engineering at UCLA has for a number of years been conducting research on human factors in transportation. Within this general area considerable activity has been directed toward studying the visual requirements of the driving task. The California Department of Motor Vehicles, because of its responsibility for selecting individuals who should be licensed to drive a motor vehicle, also has a strong interest in knowing the visual requirements of driving, so that a more valid and reliable vision-screening procedure might be used.

It is not surprising, then, to find the Institute and the Department cooperating in a joint research venture whose purpose is to determine whether relationships can be found between how well a person sees and how well he drives, as reflected in his driving record. The U. S. Public Health Service is supporting a three-year research program to study the relationship between vision test scores and driving record. A preliminary report (1) presents a detailed description of the study as well as of the background research leading to it. The purpose of the present paper is to outline the general nature of the research program and to present the results obtained thus far from preliminary data analyses.

OVERALL RESEARCH PLAN

The general procedure followed in the study may be summarized in the following steps:

1. Solicit volunteers from among driver license applicants at Department of Motor Vehicles (DMV) field offices scattered throughout California.
2. Measure visual performance and obtain personal and driving information for these volunteer test-subjects. Also, obtain as much information as possible about "non-test-subjects," i.e., the applicants who refuse to be tested, as a check on the representativeness of the sample.
3. Forward the information obtained to DMV headquarters in Sacramento, where a search is made of each subject's three-year driving record.
4. Whenever possible, locate and examine the insurance record for each applicant tested, to provide a more complete picture of his driving record.
5. Code the accumulated information, place it on IBM punch cards and process the data by means of an IBM 7094 computer at UCLA.
6. Draw conclusions and suggest modifications in present California driver license vision-screening procedures, as warranted by the results.

Each of these steps requires some elaboration.

1. Subject Sample—The goal of the study is to test some 18,000 volunteer driver license applicants from throughout the State of California, in order to obtain as representative a sample of drivers as possible. The obtained sample is periodically compared with an authoritative description of the California driving population (5) as a check on possible sampling bias. There are 46 separate testing locations, and more than 14,000 drivers had been processed as of January 1965.

2. Field Testing—Each subject is given an interview in which detailed personal and driving history information is obtained. Following this, a series of vision tests is

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Paper sponsored by Committee on Road User Characteristics.

administered, including tests for (a) static (or standard) visual acuity; (b) dynamic visual acuity (2, 3, 4), which refers to the ability to perceive an object when there is relative motion between the observer and the object; (c) field of vision; (d) acuity under low illumination; (e) glare recovery; (f) eyedness (which is similar to handedness); and (g) lateral phoria, which is concerned with the "aim" of the eyes, from cross-eyed to wall-eyed, with varying degrees in between. In addition, a record is made of each applicant who declines to take part in the study, for the comparative purposes mentioned.

3. Driving Record Compilation—All information obtained is recorded on specially constructed coding forms, which are then sent to DMV headquarters in Sacramento. The search for driving record information (which may take several months to complete) is initiated at this point.

4. Insurance Record Searching—One of the unique aspects of the study is the cooperation that the insurance industry has extended in permitting project personnel to evaluate insurance records for the people tested in the study. It is unfortunate that no complete record of all the accidents incurred by a driver can ever be available. However, by combining the information on file at DMV headquarters with that available from the insurance company, it is possible to obtain a much more complete picture of the driver's record than would be available from either source alone. As with the information obtained from the subject in the field office, all insurance information is held completely confidential, and cannot affect the subject's license or his relationship with his insurance company in any way.

5. Computer Analysis—Computer programs for the IBM 7094 have been developed, and are continually being modified and updated. An important consideration has been to make the programs as general and flexible as possible, to permit their use on data other than those accumulated in the present study. It is anticipated that these programs will be published at some future date, to make them available to others interested in the same general problem area.

6. Application of Research Results—Assuming the experimental results obtained are the consequence of properly conducted research, the University has met its primary research obligation. The more difficult task lies with operating agencies such as the Department of Motor Vehicles. Their task is to evaluate research findings in order to decide a course of action based not only on such findings, but on economic and time factors as well. In California, for example, if the results of the study were strongly to suggest the addition of 5 minutes of vision-testing in screening each applicant, this would necessitate hiring an additional 132 driver license examiners, an increase of approximately 38 percent over the present manpower requirements. If this figure sounds too high, remember that California issues 12, 700 new or renewal licenses every working day. Thus, the implications of each decision regarding the procedure for granting driver licenses must be carefully studied before action is taken.

DRIVING RECORD INFORMATION RETRIEVAL SYSTEM

Early in the design of the project it was decided that detailed information on accidents and violations was necessary to properly evaluate driving performance in relation to visual performance. For example, certain types of accidents (e.g., equipment failure, or being rear-ended while at a stop signal) obviously are unrelated to vision, and hence must be excluded from the analysis if possible relationships between driving and visual performance are to be uncovered. Thus it became necessary to have specially-trained coders to evaluate and classify each accident in terms of the circumstances surrounding it. To a reduced extent, the same caution had to be applied to evaluation of traffic citations.

Also, because of the volume and complexity of work involved in manually searching, retrieving and coding accident and violation data from the 40-million document driver record file in Sacramento, additional personnel had to be hired, and a detailed accounting system had to be devised to keep track of all work in progress. For example, interview forms for subjects with less than a three-year driving record in California at the time of their testing have to be placed in a "hold" file until such time as a three-year record has accumulated.

Each driver's file in Sacramento consists of his license application, any address changes or failure-to-appear notices, a card for each court conviction for a moving traffic violation, and a card for each accident reported. Culpable and non-culpable accidents are not differentiated in the file, and the coders make no attempt to do so. All documents in the driver record file are maintained for three years, except those for which the law requires a longer retention period.

California law does not require reporting to the State those accidents involving only property damage. Thus, this type of accident, even though important to the project, is not routinely reported by all local law enforcement agencies. The best source of information for such an accident is the driver report required under the state's financial responsibility reporting law. This law requires the driver to report every accident in which the damage to any one vehicle is in excess of $100; however, the report form used for this purpose does not provide detailed information as to the accident circumstances. Fortunately, the driver's insurance carrier and policy number are recorded, and this is useful in insurance record searching.

Since a driver's record file contains an index card indicating merely the occurrence of an accident, in order to learn the details of the accident, e.g., time of occurrence, weather conditions, road conditions, direction of impact, and other critical facts describing the accident circumstances, it is necessary to carry the search for driving record information a step further, i.e., to police investigation reports and/or insurance company records.

California Highway Patrol and other law enforcement agency accident reports are examined for details on accidents under investigation. In addition, through the cooperation of the insurance industry, claims files for subjects in the study are made available to trained project personnel for detailed evaluation.

Although all insurance carriers contacted have indicated willingness to cooperate in the project, for reasons of efficiency and economy files for only the 18 largest carriers in California are being searched. These 18 companies insure over one-half of the insured drivers in California. Results thus far indicate that this additional source of accident information has proved very valuable, since it has made possible the location of an additional 11 accidents for every 100 drivers in the study group, as well as providing detailed information not otherwise available on many other accidents.

Once all aspects of the driving record information search have been completed, the entire set of accumulated data is coded, checked, placed on IBM punch cards and transmitted to the University for data analysis.

Figure 1 shows how data are accumulated and processed for the subject who is tested; Figure 2 shows the comparable sequence for non-test subjects.

RESULTS OF PRELIMINARY ANALYSES

Because of the complexity of the driving record information, there is a lag of several months between the time a driver is tested and the time his IBM cards are at UCLA ready for analysis. In addition, almost 20 percent of the subjects are placed in the hold file until such time as they have accumulated 3 years of California driving experience. It is for these reasons that preliminary data analyses had been conducted on a much smaller number than the more than 14,000 drivers tested.

To the present time, 2 brief analyses have been run. The first one, completed in early 1964, involved 2000 test-subjects and 2200 non-test subjects. In December 1964 similiar analyses on the first 5000 test-subjects were run off. Both analyses were concerned primarily with the relation of visual acuity (both static and dynamic) to driving record. Subsequent analyses will involve other measures of visual performance as well.

In summary, the results of these analyses may be stated as follows:

1. There is evidence suggesting a positive relationship between good dynamic visual acuity and good driving record. The results do not as yet provide unequivocal evidence of a similar relationship between static visual acuity and driving record.
2. There is evidence indicating that a significant difference in driving record exists between volunteer subjects and drivers who refused to participate in the study, the latter having a poorer record.

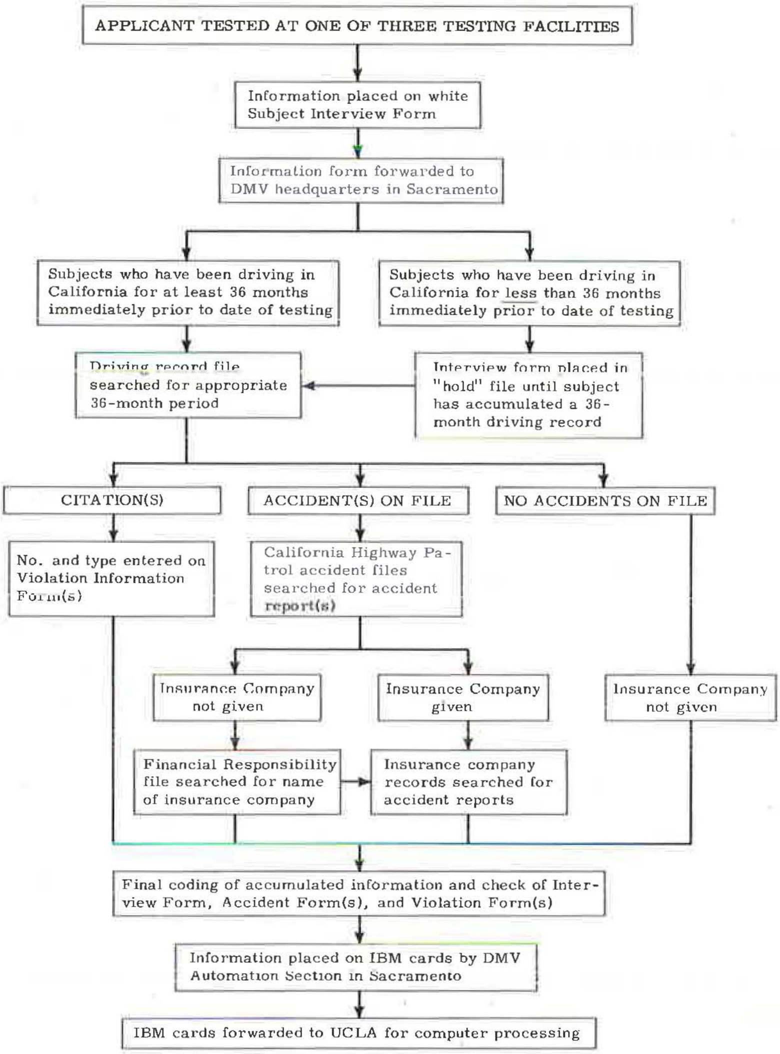

Figure 1. Flow chart of vision-test subject information.

3. The analyses show a definite relationship between performance on the dynamic visual acuity test and sex, age, and static acuity. Performance on the test is poorer for females than for males, becomes gradually poorer with increasing age, and is significantly correlated with static visual acuity. In connection with the last finding, the faster the speed of the target in the dynamic test, the lower the correlation of dynamic acuity performance with static acuity performance.

Each of these findings requires some further explanation. The reason for wishing to obtain information on 18,000 drivers is that such a large number will permit breaking down the sample into many subgroups on the basis of such factors as age, sex and annual mileage, all of which are known to be related to accidents and citations.

However, the relatively small number of subjects available for the preliminary analyses did not permit as fine a breakdown as will be possible with the total sample. For example, it was not possible to analyze separately only those people who drive less than 5000 miles per year as compared with only those who drive over 20,000 miles per year, since the bulk of drivers, who log between 5000 and 20,000 miles per year,

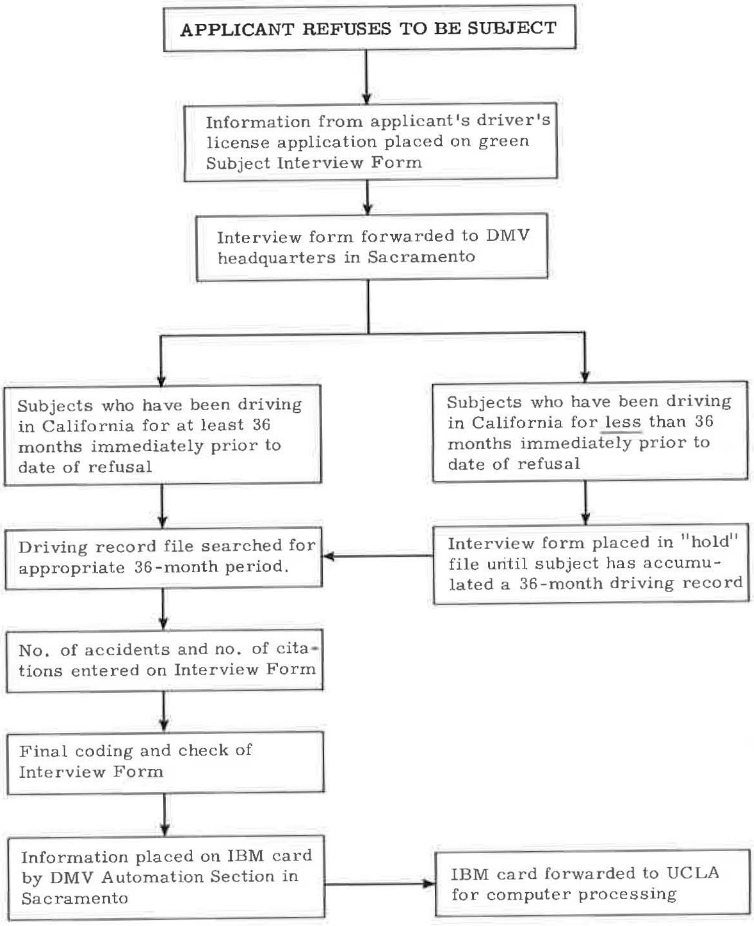

Figure 2. Flow chart of non-vision-test subject information.

would have been eliminated from the analysis. Instead, a median annual mileage was calculated for each of 6 age groups and for males and for females separately, and for each of the resulting 12 age-sex groups the drivers below the median were analyzed separately from those above the median. This provided at least a partial control over the effects of exposure on driving record, although not as much as will be possible later on, of course.

The same discussion applies to age groupings, where analysis of the total sample will permit the use of perhaps 11 age categories, instead of just 6, resulting in a "purer" measure of the relationship between vision and driving.

In view of these comments, it is encouraging that for a number of these 24 age-sex-exposure groupings, a significant chi-square relation was found between good dynamic acuity and both lack of accidents and lack of violations. While this significant relationship was not found for all age-sex-exposure groups, the very fact that any relationship at all showed up is encouraging, in view of the coarseness of the age and exposure controls referred to above. Obviously, however, it is too soon to draw any firm conclusions.

The fact that volunteer subjects appear to have better driving records than non-volunteers is not surprising. It is a small, but significant, difference, and is an important finding in that it serves to caution researchers against over-generalizing the results obtained from a volunteer sample. In the case of the present study, there is no reason to suspect that the "subjects" had significantly different visual characteristics from the "non-subjects," and hence, generalization for the driving population as a whole is permissible. This would not be the case in a study of, say, driver attitude in relation to accident experience.

The major importance of finding that dynamic visual acuity is related to age and sex is that it suggests the possible need for differential licensing requirements for different age-sex categories in the event a dynamic test is ever incorporated into the licensing procedure.

In conclusion, it should be emphasized that the foregoing results are based on limited and preliminary analyses. The findings are merely indicative, and must await confirmation or rejection based on detailed analyses of the total sample of subjects. Nevertheless, regardless of whether the final analyses demonstrate any consistent, significant relationships between vision test scores and driving record, the study will have intrinsic value because for the first time a substantial amount of normative data will be available on a large number of drivers. These normative data will concern not only visual performance and driving record, but other factors as well, such as driving habits, driving experience, age, sex, occupation, smoking habits and many other items included in the interview but not mentioned here. The final report will contain many analyses of these other items, as well as suggestions for an almost unlimited number of additional analyses and cross-tabulations which are now possible for the first time, because of the advanced state of computer technology.

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An Automatic System for Longitudinal Control Of Individual Vehicles

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•IT APPEARS today that considerable improvement in high-density traffic flow can be achieved by automatic control of individual highway vehicles. An automatic system for controlling an individual vehicle in a traffic stream in response to the immediately preceding vehicle is currently being studied. It has been found that there are a number of requirements which must be met by any system for control of vehicles in traffic. The proposed system which meets these requirements is a combination of several control techniques. It should not be surprising that the system is in some ways similar to the driver himself.

This paper includes a short description of the traffic situation variables, the requirements on the system, a description of the system itself, and a discussion of the performance of the system. It is of course impossible to treat the several aspects of this control problem in detail.

NOTATION

Consider a line of n vehicles progressing along a highway in the direction of + x as shown in Figure 1. The lead car will be indexed 1, the indexes of the others progressing to N at the rear; x_i is the distance from a fixed origin on the road to the front of the ith car. The velocity of the ith car relative to the road is

$$v_i = \frac{dx_i}{dt}$$

or, in operator notation,

$$v_i = px_i$$

where

$$p = \frac{d}{dt}$$

The absolute acceleration (relative to the road) of the ith car is

$$a_i = \frac{dv_i}{dt}$$

or, in operator form,

$$a_i = pv_i$$

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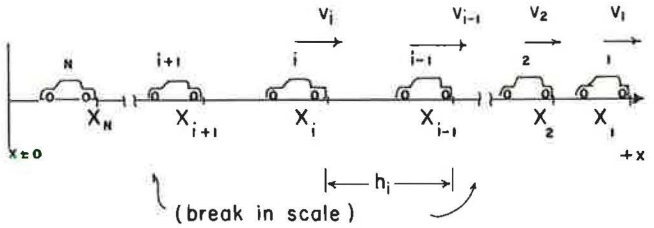


Figure 1. Traffic system variables.

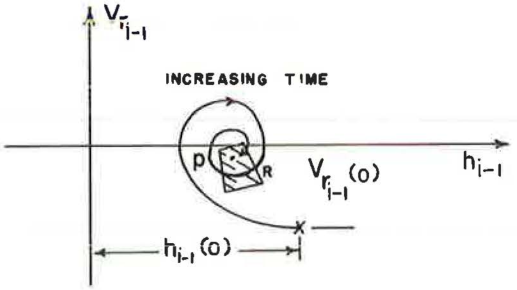


Figure 2. Typical phase plane trajectory.

The headway of the ith car is

$$h_{i-1} = x_{i-1} - x_i$$

The relative velocity or rate of closure between the ith and i - 1 st vehicle is

$$v_{r_{i-1}} = v_{i-1} - v_i$$

$$= ph_{i-1}$$

The relative acceleration of the i - 1 st car from the ith car is

$$a_{r_{i-1}} = a_{i-1} - a_i$$

$$= pv_{r_{i-1}}$$

These are all instantaneous values of variable functions of time.

These variables are conveniently represented by points on phase plane plots. On a phase plane plot, the abscissa of a point is the instantaneous value of the variable, and the ordinate is the instantaneous value of the time derivative of the variable. As time increases, the point representing the variable and its derivative traces out a phase plane trajectory. A typical plot is shown in Figure 2. If the ith car in a line of cars is controlled by an automatic control system, then the point p (the leading end of the phase trajectory) represents the current headway and relative velocity existing between the controlled car and the lead car. The region R represents a set of situations which can exist between the controlled car and the lead car. If the point p is in the region R as shown (Fig. 2), the traffic situation will be referred to as being "in region R" for the purpose of brevity.

Techniques have been developed which make possible the sensing of the lead car by the controlled car. When it is sensed, the controlled car is in the region of influence of the lead car. This region is finite in length, but adequate. Also, the variables $v_{r_{i-1}}$ and h_{i-1} can be computed by electronic circuits in the controlled i th car. The outputs of these circuits are electrical signals proportional to $v_{r_{i-1}}$ and h_{i-1}. In the remainder of this paper this measurement of $v_{r_{i-1}}$ and h_{i-1} is considered ideal.

REQUIREMENTS OF INDIVIDUAL VEHICLE CONTROL SYSTEM

An individual vehicle control system must operate in 2 highway situations: (a) the controlled vehicle by itself on the open road or with large clear distance ahead; and (b) the vehicle in heavy traffic where the controlled vehicle must respond to the vehicle ahead. The first environment indicates the first requirement on the automatic control system: if the headway (the clear distance ahead of the controlled vehicle) is large, then the vehicle must not respond to traffic ahead, but instead must maintain a constant speed chosen by the occupant. It is of course implied that the controlled vehicle in the presence of heavy traffic will not exceed the chosen open road speed.

The remainder of the requirements are associated with the control of the vehicle in response to traffic. In any maneuver the peak acceleration of the controlled vehicle must not exceed its capabilities. Accelerations are usually engine-limited to about 0.2 g to 0.3 g, while decelerations are limited by traction to about 0.5 g, but with considerable variability. Demands of the control system for accelerations higher than the limits of the vehicle result in "saturation," which may take the form of skidding in the case of deceleration. Comfort of passengers dictates peak acceleration and deceleration of 0.1 g to 0.15 g.

A defined steady-state displacement between 2 adjacent vehicles in the same lane of traffic must be maintained, which is a function of the average speed of the traffic stream and not a function of the state at which control was initiated. This headway H should be as small as possible, so as to cause the traffic density (veh/mi) to be as large as possible. An upper bound upon this headway might be

$$H < 2v_{ss} \text{ ft}$$

where v_{ss} is traffic average speed in feet per second (fps).

Finally, and most important, the response of the automatically controlled vehicle to the motion of the preceding vehicle must be stable. This condition is termed local stability. Also, a disturbance in a lead vehicle in a line of identically controlled vehicles must be attenuated as this disturbance propagates back along the line. This is a second type of stability and is termed asymptotic stability (1, 2). In local stability, small limit cycles may be tolerated, but accelerations should be less than 0.1 g, and rear-end collisions must be avoided. Asymptotic stability is assured for linear systems if the response spectrum of the control system (the transfer function with p or S replaced by $j\omega$) has maximum magnitude equal to or less than unity for all frequencies (3). This condition will be considered later.

THRESHOLD CONTROL SYSTEM

A simple threshold device has a single continuously variable input x and an output y of 2 discrete levels. If the input is less than a prescribed value x_0, the output is A, and if the input is greater than x_0, the output is B. This can be described analytically as

$$y = A + (B - A)\, u\, (x - x_0)$$

where

u is the unit step function,
e is any real variable,
$u(e) = 1$ for $e > 0$, and
$u(e) = 0$ for $e < 0$.

Now suppose the device has 2 input variables, x and z. The variable e is now a function of 2 variables. For instance, let e be defined by

$$e = x - x_0 - \frac{z^2}{2}$$

Now $y = A$ when $e < 0$, or when $x < x_0 + \frac{z^2}{2}$. When $x > x_0 + \frac{z^2}{2}$, $y = B$. If a plot is made of z vs x, the threshold is a parabola

$$x = x_0 + \frac{z^2}{2}$$

which divides the z - x plane into 2 regions, one to the left of the parabola and one to its right.

If the variable x is replaced by headway, the variable z by relative velocity, the variable y by acceleration of the controlled car, and if B = 0 and A = a deceleration level, then a very simple control system is described. When the headway h_{i-1} is less than $x_0 + \frac{\left(v_{r_{i-1}}\right)^2}{2}$, the controlled car is decelerated by A ft/sec², and when $h_{i-1} > x_0 + \frac{\left(v_{r_{i-1}}\right)^2}{2}$, the controlled car's velocity is constant. Thus the $v_{r_{i-1}} - h_{i-1}$ phase plane is divided into 2 regions by the parabola,

$$h_{i-1} = x_0 + \frac{\left(v_{r_{i-1}}\right)^2}{2}.$$

To meet the requirements of the traffic environment, a combination of threshold devices is needed which divides the $v_{r_{i-1}} - h_{i-1}$ phase plane into several regions (Fig. 3). There are of course many alternatives, which are being investigated at the present time. A simplified version of Figure 3 is discussed elsewhere (4) in detail, including the performance of the threshold system and the electronic operations necessary to its actuation. The major difference in Figure 3 is the addition of a linear mode, which is discussed in the next section.

The phase plane representation for the threshold control of the ith car is divided into a number of regions (Fig. 3). Each region has associated with it a certain mode of control of the ith car. For example, if $v_{r_{i-1}}$ and h_{i-1} are coordinates of a point in region 2, the ith car is decelerating at a constant 0.1 g. The boundaries of the regions are not trajectories, although certain trajectories can be coincident with some of the boundaries. For instance, the parabolic trajectory of constant relative acceleration $a_{r_{i-1}}$ of + 0.1 g magnitude would be coincident with the parabolic boundary between regions 1 and 2 if the initial point of the trajectory were on the boundary, such as point A. The control in the individual regions is as follows (numbers of regions are circled in Figure 3):

1. In region 1 the system is a speed regulator with constant speed v_d chosen by the driver.
2. In regions 2, 3, 5, 7, 8, 9, and 10, the controlled car is accelerated at the constant values indicated for each region.
3. Region 6 is a linear mode as shown; this provides stability, which will be discussed in the next section.
4. Region 4 control depends on that of the previous region. If region 4 is entered from region 3, then $a_i = -0.5$ g. If region 4 is entered from region 5, $a_i = +0.1$ g in region 4. If region 4 is entered from region 6, $a_i = +0.1$ g in region 4.

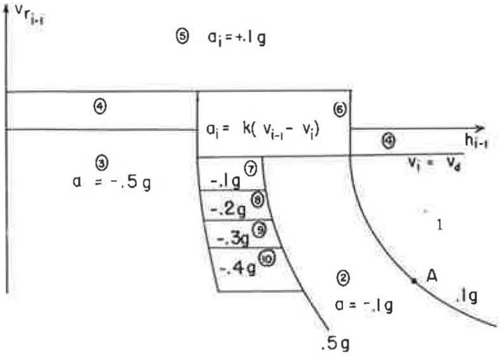


Figure 3. Phase plane representation of the threshold system.

5. An acceleration of 0.1 g initiated in region 5 will be continued through regions 4 and 1 until region 2 is reached.

6. Although not shown on the phase plane, control is $v_i = v_d$ (speed regulation at open road speed) whenever $v_{i-1} > v_d$.

A detailed discussion of the techniques for generating electrical signals $v_{r_{i-1}}$ and h_{i-1} and for actuating the various modes according to Figure 3 is too lengthy to include here. A previous paper (4) discusses these and also presents a detailed description of the response of the threshold system to large disturbances and large transient situations. The present system is essentially the same, except for the inclusion of the linear mode.

LINEAR MODE OF CONTROL

In the study of longitudinal control systems (4) with only threshold modes of control it has been found that the systems give rise to classical limit cycles in the 2-vehicle situation and asymptotic stability problems in a platoon situation. The limit cycles occur because discrete levels of acceleration and deceleration of the controlled car are alternately actuated by means of proper switching to force the controlled car to follow the lead car with a headway fluctuating about a fixed value. The velocity of the controlled car fluctuates about a mean value which is equal to the velocity of the lead car. In the steady state then the acceleration of the controlled car will be a rectangular function of time with zero mean value. Since the points at which switching occurs between the discrete levels of acceleration and deceleration are fixed, the acceleration function is periodic with zero mean. This results in limit cycles. Although limit cycles are not inherently undesirable they tend to cause asymptotic instabilities, and it can be said that the system provides excessive control when the relative velocity between 2 vehicles is small. Such over control would make the ride somewhat uncomfortable while the braking and accelerating components in a vehicle would operate at average levels which are higher than necessary. With these facts in mind a linear mode of operation has been included in the automatic system to operate in the region of desired headway and small relative velocity.

An idealized linear mode of operation for the automatic longitudinal control system valid for small values of v is described by

$$pv_2 = k_1 (v_1 - v_2) \qquad (1)$$

where p is the differential operator equal to d/dt. The acceleration or deceleration of the controlled vehicle in the linear zone is proportional to the relative velocity.

Consider the phase plane diagram (Fig. 4). In a system with only threshold modes of control and the lead vehicle at a constant velocity, classical limit cycles will exist within the region indicated by the dotted lines. Adding a linear mode of the type characterized by Eq. 1 such that the linear mode is activated approximately in the region of classical limit cycles will eliminate these limit cycles. Since $pv_1 = 0$, $pv_2 = -pv$. Eq. 1 then becomes

$$-pv = k_1 v \qquad (1a)$$

which has the solution

$$v = v_o e^{-k_1 t}$$

Integrating both sides of Eq. 1a,

$$v = -k_1 (h + h_o)$$

which is the trajectory in the linear mode. Thus in the linear mode the trajectory approaches the v = 0 axis along a straight line, and the limit cycles are eliminated.

The transfer function* $G_V(p)$ for this type of control relating the velocities of 2 vehicles, v_1 and v_2, is

$$G_V(p) = \frac{v_2(p)}{v_1(p)} = \frac{k_1}{p + k_1} \tag{2}$$

The asymptotic stability of a platoon of vehicles requires that

$$\left| G(j\omega) \right| < 1 \tag{3}$$

$$\left| G(j\omega) \right| = \left| \frac{v_2(j\omega)}{v_1(j\omega)} \right| = \frac{k_1}{\sqrt{k_1^2 + \omega^2}} \tag{4}$$

which is less than or equal to one for all frequencies. Therefore, the system is asymptotically stable for operation entirely within the linear mode.

Another requirement on an automatic system restricts the maximum acceleration and deceleration of a controlled vehicle to approximately 0.1 g for normal operation. The maximum magnitude of trailing car acceleration will occur at either the upper or lower boundary of the region of linear operation. The peak acceleration requirement is satisfied, and also the system acceleration is continuous when switching from the nonlinear region of operation to the linear mode if the velocity boundary of the linear mode is given by

$$\left| v_o \right| = \frac{3.22}{k_1} \text{ fps} \tag{5}$$

---

*The transfer function is a common way of representing a device whose output y is related to its input x by a linear differential equation such as $(a_2p^2 + a_1p + a_o)\, y = (b_1p = b_o)\, x$. The ratio

$$\frac{y}{x} = \frac{b_1p + b_o}{a_2p^2 + a_1p + a_o}$$

is termed the transfer function of the device. If x is assumed to be of the form sin ωt, then replacing p by $j\omega$ gives the magnitude and phase of the steady state solution y relative to the sinusoidal input x.

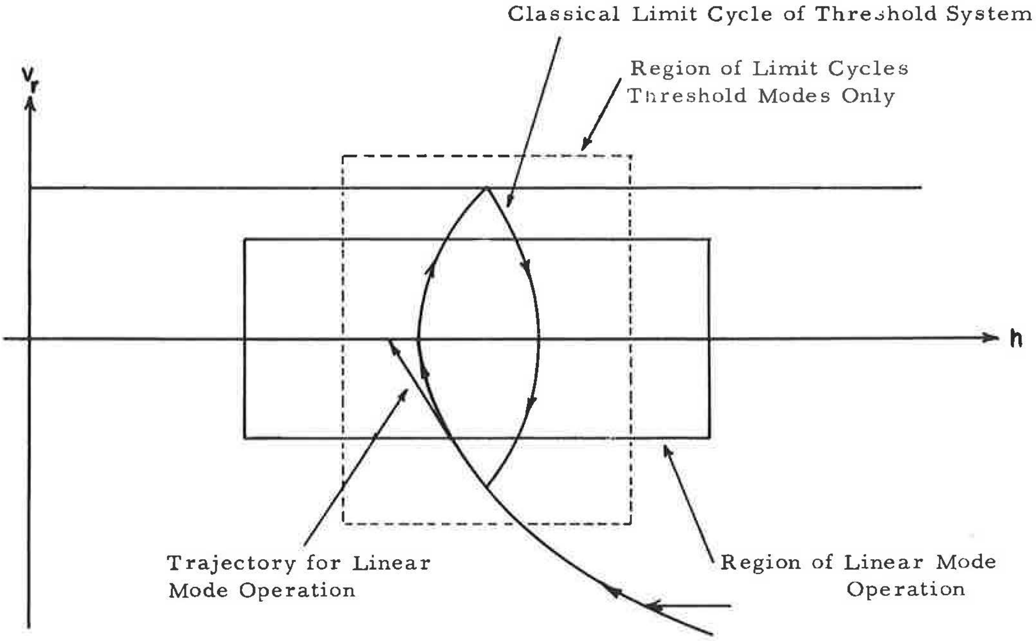


Figure 4. Comparison of trajectories for a system with and without a linear mode of operation (v_1 = constant).

In a platoon of vehicles in steady state traffic flow, lead vehicle velocity may be expressed as

$$v_L = v_{ss} + v_p \tag{6}$$

where

v_L = lead vehicle velocity, v_1 if the first in a platoon;
v_{ss} = constant component of lead vehicle velocity; and
v_p = component due to perturbation.

In this analysis v_p is periodic. The frequency of v_p can vary over a range of values, which are bounded by the dynamic response of an actual vehicle. The lead vehicle velocity is now expressed as

$$v_L = v_{ss} + V_a \sin(\omega t + O) \tag{7}$$

The peak magnitude of lead vehicle acceleration is

$$\left| a_L \right| = \left| \omega V_a \right| \tag{8}$$

In measuring response characteristics, the magnitude of the lead vehicle acceleration was within the range

$$0.03\ g < \left| \omega V_a \right| < 0.5\ g \tag{9}$$

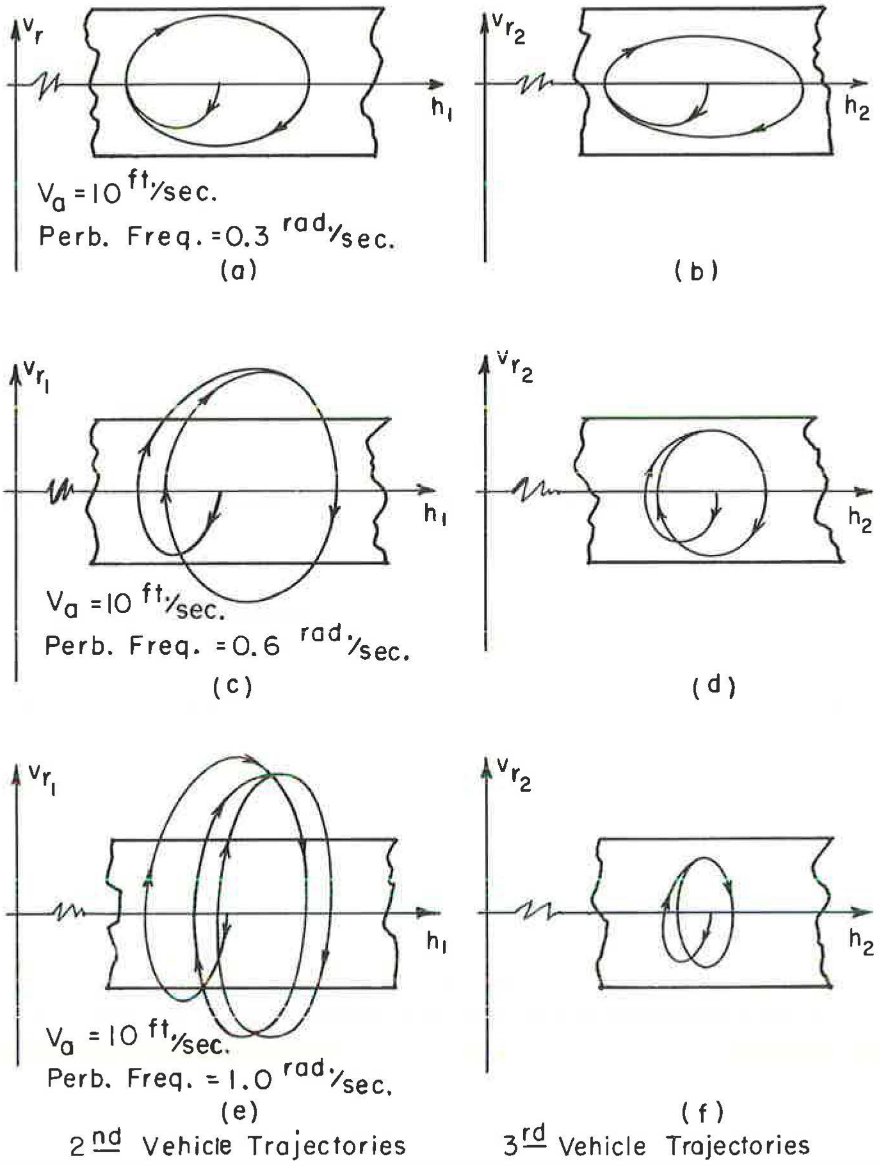
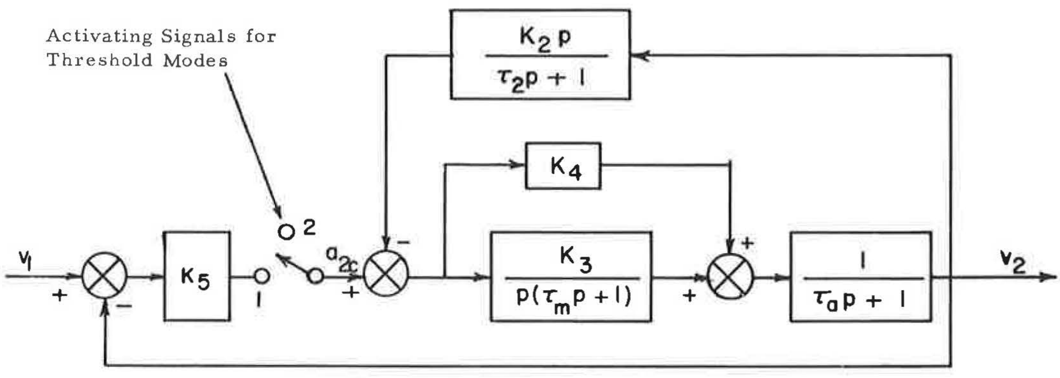


Figure 5. Trajectories illustrating platoon dynamics. Scales: velocity—3/4 in. = 10 ft/sec; headway—3/4 in. = 20 ft.

Figure 5 illustrates some samples of response characteristics for the 3-vehicle platoon with the lead vehicle perturbed at various frequencies. These characteristics were obtained from an analog computer simulation of the automatic system. The trajectories are not limit cycles, but are the system's steady state response to the sinusoidal input. The headway variation of the second vehicle has been reduced by the inclusion of the linear zone.

The platoon characteristics can be observed from the phase plane trajectories of the third vehicle. Figure 5 shows that there is a reduction in headway and relative velocity variations between the second and third vehicles. The desired attenuation of disturbances can be seen in Figures 5d and 5f. In these cases the perturbation frequency is sufficiently high to cause the phase plane trajectory of the second vehicle to pass in and



Switch Positions: 1) Linear Mode of Operation, 2) Threshold Modes of Operation

Figure 6. Block diagram of automatic system (a_{2C} = command acceleration).

out of the region of linear mode control. In spite of this, the trajectory of the third vehicle remains entirely within the linear mode region of control with considerable attenuation in the headway and relative velocity variations.

DESIGN OF A PRACTICAL LINEAR MODE SYSTEM

It is now necessary to include important factors which will be inherent in an actual system but which were not considered in the ideal system of the previous section. The performance of such a vehicle may be approximated by

$$\frac{v_a}{v_c} = \frac{1}{t_a p + 1} \tag{10}$$

where

v_a = actual velocity of vehicle,
v_c = velocity command to vehicle, and
t_a = automobile time constant.

This will be termed a velocity controller. If the acceleration of the controlled vehicle is made to have a component proportional to the headway, several problems arise (1). To actually achieve constant accelerations and decelerations of the controlled vehicle, acceleration feedback is required. A somewhat idealized acceleration feedback loop is shown in Figure 6 because it is relatively straightforward. In practice, however, it is much more convenient to accomplish the same synthesis starting with a rearrangement of Figure 6 which is dynamically equivalent to that shown. The transfer function of an accelerometer can be represented by

$$\frac{a_m}{v_2} = \frac{k_2 p}{t_2 p + 1} \tag{11}$$

where

a_m = output signal of the accelerometer,
v_2 = velocity of vehicle,

t_2 = time constant associated with accelerometer, and
k_2 = gain factor associated with accelerometer.

In the forward path of the system, proportional and integral control are included to provide design flexibility. The system may be represented in block diagram form (Fig. 6). The open-loop transfer function of the acceleration loop is

$$GH = \frac{k_2\,(k_4 t_3 p^2 + k_4 p + k_3)}{(t_m p + 1)\,(t_2 p + 1)\,(t_a p + 1)} \tag{12}$$

where G is the forward path transfer function and H is the feedback path transfer function. The zeros of GH may be used to cancel the poles at $-1/t_2$ and $-1/t_a$ by setting

$$k_3 = \frac{k_4}{t_a}\left[1 - \frac{t_m}{t_a}\right]$$

and

$$\frac{1}{t_2} = \frac{1}{t_m} - \frac{1}{t_a}$$

The complex frequency plane considering the poles and zeros of the expression given by Eq. 12 is shown in Figure 7.

The transfer function of the system with the velocity feedback path open is

$$\frac{v_2}{v_r} = \frac{k_4 k_5\,(t_2 p + 1)}{t_a\left[1 - \frac{t_m}{t_a}\right] p \left[t_m\,p + 1 + \frac{k_2 k_4}{t_a\left[1 - \frac{t_m}{t_a}\right]}\right]} \tag{13}$$

(see Fig. 6). The root locus is shown in Figure 8.

This design procedure enables one to specify the dominant pole of $G_V(p) = \frac{v_2\,(p)}{v_1\,(p)}$ which determines the transient response of the system. Further specification of the system will be accomplished by fixing the dominant pole of the closed loop transfer function at an arbitrary value $-1/t_o$. To have a pole of the transfer function at $-1/t_o$, the gain factor

$$\frac{k_4 k_5}{t_a\left[1 - \frac{t_m}{t_a}\right]}$$

is determined by

$$\frac{k_4 k_5}{t_a\left[1 - \frac{t_m}{t_a}\right]} = \frac{\frac{1}{t_o}\left[\frac{1}{t_m} + \frac{k_2 k_4}{t_a t_m\left[1 - \frac{t_m}{t_a}\right]} - \frac{1}{t_o}\right]}{\left[\frac{1}{t_2} - \frac{1}{t_o}\right]} \tag{14}$$

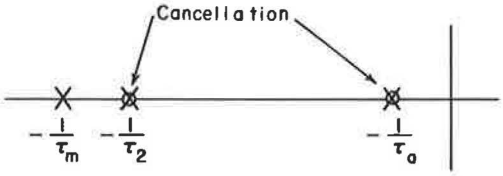


Figure 7. Cancellation of poles and zeros of GH expression.

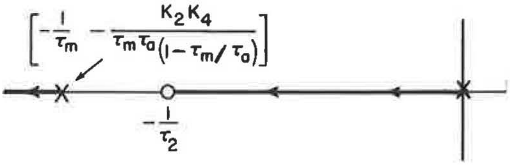


Figure 8. Root locus of the velocity feedback loop.

Solving for k_4

$$k_4 = \frac{\dfrac{t_a\left[1 - \dfrac{t_m}{t_a}\right]}{t_o}\left[\dfrac{1}{t_m} - \dfrac{1}{t_o}\right]}{k_5\left[\dfrac{1}{t_2} - \dfrac{1}{t_o}\right] - \dfrac{k_2}{t_ot_m}} \tag{15}$$

It is desirable in this system that the command acceleration be continuous at the boundary of linear and nonlinear modes. Continuity can be provided at this point if

$$A_1k_2 = v_ok_5 \tag{16}$$

where

A_1 = magnitude of command acceleration at boundary
= 0.1 g = 3.22 ft/sec^2,
v_o = magnitude of relative velocity at boundary, and
v_k = 5 ft/sec.

Therefore, $k_2 = B_1k_5$ where $B_1 = \frac{v_k}{A_1}$. It is now possible to specify the product k_4k_5 as

$$k_4k_5 = \frac{\dfrac{t_a}{t_o}\left[\dfrac{1}{t_m} - \dfrac{1}{t_o}\right]\left[1 - \dfrac{t_m}{t_a}\right]}{\left[\dfrac{1}{t_2} - \dfrac{1}{t_o} - \dfrac{B_1}{t_ot_m}\right]} \tag{17}$$

Asymptotic stability of the system requires that the v_2/v_1 transfer function satisfy

$$\left|\frac{v_2}{v_1}\right| < 1$$

For this system,

$$\frac{v_2(p)}{v_1(p)} = \frac{\frac{k_4 k_5}{t_a}\left[t_2 p + 1\right]}{t_2 p^2 + \left[1 + \frac{k_2 k_4}{t_a} + \frac{t_2 k_4 k_5}{t_a}\right] p + \frac{k_4 k_5}{t_a}} \qquad (18)$$

The inequality is easily satisfied by investigating the magnitude of Eq. 18 as a function of frequency. The constraints that have already been placed on the system performance have also insured asymptotic stability of the system.

SUMMARY

An automatic longitudinal control system for control of individual vehicles in the traffic stream has been presented. In order to meet the many requirements on such a system it was necessary to combine both linear and nonlinear modes of control in the system. The system has been analyzed in the car-following situation in single lane traffic with up to 3 cars in a line. More extensive evaluation for many cars in a platoon and for comparison with the present manual system has not been completed. However, the results of present analysis indicate that good performance can be expected.

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Experimental Isolation of the Driver's Visual Input

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•AN UNDERSTANDING of the driver's visual input provides a rational basis for many aspects of highway design. Knowing what information the driver uses, we can design roads which insure that he receives this information. Since no experimental technique existed by which the visual factors in driving could be isolated, their nature has been mainly the subject of conjecture.

From a scientific viewpoint, the isolation of visual input is both important and baffling. This information used by the driver sets off an action sequence which eventuates in the steering, braking, and acceleration of the car itself. Without knowing the stimulus which first triggers the driver's reactions, the consequent reactions are not easily understood. And when man's input has been specified, driving itself will be to a considerable extent described. But the problem is difficult. The binocular field presents an enormous amount of information. We do not have communication lines to the driver's eyes or brain allowing us to determine how he selects and sorts this sensory input. If we ask the driver what he is responding to, we obtain suggestive, but in no sense trustworthy answers.

A technique to determine what features of the road and terrain the driver is responding to is presented in this study. The method involves having the driver guide the car while looking through a device containing a small aperture. By decreasing the visual field, the essential information, whatever it is, cannot be seen at once, i.e., the driver is forced to obtain this information in separate visual fixations. A continuous film record is made of the driver's field of view which is later analyzed to indicate the center of his visual aim and the content of each fixation. The essential information he is using is easily identified in each separate restricted fixation. (This technique may also be used to determine the aircraft pilot's perceptual input, and may be applicable, with modifications, to problems of human console design.) This approach has advantages over eye camera techniques which provide a record of fixation position. The eye camera does not show the contribution of peripheral vision, nor does it provide a means of distinguishing essential from nonessential information.

BACKGROUND

Various sorts of information have been suggested as underlying the maneuvers of driving (2, 3, 4, 5). A general listing, made by a race driver and the editor of a scientific magazine who evaluated the attention paid to conspicuous features of the environment, may be taken as representative (6):

Race driver	Rank	Editor
View of the road ahead	1	View of the road ahead
Seat of the pants feel (transverse accelerations)	2	View of the car ahead
Tachometer	3	Feel of steering wheel
Feel of steering wheel	4	View of the road edge
Engine sound	5	Speedometer
View of the road behind	6	View of the road behind

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Race driver	Rank.	Editor
Oil pressure gage	7	Seat of the pants feel (transverse accelerations)
View of the car ahead	8	Engine sound
View of the road edge	9	Blinking lights
Smells	10	Tire noise
Tire noise	11	Smells
Blinking lights	12	Oil-pressure gage
Speedometer	13	—

The view of the road ahead was assigned first place by both raters. Otherwise, there is a considerable lack of conformity in the ratings of the race driver and editor, possibility reflecting a real difference in approach to driving.

A rigorous experimental method is obviously required to determine what the driver is actually looking at and responding to. Michaels and Cozan (5) have been perhaps the first to use rigorous experimental methods to validate a driving input. In field tests using lateral movement detectors, they showed that the driving response is inversely related to the sidewise drift of the approaching object or vehicle.

APPARATUS

An aperture device was developed which restricted the driver's vision and recorded his visual fixation positions. This device has the following main parts (Fig. 1):

1. Head helmet—Large plastic football helmet with frame supports to hold aperture and fiberglass pulpit. An inflatable bladder fills the space between helmet and head and holds the helmet firmly in place.
2. Aperture observation tube—Tube 3½ in. in length, 1 in. in diameter. The tube can be raised or lowered to accommodate the observer's eye. Aperture disks of varying size may be fitted on the end of the tube. A circular screen covers peripheral areas of the driver's field, and an eye patch fits on his unused eye.
3. Camera—8-mm camera mounted coaxially with the aperture tube. The camera has automatic (photoelectric) shutter and battery powered feed. Zoom lens is set at 8-mm focal length. Speed of camera is slowed to 11 frames per sec. The 25-ft film roll gave 178 sec of record, enough to cover the experimental course.

THE DRIVERS

Ten volunteers (7 male, 3 female) from the Bureau of Public Roads served as test drivers. All subjects had vision rated good enough to drive without glasses. The drivers ranged in age from 19 to 38; mean age was 27.7 years. Number of years of driving experience ranged from 1 to 24, with a mean of 10.3 years.

DRIVING COURSE AND TEST VEHICLE

A curved 2-lane road at Fairbank Research Center, with low traffic density, served as test course (Fig. 2). It was 22 ft in width, had a 4-in. wide yellow center strip and was paved in blacktop. The shoulders of the road were planted in grass. The 2,805-ft length included a left and right curve. A "Carryall" station wagon was used as test vehicle. To permit headroom for the helmet, the front seat of the vehicle was removed and a low cushion substituted for it. The test drivers could see over the hood without difficulty.

PROCEDURE

The procedure included both practice and experimental phases. The program was carried out in a single hour session.

Practice and Familiarization Phase

The driver was instructed that he would be required to guide the car with restricted vision. He then practiced on a curved and hilly course (not the test course) first without

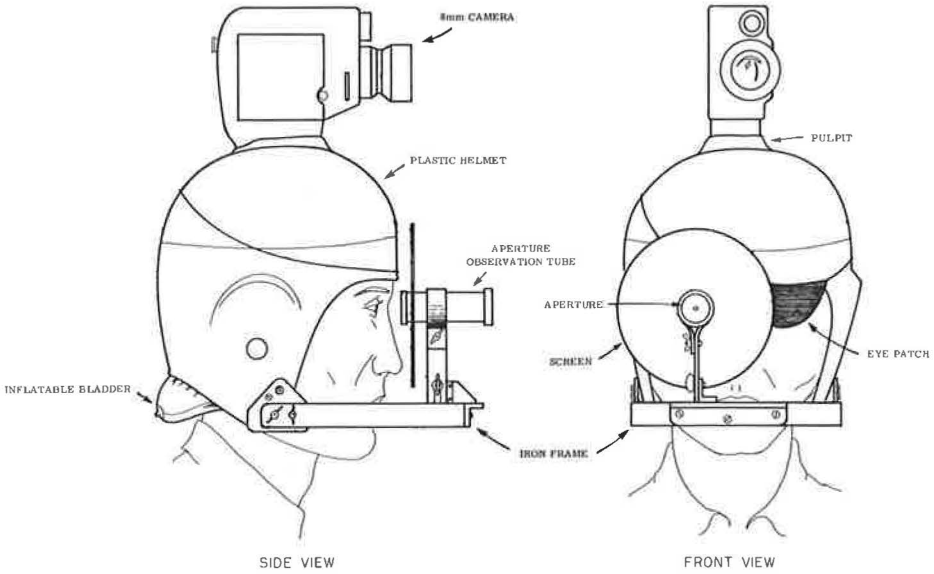

Figure 1. The aperture device.

the aperture device, and later with it. After practice, he was asked 3 questions:

1. On the left curves, what did you look at mainly?
2. On the right curves, what did you look at mainly?
3. Was there any consistent pattern of movement of fixations from side to side or backwards and forwards that you adopted?

Experimental Phase

The driver operated in this phase with (a) open vision, (b) a large ($9\frac{3}{4}$ deg) aperture, and (c) a small (4 deg) aperture.

Open Viewing.—This condition was intended to provide a comparison of aperture driving with normal driving. The observer continually reported his visual fixation position on a tape recorder. After driving, the observer was asked the 3 questions listed under practice and familiarization.

Large Aperture Viewing.—The comparison of this condition with the small-aperture conditions which followed permitted an analysis of size effects. The procedure included calibration of the aperture device and data collection.

Calibration of the Aperture Device.—The driver centered-in the aperture, using the image of a 2-in. square piece of white paper tacked to a tree situated about 50 ft away. The experimenter then adjusted wooden uprights until they appeared exactly on the left and right limits of the driver's field of view (Fig. 3). The experimenter made a brief film record of the adjustment and cautioned the driver not to shake the helmet. The center spot and stakes appeared later on the developed film and thus indicated the center and limits of the driver's field of view.

Data Collection.—The driver drove the course while a continuous film record of his visual fixations and a tape recording of his verbal identifications of position were taken. Camera and tape recordings were synchronized by the experimenter who periodically interrupted the lens field, simultaneously producing an auditory signal. After the trial, the driver was asked what he looked at on the left and right curves.

Small Aperture Viewing.—The small aperture condition showed the driver's visual behavior under the stress of extreme information limitation. The procedure was

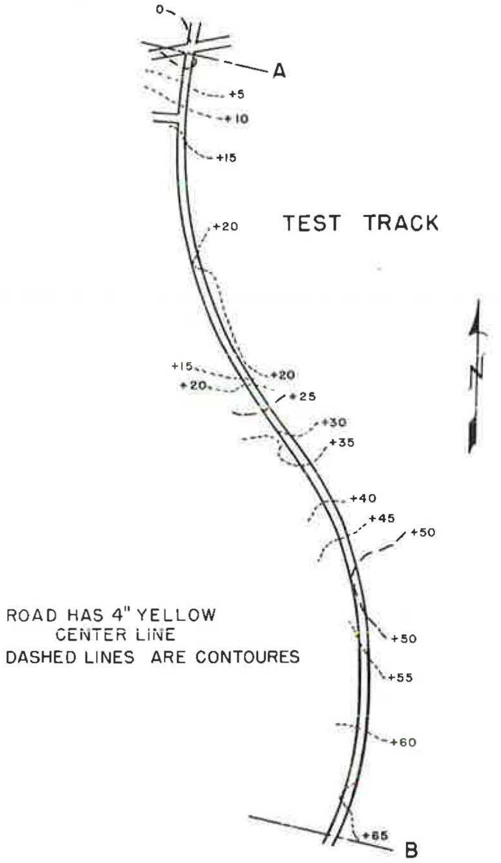

Figure 2. The experimental course.

essentially the same as that in the large aperture condition. Four drivers started at the A end of the track, four at B (Fig. 2). Sequence 1 and Sequence 2 (5 drivers each) were as follows:

Open viewing	A — B — A	B — A — B
Large aperture	B — A — B	A — B — A
Small aperture	A — B — A	B — A — B

The variation in starting position provided a replication of the procedure.

ANALYSIS—FIXATION AREA AND FIXATION POSITION

Each driver's record was divided into separate fixations, i.e., visual positions held until another was clearly assumed. Duration of each fixation was determined from its film length, using the known rate of film movement. A total of 3,305 separate fixations were analyzed on the 4,152 inches of film recorded by the 10 drivers.

The records were considered from the viewpoint of fixation area and fixation position. The area of fixation described the most inclusive road region covered in the 4 deg (small) or 9¾ deg (large) aperture. This analysis may be clarified by the sample areas shown in Figure 4. The "whole road" area implied that both left and right edges of the road were included in the fixation. The "left lane" included

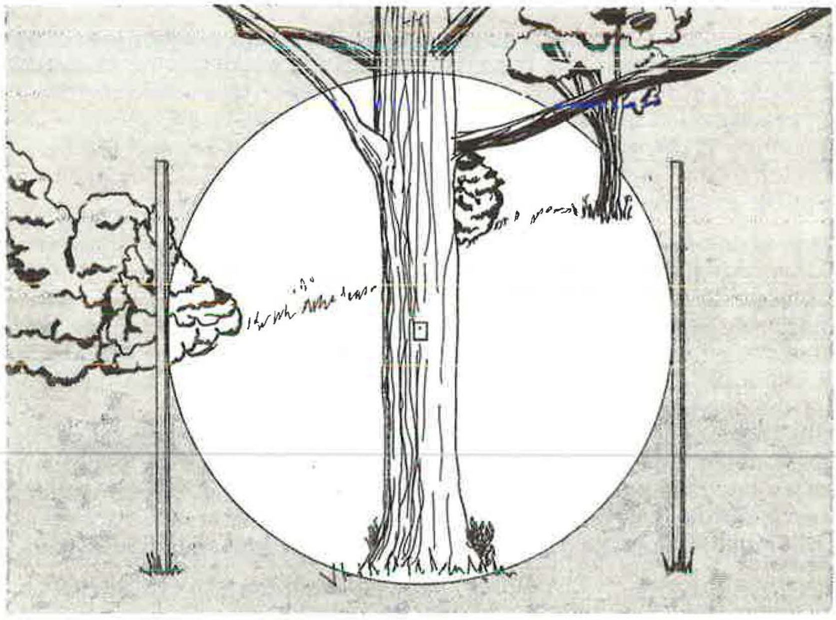

Figure 3. The calibration arrangement.

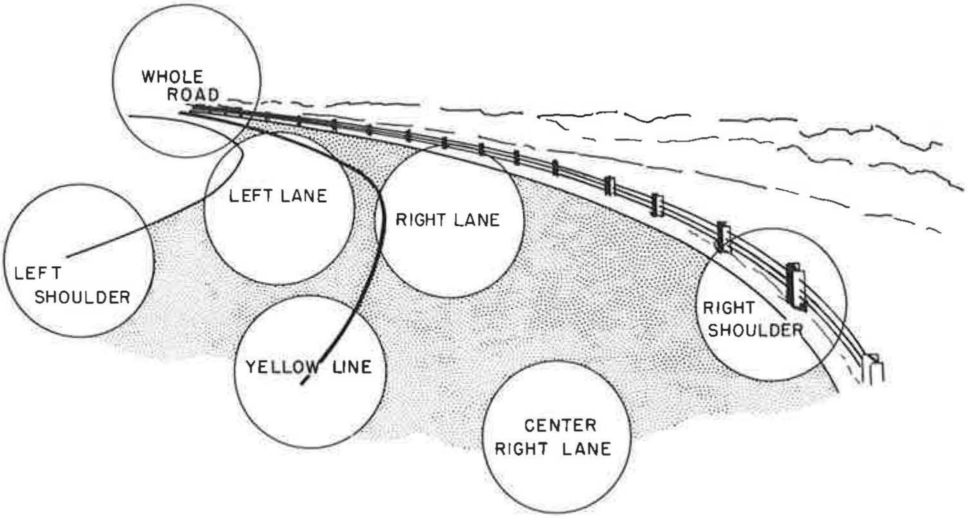

Figure 4. Sample fixation areas.

the left edge and center line, "right lane" covered the center line and right edge. The "yellow line," "left shoulder" and "right shoulder" designations required that visual fixation cover these features singly. In a few instances the fixations were coded as "center of the left lane" or "center of the right lane." These areas did not include an edge or the center line.

Fixation position designated the center of the fixation circle, which usually fell on the left shoulder, yellow line, right shoulder, or center of the right or left lane. Distance from the driver's eye was determined by noting on the film editor the width of the road at the center of aim. This width could then be compared with precalibrated road widths at 50, 100 and 150 ft from the camera. The fixations could be classified as less than 50 ft, 50-100 ft, 100-150 ft, or greater than 150 ft.

RESULTS

Essential Information Used by the Driver

The essential information, as revealed by the drivers' fixations, is the road edges and centerline. The importance of these features is shown by the summary results of fixation area and position given in Tables 1 and 2. It is significant that 96.4 percent of small aperture viewing and 99.8 percent of large include an edge or center of the road. (Fixation times coded under "other areas" may not have included an edge or the center.)

The fixation position data given in Table 2 confirm the importance of edge and centerline information. It appears that 80.9 percent of the large aperture fixations and 85.7 percent of the small fell on edges or the centerline. Fixations not on these features include "center of right lane," "center of left lane" and "trees on left and right." In view of the legitimate demands on the driver's attention of signs and passing cars, it is noteworthy that so high a proportion of fixations centered on the road and edge borders.

The road edges and centerline are also referred to in taped verbal statements made by the drivers on-route, summarized in Table 3. Statements such as "now my eye is on the yellow line" or "right shoulder—near" are coded as referring to the road. Such statements as "my vision just shifted back out where the sign is on the curve," or "there is an electric pole in front of us" are coded as not referring to the road. It may be seen that 96.3 percent of the small aperture comments, 95.5 percent of the large, and 87.2 percent of the comments with no aperture, referred to the road. The answers to the questions asked at the conclusion of each run support the same conclusion. All 10 drivers stated that they used the yellow line, and 9 of the 10 mentioned the right

TABLE 1

TIME ON VARIOUS FIXATION AREAS

(Summary—10 Drivers, Combined Left and Right Curves)

Aperture	Distance (ft)	Left Lane		Yellow Line		Right Lane		Whole Road		Other Areas[a]		Total	
		Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
Large	>150	51.82	4.30	2.58	0.21	140.84	11.70	486.42	40.38	—	—	681.66	56.59
	100-150	26.58	2.20	3.08	0.26	53.41	4.43	156.77	13.02	—	—	239.84	19.91
	50-100	12.98	1.08	4.41	0.37	63.02	5.23	155.07	12.87	1.00	0.08	236.48	19.63
	<50	3.45	0.29	5.60	0.46	12.15	1.01	24.56	2.04	0.82	0.07	46.58	3.87
	Total	94.83	7.87	15.67	1.30	269.42	22.37	822.82	68.31	1.82	0.15	1,204.56	100.00
Small	>150	179.22	14.27	75.21	5.99	355.49	28.31	197.09	15.70	19.23	1.53	826.24	65.80
	100-150	25.32	2.02	46.60	3.71	97.87	7.80	33.13	2.64	13.13	1.04	216.05	17.21
	50-100	8.67	0.69	52.91	4.21	102.65	8.17	11.38	0.91	11.04	0.88	186.65	14.86
	<50	0.86	0.07	8.41	0.67	14.31	1.14	1.34	0.10	1.85	0.15	26.77	2.13
	Total	214.07	17.05	183.13	14.58	570.32	45.42	242.94	19.35	45.25	3.60	1,255.71	100.00

[a] Left shoulder, center left lane, center right lane, right shoulder.

TABLE 2

TIME ON VARIOUS FIXATION POSITIONS

(Summary—10 Drivers, Combined Left and Right Curves)

Aperture	Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Center Right Lane		Center Left Lane		Trees, Left & Right		Total	
		Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
Large	>150	150.28	12.47	129.19	10.72	340.89	28.30	44.15	3.67	10.19	0.85	6.96	0.58	681.66	56.59
	100-150	37.82	3.14	58.49	4.86	83.81	6.96	41.37	3.43	18.16	1.50	0.19	0.02	239.84	19.91
	50-100	12.01	1.00	49.06	4.07	85.28	7.08	83.90	6.96	6.22	0.52	—	—	236.48	19.63
	<50	—	—	12.53	1.04	15.28	1.27	18.59	1.54	0.19	0.02	—	—	46.58	3.87
	Total	200.11	16.61	249.27	20.69	525.26	43.61	188.01	15.60	34.76	2.89	7.15	0.60	1,204.56	100.00
Small	>150	104.49	8.32	357.60	28.48	252.88	20.14	87.41	6.96	10.71	0.85	13.15	1.05	826.24	65.80
	100-150	18.50	1.47	80.34	6.40	77.80	6.20	34.04	2.71	5.37	0.43	—	—	216.05	17.21
	50-100	2.72	0.22	79.91	6.36	79.11	6.30	21.65	1.72	3.26	0.26	—	—	186.65	14.86
	<50	0.33	0.03	12.53	1.00	10.39	0.82	2.93	0.23	0.59	0.05	—	—	26.77	2.13
	Total	126.04	10.04	530.38	42.24	420.18	33.46	146.03	11.62	19.93	1.59	13.15	1.05	1,255.71	100.00

TABLE 3

ON-ROUTE IDENTIFICATION OF FIXATION POSITIONS
(10 Drivers, Tape Recorder Data)

Driver	Open Viewing		Large Aperture		Small Aperture	
	Total No. Statements	Referring to Road	Total No. Statements	Referring to Road	Total No. Statements	Referring to Road
E. C.	7	4	13	10	9	7
G. W.	28	26	15	14	11	11
D. U.	11	6	13	13	9	9
G. R.	23	22	34	34	38	38
L. H.	3	3	9	9	15	15
S. B.	33	33	65	65	58	58
G. P.	16	14	11	11	22	20
R.O'C.	37	32	60	59	105	103
B. C.	18	14	30	24	30	27
F. T.	11	9	15	14	25	22
Total	187	163 (87.2%)	265	253 (95.5%)	322	310 (96.3%)

shoulder at least once during the trials. The remaining comments referred mainly to anticipation and alignment.

The finding that the driver depends upon road edges and the centerline for guidance has a number of implications for highway research. The desirability of marking these highway edges is shown. Poor road edge contrast will affect the safety of the driver and the movement of traffic, particularly at night or in fog. These findings also have a bearing on lateral guidance theories. The suggestion is supported that steering the car involves the maintenance of an acceptable steady-state visual condition and the nulling of deviations from an acceptable state (2). The theory that the visual feedback for steering is the slewing and sideslipping movements of road boundaries is also supported (2). However, present findings do not themselves prove these theories to be correct. The findings also have implications for the direction of future research. Visibility studies should be undertaken of road edges and centerlines under conditions of night and fog. Such researches would assess the penalty of adverse visibility conditions and show the advantages of highway markings, reflectors, luminaires and other devices. The visibility of lane and edge markings may be assessed through available formulas involving luminance, size, and background contrast (1).

How Drivers Obtain Essential Information; Forward Reference Distance

Although all drivers guided the vehicle by reference to the road edges and the centerline, the manner in which information was obtained differed. The variation in approach is clearly illustrated in individual records given in Tables 4 to 15. Driver G. P. (Tables 4 to 7) tended to view the yellow centerline at a distance beyond 150 ft, thus including the yellow line or right lane in the field of view of the small aperture and the entire road in the large. G. W. (Tables 8 to 11) looked mainly at the right shoulder. A third approach was taken by R.O'C. (Tables 12 to 15) who shifted fixations between the centerline and the right shoulder. His main center of viewing was beyond 150 ft. These records refute the notion that a common sequence of viewing is shared by all drivers.

It has been proposed that the driver has a fixed forward fixation distance which increases with vehicular speed (8). If the driver did not look ahead to compensate for man-vehicle reaction, he could not meet the current situation. Forward reference distance should increase with vehicular speed to compensate for increased stopping time.

To test the validity of the forward reference formulation, correlations were computed on the 10 test drivers between speed and average forward reference distance. Driver speed was obtained by determining the film time between known points on the course. Distance divided by time then indicated rate. The average forward reference distance was obtained by averaging fixation distances.

TABLE 4

DRIVER G.P.—FIXATION AREA TIME WITH SMALL APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Left Lane		Yellow Line		Right Lane		Whole Road		Left Shoulder		Right Shoulder		Total	
	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
>150	35.47	23.9	37.73	25.5	18.61	12.6	38.96	25.8	7.12	4.8	2.63	1.8	139.82	94.4
100-150	—	—	4.67	3.1	—	—	—	—	—	—	—	—	4.67	3.1
50-100	—	—	2.45	1.6	—	—	0.70	0.5	—	—	0.11	0.1	3.26	2.2
<50	—	—	0.41	0.3	—	—	—	—	—	—	—	—	0.41	0.3
Total	35.47	23.9	45.26	30.5	18.61	12.6	38.96	26.3	7.12	4.8	2.74	1.9	148.16	100.0

TABLE 5

DRIVER G.P.—FIXATION POSITION TIME WITH SMALL APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Total	
	Sec	%	Sec	%	Sec	%	Sec	%
>150	3.26	2.2	124.11	83.3	12.45	8.4	139.82	94.4
100-150	—	—	4.67	3.1	—	—	4.67	3.1
50-100	—	—	3.15	2.1	0.11	0.1	3.26	2.2
<50	—	—	0.41	0.3	—	—	0.41	0.3
Total	3.26	2.2	132.34	89.3	12.56	8.5	148.16	100.0

TABLE 6

DRIVER G. P.—FIXATION AREA TIME WITH LARGE APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Yellow Line		Whole Road		Total	
	Sec	%	Sec	%	Sec	%
>150	0.82	0.7	111.43	93.3	112.25	94.0
100-150	0.89	0.8	4.67	3.9	5.56	4.7
50-100	—	—	1.19	1.0	1.19	1.0
<50	—	—	0.37	0.3	0.37	0.3
Total	1.71	1.5	117.66	98.5	119.37	100.0

TABLE 7

DRIVER G.P.—FIXATION POSITION TIME WITH LARGE APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Trees		Total	
	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
>150	27.69	23.2	39.60	33.2	43.74	36.6	1.22	1.0	112.25	94.0
100-150	.74	0.6	3.22	2.7	1.60	1.4	—	—	5.56	4.7
50-100	—	—	1.19	1.0	—	—	—	—	1.19	1.0
<50	—	—	.37	0.3	—	—	—	—	0.37	0.3
Total	28.43	23.8	44.38	37.2	45.34	38.0	1.22	1.0	119.37	100.0

TABLE 8

DRIVER G. W.—FIXATION AREA TIME WITH SMALL APERTURE, COMBINED LEFT AND EIGHT CURVES

Distance (ft)	Right Lane		Whole Road		Total	
	Sec	%	Sec	%	Sec	%
>150	8.23	8.4	7.12	7.2	15.35	15.6
100-150	30.40	30.8	3.15	3.2	33.55	34.0
50-100	47.15	47.9	0.11	0.1	47.26	48.0
<50	2.37	2.4	—	—	2.37	2.4
Total	88.15	89.5	10.38	10.5	98.53	100.0

TABLE 9

DRIVER G. W.—FIXATION POSITION TIME WITH SMALL APERTURE, COMBINED LEFT & RIGHT CURVES

Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Center Right Lane		Total	
	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
<150	0.41	0.4	2.74	2.8	12.20	12.4	—	—	15.35	15.6
100-150	—	—	0.26	0.2	32.92	33.4	0.37	0.4	33.55	34.0
50-100	—	—	0.11	0.1	47.15	47.9	—	—	47.26	48.0
<50	—	—	—	—	2.37	2.4	—	—	2.37	2.4
Total	0.41	0.4	3.11	3.1	94.64	96.1	0.37	0.4	98.53	100.0

TABLE 10

DRIVER G.W.—FIXATION AREA TIME WITH LARGE APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Right Lane		Whole Road		Total	
	Sec	%	Sec	%	Sec	%
<150	32.66	30.8	64.20	60.7	96.86	91.5
100-150	7.34	7.0	0.56	0.5	7.90	7.5
50-100	0.52	0.5	0.52	0.5	1.04	1.0
<50	—	—	—	—	—	-
Total	40.52	38.3	65.28	61.7	105.80	100.0

TABLE 11

DRIVER G. W.—FIXATION POSITION TIME WITH LARGE APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Center Right Lane		Total	
	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
>150	13.72	13.0	6.86	6.5	72.65	68.6	3.63	3.4	96.86	91.5
150-100	—	—	—	—	7.90	7.5	—	—	7.90	7.5
50-100	—	—	0.52	0.5	0.52	0.5	—	—	1.04	1.0
<50	—	—	—	—	—	—	—	—	—	—
Total	13.72	13.0	7.38	7.0	81.07	76.6	3.63	3.4	105.80	100.0

TABLE 12

DRIVER R.O'C.—FIXATION AREA TIME WITH SMALL APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Left Lane		Yellow Line		Right Lane		Whole Road		Total	
	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
>150	53.45	31.5	10.94	6.4	56.64	33.3	31.17	18.4	152.20	89.6
100-150	1.74	1.0	2.19	1.3	13.16	7.7	—	—	17.09	10.0
50-100	—	—	—	—	0.63	0.4	—	—	0.63	0.4
<50	—	—	—	—	—	—	—	—	—	—
Total	55.19	32.5	13.13	7.7	70.43	41.4	31.17	18.4	169.92	100.0

TABLE 13

DRIVER R.O'C.—FIXATION POSITION TIME WITH SMALL APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Center Right Lane		Center Left Lane		Total	
	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
>150	22.28	13.1	57.90	34.1	42.00	24.7	28.20	16.6	1.82	1.1	152.20	89.6
100-150	0.07	0.0	4.82	2.8	9.68	5.7	2.52	1.5	—	—	17.09	10.0
50-100	—	—	—	—	0.63	0.4	—	—	—	—	0.63	0.4
<50	—	—	—	—	—	—	—	—	—	—	—	—
Total	22.35	13.1	62.72	36.9	52.31	30.8	30.72	18.1	1.82	1.1	169.92	100.0

TABLE 14

DRIVER R.O'C.—FIXATION AREA TIME WITH LARGE APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Right Lane		Whole Road		Total	
	Sec	%	Sec	%	Sec	%
>150	20.80	16.2	72.39	56.1	93.19	72.3
100-150	7.12	5.5	27.58	21.4	34.70	26.9
50-100	1.07	0.8	—	—	1.07	9.8
<50	—	—	—	—	—	—
Total	28.99	22.5	99.97	77.5	128.96	100.0

TABLE 15

DRIVER R.O'C.—FIXATION POSITION TIME WITH LARGE APERTURE, COMBINED LEFT AND RIGHT CURVES

Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Center Right Lane		Total	
	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
>150	13.61	14.4	12.49	9.7	60.20	46.7	1.89	1.5	93.19	72.3
100-150	4.97	3.9	5.56	4.3	21.09	16.3	3.08	2.4	34.70	26.9
50-100	—	—	—	—	0.18	0.1	0.89	0.7	1.07	0.8
<50	—	—	—	—	—	—	—	—	—	—
Total	23.58	18.3	18.05	14.0	81.47	63.1	5.86	4.6	128.96	100.0

Separate figures were obtained on the drivers who started at the 2 ends of the course. Correlations of 0.55 and - 0.37 were found for the small aperture, and - 0.52 and 0.15 for the large (N = 5). These results indicate no systematic relation between average forward reference distance and vehicular speed. The average fixation distance of 142 ft, which was the same for both apertures, seems larger than required to respond at average speeds of 13.4 mph (small aperture) or 14.7 mph (large aperture). Even if a relation were found between average forward reference distance and speed, it would not be very meaningful, in view of the variability of the fixation positions. The driver looks far ahead of the car and then, seemingly in disregard of anticipation requirements, he may check his alignment with the road. This variability and the adjustment of fixation to particular road conditions makes the concept of average forward reference distance largely an abstraction.

Left and Right Curves

The fixation pattern differed somewhat on left and right curves (Tables 16 to 19). The point of fixation in distant vision deserves special attention. Signs and other visual aids should presumably be located where the motorist's eye tends to fall. When drivers viewed through the large aperture, their eye fell 6.48 ft from the right edge of the road (left curve, average of fixations beyond 150 ft). The corresponding figure for the right curve was 8.91 ft. The figures for the small aperture are 6.95 and 10.38 ft. The average shifts in fixation position are statistically significant at the 0.01 level (t-test). Apparently the eye moves to the left on a right hand curve; but on the average, it does not cross into the opposing lane. The results support the placement of signs on the right side of the road.

Perceptual Anticipation and Alignment

Most records show continuous visual shifts, forward to the limit of the road and backward toward the vehicle. The record of E.C. illustrates these movements (Fig. 5). On the left curve, rapid fixation movements occur between positions beyond 150 ft and those less than 50 ft. These shifts also occur along the right shoulder when the driver is on a right curve. Forty-eight percent of all drivers' fixations with the small aperture and 55 percent with the large cross the zone borders at 50, 100, or 150 ft. These movements may be explained by the contradictory requirements of perceptual anticipation and vehicular alignment. Perceptual anticipation requires the driver to look far ahead to get a general idea of conditions which will have to be met. Alignment behavior requires viewing close up to insure that the vehicle is on the road.

The drivers mentioned anticipation and alignment in explaining how they guided the car. The record excerpts illustrate these activities:

Question: How did you guide yourself on the right curve?
Answer: Well, I just saw the same thing. My vision would go out to the curve. I'd see as much as I could and then come back again. One time I stayed out too long and I was out of the road. (O: G.P., small aperture)

Question: Was there any pattern of movement?
Answer: Just that I . . . you look ahead frequently to see the whole situation, then come back to your immediate points of reference. I wanted to see what was ahead and then put myself within the lane by something closer—center-line or shoulder line. (O: R.O'C., small aperture)

Question: How did you guide yourself on the left curve?
Answer: Going into a left turn, generally I was looking at the center strip and the curvature in the distance along the left side of the road. And as I approached the curve—got into the curve—I was looking generally at the center strip and the right side of the shoulder. (O: N.M., standardization procedure, no aperture)

TABLE 16

TIME ON VARIOUS FIXATION POSITIONS
(Summary—10 Drivers, Large Aperture)

Curve	Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Center Right Lane		Center Left Lane		Trees, Left & Right Sides		Total	
		Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
Left	>150	49.86	7.91	88.34	14.02	192.06	30.50	19.05	3.03	8.63	1.37	6.59	1.04	364.53	57.87
	100-150	14.68	2.33	37.66	5.98	47.89	7.60	25.02	3.97	17.05	2.71	0.19	0.03	142.49	22.62
	50-100	6.79	1.08	35.45	5.63	15.89	2.52	42.22	6.70	4.52	0.72	—	—	104.87	16.65
	<50	—	—	9.82	1.56	1.45	0.23	6.56	1.04	0.19	0.03	—	—	18.02	2.86
	Total	71.33	11.32	171.27	27.19	257.29	40.85	92.85	14.74	30.39	4.83	6.78	1.07	629.91	100.00
Right	>150	100.42	17.47	40.85	7.11	148.83	25.90	25.10	4.37	1.56	0.27	0.37	0.07	317.13	55.19
	100-150	23.14	4.03	20.83	3.62	35.92	6.62	16.35	2.85	1.11	0.19	—	—	97.35	16.94
	50-100	5.22	0.91	13.61	2.37	69.39	12.07	41.68	7.25	1.70	0.30	—	—	131.60	22.90
	<50	—	—	2.71	0.47	13.83	2.41	12.03	2.09	—	—	—	—	28.57	4.97
	Total	128.78	22.41	78.00	13.57	267.97	46.63	95.16	16.56	4.37	0.76	0.37	0.07	574.65	100.00

TABLE 17

TIME ON VARIOUS FIXATION AREAS
(Summary—10 Drivers, Large Aperture)

Curve	Distance (ft)	Left Lane		Yellow Line		Right Lane		Whole Road		Other Areas[a]		Total	
		Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
Left	>150	5.41	0.85	2.58	0.41	135.72	21.55	220.82	35.06	—	—	364.53	57.87
	100-150	6.52	1.04	3.08	0.49	53.41	8.48	79.48	12.61	—	—	142.49	22.62
	50-100	3.60	0.57	4.41	0.70	52.42	8.32	43.44	6.90	1.00	0.16	104.87	16.65
	<50	1.19	0.19	5.23	0.83	6.67	1.06	4.11	0.65	0.82	0.13	18.02	2.86
	Total	16.72	2.65	15.30	2.43	248.22	39.41	347.85	55.22	1.82	0.29	629.91	100.00
Right	>150	46.41	8.08	—	—	5.12	0.89	265.60	46.22	—	—	317.13	55.19
	100-150	20.06	3.49	—	—	—	—	77.29	13.45	—	—	97.35	16.94
	50-100	9.38	1.63	—	—	10.60	1.85	111.63	19.42	—	—	131.60	22.90
	<50	2.26	0.39	0.37	0.07	5.48	0.95	20.45	3.56	—	—	28.57	4.97
	Total	78.11	13.59	0.37	0.07	21.20	3.69	474.97	82.65	—	—	574.65	100.00

[a] Left shoulder, center left lane, center right lane, right shoulder.

TABLE 18

TIME ON VARIOUS FIXATION POSITIONS
(Summary—10 Drivers, Small Aperture)

Curve	Distance (ft)	Left Shoulder		Yellow Line		Right Shoulder		Center Right Lane		Center Left Lane		Trees, Left & Right Sides		Total	
		Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
Left	>150	33.40	4.50	174.56	23.50	176.97	23.83	56.08	7.55	10.71	1.44	11.20	1.51	462.92	62.33
	100-150	11.23	1.51	53.56	7.21	35.55	4.79	14.86	2.00	5.38	0.73	—	—	120.58	16.24
	50-100	2.37	0.32	64.17	8.64	58.05	7.81	7.71	1.03	3.00	0.40	—	—	135.30	18.20
	<50	0.33	0.04	12.34	1.66	8.86	1.19	1.90	0.26	0.59	0.08	—	—	24.02	3.23
	Total	47.33	6.37	304.63	41.01	279.43	37.62	80.55	10.84	19.68	2.65	11.20	1.51	742.82	100.00
Right	>150	71.10	13.87	183.05	35.69	75.92	14.80	31.32	6.11	—	—	1.96	0.38	363.35	70.85
	100-150	7.27	1.42	26.76	5.22	42.26	8.24	19.16	3.73	—	—	—	—	95.45	18.61
	50-100	0.33	0.06	15.75	3.07	21.06	4.11	13.94	2.72	0.26	0.05	—	—	51.34	10.01
	<50	—	—	0.19	0.04	1.51	0.29	1.04	0.20	—	—	—	—	2.74	0.53
	Total	78.70	15.35	225.75	44.02	140.75	27.44	65.46	12.76	0.26	0.05	1.96	0.38	512.88	100.00

TABLE 19

TIME ON VARIOUS FIXATION AREAS
(Summary—10 Drivers, Small Aperture)

Curve	Distance (ft)	Yellow Line		Left Lane		Whole Road		Right Lane		Other Areas[a]		Total	
		Sec	%	Sec	%	Sec	%	Sec	%	Sec	%	Sec	%
Left	>150	53.34	7.18	21.53	2.90	68.84	9.27	310.69	41.83	8.52	1.15	462.92	62.33
	100-150	37.03	5.00	6.64	0.89	12.93	1.74	56.00	7.54	7.98	1.07	120.58	16.24
	50-100	43.19	5.80	2.70	0.36	6.82	0.92	77.59	10.45	5.00	0.67	135.30	18.20
	<50	8.41	1.13	0.86	0.12	1.15	0.15	12.79	1.72	0.81	0.11	24.02	3.23
	Total	141.97	19.11	31.73	4.27	89.74	12.08	457.07	61.54	22.31	3.00	742.82	100.00
Right	>150	21.87	4.26	157.70	30.75	128.25	25.01	44.82	8.74	10.71	2.09	363.35	70.85
	100-150	9.57	1.87	18.68	3.64	20.20	3.94	41.85	8.16	5.15	1.00	95.45	18.61
	50-100	9.72	1.90	5.96	1.16	4.56	0.88	25.06	4.89	6.04	1.18	51.34	10.01
	<50	—	—	—	—	0.18	0.04	1.52	0.29	1.04	0.20	2.74	0.53
	Total	41.16	8.03	182.34	35.55	153.19	29.87	113.25	22.08	22.94	4.47	512.88	100.00

[a] Right shoulders, left shoulders, center right lane, center left lane.

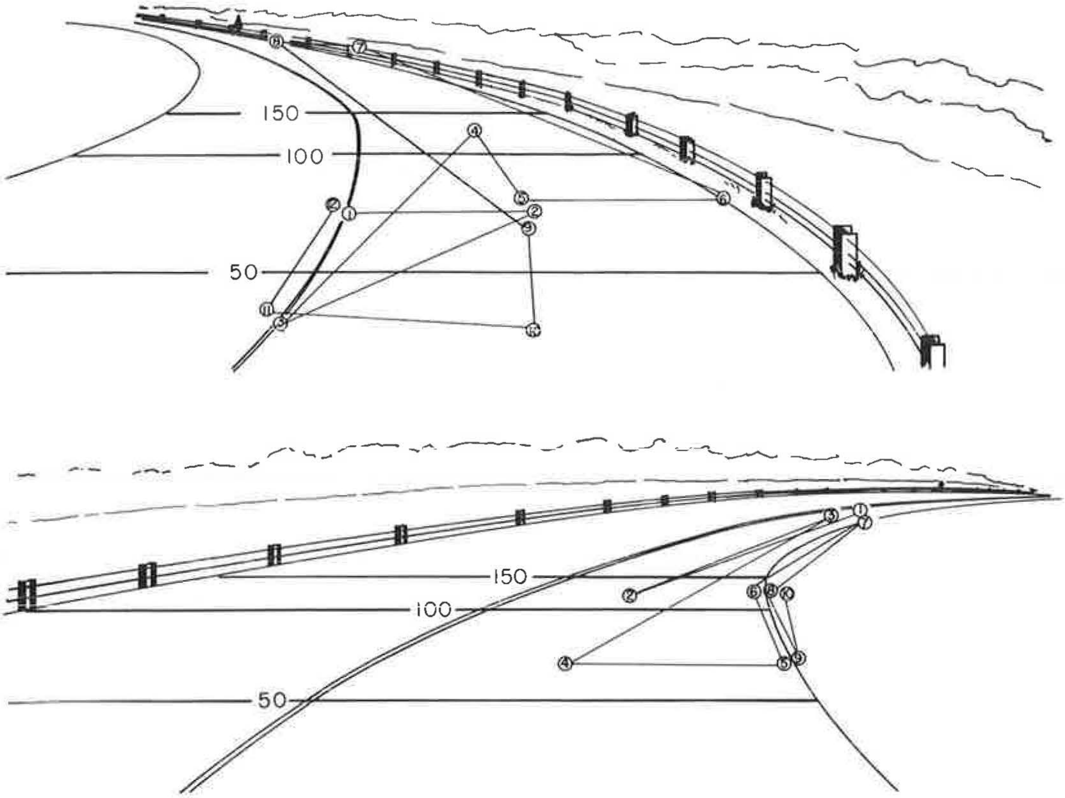

Figure 5. Anticipation and alignment (Driver E.C.).

Methodological Problems

Two methodological problems arising in this study are (a) the adequacy of introspective data (on-route statements of fixation, answers to questionnaires) for indicating the driver's visual input, and (b) the effects of the stress imposed by limiting information with the small aperture.

The on-route statements and the questionnaire data were suggestive—as far as they went. The main shortcoming of the introspective data was its incompleteness. The 3,305 separate film fixations obtained permitted a reliable analysis of the distribution and sequence of eye positionings. In contrast, the 563 statements given on-route and the 20 questionnaire responses offered only a skeletal indication of what was going on. However, introspective data did offer confirming evidence of the validity of the film analysis, and were valuable in revealing the drivers' purposes in perceptual anticipation and alignment. These uses and limitations of introspective data are similar to those generally encountered in experimental work. The complexity of fixation data has been noted in previous eye camera studies (9).

The adaptation made by drivers to the stress of limited information is revealed by a comparison of small and large aperture results given in Tables 1 and 2. In looking through the small aperture, drivers mainly fixated the yellow line (42.2 percent of the time, Table 2) and the right shoulder (33.5 percent) enabling them to track the yellow line, or view the whole right lane. In looking through the large aperture, drivers could see the entire road, and this inclusive feature was used 68.3 percent of the time (Table 1). The right lane also had high usage (22.4 percent) as it could be covered even when the driver looked close to the car. The records seem to indicate that the driver selects a view which permits him to do the job. Under stress it may be as simple as holding fast to the yellow line and tracking it, as in the record of G. P. (Tables 4 to 7). However, the driver prefers to see more of the road, even in the small aperture condition, the entire right lane was viewed 45.4 percent of the time (Table 1) and the entire road 19.4 percent.

APPLICATIONS TO HIGHWAY DESIGN

The experimental evidence of this study leads to a number of suggestions for the design of highway markings. The experimental evidence must be weighed along with considerations of cost, public acceptance, current usage, etc., before it can be applied. But experimental findings have special status, for they are perhaps less subject to debate than other considerations.

1. Since drivers use the road edges and center lane marker to guide the vehicle, these features should be visible to the driver.

Results of this experiment provide a rationalization for edge and center lane markings. The question remains which features should be emphasized by being specially marked. The evidence indicates that driving can be done using only the centerline (Table 1, small aperture) and this might lead to the recommendation that it alone be presented. However, drivers prefer to see the right lane and the entire road, as evidenced by the high total time spent on these features (Table 1). Factors other than those considered in this experiment will dictate road marking policy. For example, road edges differ in luminance and contrast, and hence in their need to be painted. Where contrast is low or where there is heavy night usage, edge markings are recommended. Where 2-way traffic is heavy, a centerline should be used.

2. Curve markings (signs, fences, and edge markings) should be positioned on the right edge of the road on both left and right curves.

The analysis of fixations on curves indicates that a driver tends to shift his distant fixation to the left on a right curve. However, the movement is not large enough to move the average fixation position across into the opposing lane. Hence, highway markings should presumably be presented on the right side of the road.

3. The driver should always be given sufficient unimpeded view ahead to satisfy his anticipation requirements.

The driver's need to anticipate conditions ahead has been recognized in traffic regulation and guidance, as well as road design manuals, and comes out clearly in the data of this experiment. Little is known about perceptual anticipation requirements in the variety of situations met on the highway, and further research in this area may be quite fruitful.

SUMMARY AND CONCLUSIONS

A technique to determine what features of the road and terrain the driver is responding to is presented in this study. The method involves having the driver guide the car while looking through a device containing a small aperture. By decreasing the visual field, the essential information, whatever it is, cannot be seen at once, i.e., the driver is forced to obtain this information in separate visual fixations. A continuous film record is made of the driver's field of view, which is later analyzed to indicate the center of his visual aim and the content of each fixation. Using this aperture device, visual positional data were obtained on 10 drivers who followed a 2-lane low traffic density road. The film records provided 3,305 separate fixations, which were coded for position, distance from the eye, and duration. The following conclusions were reached on the basis of the analysis:

1. The essential information required by the driver is provided by the road edges and center lane marker. It was found that 98.2 percent of the fixations made using the small aperture, and 100 percent of those made with the large, included at least one of these road features. The drivers' on-route statements of fixation position and the answers to a questionnaire also indicated the importance of the road edges and lane marker.

2. Although all drivers utilized the road edges and centerline to guide the vehicle, the manner in which this information was obtained differed from subject to subject. The film records refute the notion that the driver has a fixed point of forward reference, or that a common pattern of viewing is shared by all drivers.

3. In going from a left to a right curve, the position of fixation tended to shift in the opposite direction, i.e., from right to left. However, the average point of fixation beyond 150 ft did not cross the centerline into the opposing lane.

4. The hypothesis is presented that the persistent pattern of fixation movements forward to the limits of the road and back again to the vehicle are explained by the contradictory requirements of perceptual anticipation and vehicular alignment with the road.

5. Methodological problems concerning the adequacy of introspective data for determining the driver's visual input, and the stress of small aperture viewing, are discussed.

6. The implications of these results for the placement of signs and highway markings are presented.

The conclusions in 3 and 4 should be tested, if possible, with eye camera techniques.

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Wrong-Way Driving: Off-Ramp Studies

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Drivers were observed and questioned and their responses were measured as they unexpectedly came upon "do not enter" signs while "driving" in the driving simulation laboratory.

Red-and-white signs elicited an earlier response than did the black-and-white signs, and more drivers responded correctly to the red-and-white signs. This finding was cross-validated by tests at another location.

A second set of signs was tested at the second location. Results at this writing are not conclusive regarding the relative "noticeability" of the four different messages.

Preliminary evaluation was made of the appearance of lane-line arrowheads painted on every fourth dashed line of an otherwise standard lane marking. The arrowheads were oriented in the direction of normal flow, so that a wrong-way driver would encounter a series of arrows with their points facing him. This particular type of lane-line arrow marking was judged not sufficiently noticeable to alert a wrong-way driver.

Observations were made of several styles of pavement marking arrows. When approaching them from the pointed end, as a wrong-way driver would in attempting to enter an off-ramp, the standard arrows (which originally were developed as directional guides) are not as detectable as two different styles.

•THIRTEEN fatal accidents killed 19 persons as a result of head-on collisions caused by wrong-way drivers on California freeways during 1961. In 1962, wrong-way drivers caused 23 fatal accidents killing 37 persons. This was 6 percent of all the fatalities on freeways in 1961 and 8 percent in 1962.

Recognizing this problem, a study of wrong-way driving movements was initiated as part of the highway safety research authorized by the California legislature. A portion of this study was conducted by the Institute of Transportation and Traffic Engineering at UCLA and is reported here.

The wrong-way ramp study is an attempt to predict the relative effectiveness of various types of signs in preventing drivers from entering freeways via off-ramps. The signs are viewed unexpectedly by drivers in the UCLA driving simulation laboratory, and driver reactions to the different signs are used as the bases for comparison.

The study was conducted in two phases with films made at two locations. Each phase will be described separately and in the chronological order in which they were conducted.

Definite conclusions have been reached regarding some of the signs and markings. These conclusions have been reported to the California State Traffic Engineer and are reflected in current remedial efforts to reduce the incidence of wrong-way driving. These California remedial efforts were reported in 1963 by F. E. Baxter (1) and in 1964 by George Hill (2).

Paper sponsored by Committee on Road User Characteristics.

Two surveys have been made of wrong-way driving incidents in California. The first in 1963 was by C.V. Gay (3)—and the second in 1963 by D.J.Theobald (4). There is evidence from these surveys and from one special installation involving a hidden camera that older drivers and drunk drivers are many times more likely to be caught mistaking an off-ramp for an on-ramp, and that the ratio of reported to unreported incidents is probably much higher than previously thought. Over half of the reported incidents involved entering via an off-ramp.

PHASE I

Four different DO NOT ENTER signs were evaluated. Each sign (in turn) was correctly positioned on a freeway on-ramp which temporarily was made to appear an off-ramp. (Los Angeles police officers provided traffic control.) A 35-mm color motion picture film was taken of each sign from a moving vehicle and included a two-block-long approach to the ramp. The Dimension 150 optical system was used.

The signs filmed carried the message DO NOT ENTER in the following configurations:

1. California standard, white on black (Fig. 1a);
2. California standard, black on white (Fig. 1b);
3. California experimental sign, white on red (Fig. 1c); and
4. New York experimental sign, white letters and a horizontal white bar on a circular red background (Fig. 1d).

Some trial work was done to determine the visibility of lane-line arrowheads in alerting drivers that they are on the wrong side of the freeway. Concerning pavement arrows for ramps, the appearance of several shapes of pavement arrows is reported, as a result of trial work with paper cutouts viewed on a flat black-topped area.

Procedure

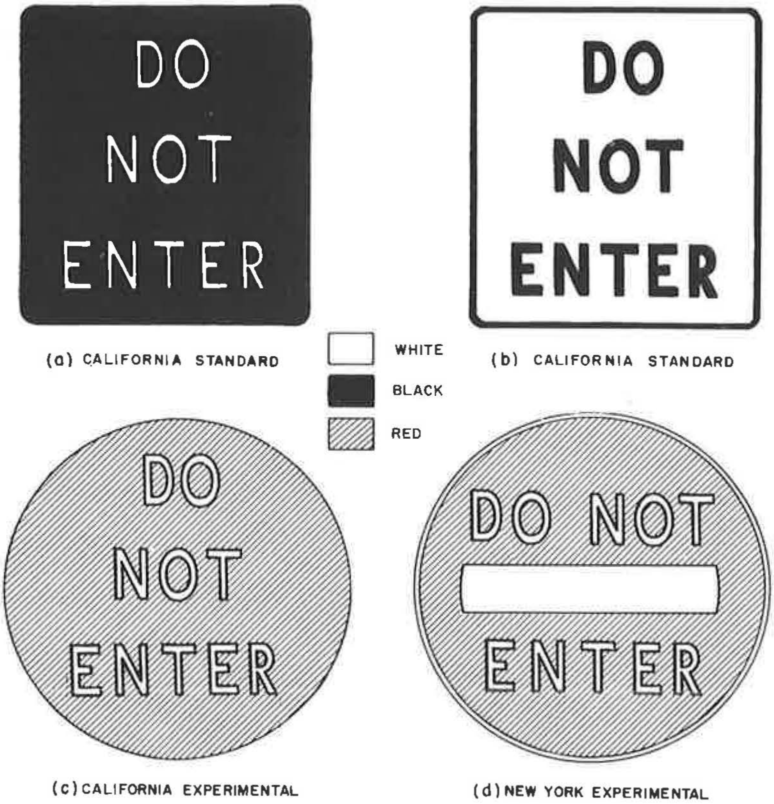
Initial testing consisted of recording reactions of 27 subjects to sign 1 (white on black), to determine the feasibility of using the simulation technique and to refine the experimental procedure. The test behavior of these subjects indicated that the drivers in the simulation laboratory would react in an apparently normal way and were not overly critical of the illusion that was created. The entire range of reactions encountered later was encountered in this initial testing.

During this trial work, an automatic event-indicating system (autopip) was designed, built, and installed to indicate events, landscape and sign cues for accurate measurement of reaction time. The autopip was utilized to indicate six location cues, both prior to and at the point of passing the signs.

The study consisted of testing 81 subjects on the four signs (each subject saw only one sign). Observation of the subjects and analysis of the recorded data were made and the results are reported below.

Subjects were recruited from undergraduate psychology classes on the UCLA campus. No requirements or limitations were set, including that of knowing how to drive. Past experience had shown that only a very small percentage of college students do not drive or have not had any driving experience, and this held true for the sample obtained for this study. Of 81 subjects recruited, only one subject had never driven before and only three others did not have licenses (they did have experience). No special attempt was made to recruit either males or females, and the 81 subjects consisted of 42 males and 39 females, ranging in age from 16 to 30 with an average age of 18.55 years.

The same experimental procedure was used for all subjects. They were told they were going to drive on two types of road: they would drive a two-lane mountain road, and then they would drive in a residential area. No mention was made of the freeway ramp they would encounter. The subjects were told to come to a full stop when the room lights came on, not to drive over 60-mph maximum, and to drive "as if they really were out on the road." The experimenter avoided answering questions until after the completion of the run, unless such questions pertained to the operation of the vehicle or to the driving task.



(a) CALIFORNIA STANDARD

(b) CALIFORNIA STANDARD

(c) CALIFORNIA EXPERIMENTAL

(d) NEW YORK EXPERIMENTAL

Figure 1. Test signs.

As a practice trial, all subjects first drove about one-third of a 30-min "drive" on a two-lane mountain road. The first subject each day saw the first third, the second subject the second third, the third subject the last third, the fourth subject a repeat of the first third, and so on throughout the day. Although each subject did not drive exactly the same stretch of practice road, they all drove the same type of road for the same length of time. Repetition of exactly the same film sequence for each subject was not deemed necessary since no analysis was to be made of this practice trial, and the entire road is quite similar in safe speed, frequency of curves, events, and landscapes.

At the end of approximately 10 minutes, the room lights were turned on, and the subject was requested to bring the car to a complete stop. This was necessary not only for the switchover to the second projector, but also because the second film begins from a near standstill (achieved by having the camera car start forward after the camera started running).

The second part of the test then began, in which the driver "drove" one of the wrong-way ramp test films. These films were preassigned in a random order set repeating each sign five times. At the end of a set, or each twenty runs, the random set was repeated. Thus the order was a randomly forced balance to assure an approximately equal number of exposures to each sign for each set of twenty subjects.

Each test drive is for two city blocks down a straight residential street, at the end of which is an on- and off-ramp to a freeway (Fig. 2). This intersection was changed for purposes of this experiment, and the film that each driver saw was of the intersection shown in Figure 3. Although there was no stop sign and no cross traffic, there was a road intersecting from the driver's left. The drivers reacted in several ways when coming upon this choice point. The test was terminated when the driver either reacted or when, after failing to react, he had traveled about three-quarters of the

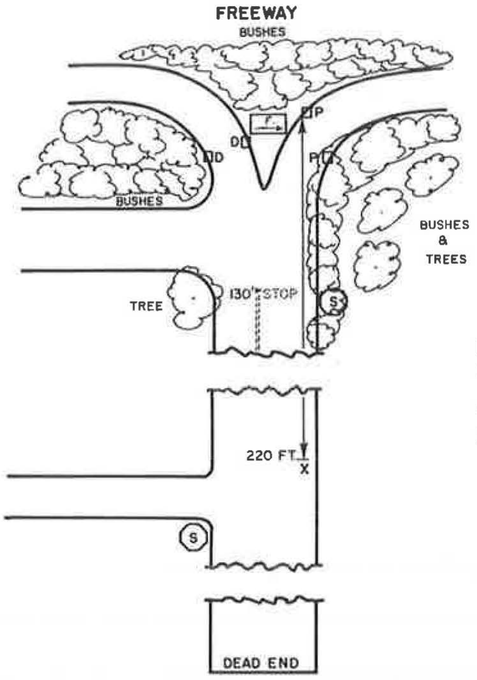


Figure 2. Actual intersection.

SIGNS

D - DO NOT ENTER
P - PEDESTRIANS, ETC., PROHIBITED
S - STOP
F. - FREEWAY

X - MAXIMUM DISTANCE CAN READ SIGNS ON SIMULATOR 220 FT.

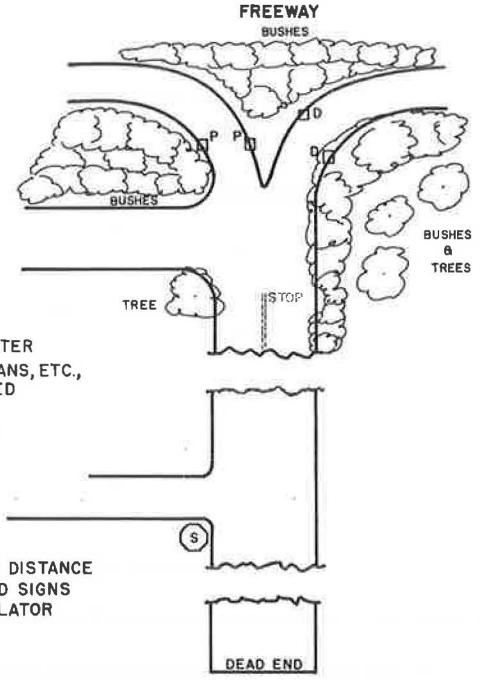


Figure 3. Experimental intersection.

distance up the ramp beyond the DO NOT ENTER signs. The wrong-way test drive consumed from 60 to 90 seconds of driving time, depending upon the speed the subject chose.

At the conclusion of the test, each driver completed a form requesting general information, such as number of years of driving experience and type of car usually driven. In addition, some interrogation was made of the driver's impression of his experience on the simulator. The experimenters carefully noted the obvious reactions of each subject and interrogated the subject after the test to determine his "observed reaction" to the sign. Subjects were never directly asked about a DO NOT ENTER sign, but if spontaneous verbalization or indirect questioning did not reveal that the subject saw the sign, he was asked if he "saw any signs" and, if so, "did he know what they were." At this time an attempt was also made to answer any questions the subject might have had concerning the laboratory and the study. Before he left, each subject was cautioned against discussion of the last (wrong-way) film with his classmates, although he was told that it was permissible to talk about the simulator. After the subject had left, his comments were written on the information sheet and his reactions logged into the study record.

Observations

After viewing all four DO NOT ENTER signs in the driving simulation laboratory, the experimenters concluded that the red-and-white signs can be seen from a much greater distance than the black-and-white signs when the viewer knows where to look. The latter tend to blend into the green foliage background more easily than the red signs. Landmarks noted in the film were measured at the actual location, and it was determined that the black-and-white signs could not be seen in the simulator except at an apparent distance of less than 500 ft, whereas the red-and-white signs were obvious at apparent distances in excess of 700 ft. While no such observations were made in the field, it is believed that these relative differences would have occurred there also. When the signs first become visible, the red-and-white signs can easily be

TABLE 1

	VERBALIZED STOP SIGN	DID NOT VERBALIZE STOP SIGN	TOTAL
BLACK & WHITE	1 (4.31)	34 (30.69)	35
RED & WHITE	7 (3.69)	23 (26.31)	30
TOTAL	8	57	65

Test for Independence Between Sign Color and Verbalizing it as a Stop Sign. (Theoretical frequencies in parentheses.) $x^2 = 6.27$ with 1 df significant at >0.02 level.

mistaken for stop signs (same color and same general shape). In all cases, the sign message cannot be read on the simulator until reaching an apparent distance of 220 ft or less (Fig. 2).

Comment is also necessary concerning the subjects who were lost to the study because they came to a stop at the intersection before reaching the ramp signs. All of these subjects commented that they saw "stop" written on the street, and in addition two of them said they "saw a stop sign." (The stop sign had been removed but a very worn STOP was faintly visible on the pavement.) Of those 40 subjects who encountered the black-and-white DO NOT ENTER signs, 10 percent (four) of them stopped because of the STOP on the street. Of those 41 subjects seeing the red-and-white signs, nearly 25 percent (ten) stopped at the STOP. In addition, 7 of the 30 subjects who completed the test on the red-and-white signs commented that they initially thought the sign was a stop sign, but then as they drove closer, they were able to read it. (A few never really read the sign but actually believed it to be a stop sign even though they had driven by it.) Only one of the 35 subjects completing the test on a black-and-white sign said he thought it was a stop sign.

Utilizing 2 x 2 chi square test for independence, the proportion of subjects reporting having perceived the DO NOT ENTER sign as a STOP sign is significantly better than chance for the red-and-white signs over the black-and-white signs (Table 1).

Results

The results of the data collected are presented in two categories: observed reactions and response measurements taken from the ink oscillograph record of speed, steering, brake, and accelerator pedal position.

Observed Reactions.—Most subjects could report having seen a DO NOT ENTER sign but many commented that the red-and-white signs looked like stop signs and two others believed the signs to be advertisements. On the basis of his answers, each subject was assigned a code signifying his "observed reaction" (before and independent of the examination of the oscillograph records). The codes used were divided into two sections as follows:

1. No reaction
    - (a) Did not react, did not see sign.
    - (b) Did not react, but reported seeing a sign.
2. Reacted
    - (a) Slowed, saw sign, but continued up the ramp.
    - (b) Stopped.
    - (c) Turned left.
    - (d) Pulled off road to right.
    - (e) Attempted to enter on ramp.

Although the drivers who slowed, but continued up the ramp against the DO NOT ENTER sign did not react in a fully positive manner, many of them commented after the run that they saw the sign but that "the car was going that way," or that they tried to brake but the "car wouldn't stop." These drivers were included in the "reacted" column because it is believed that in the field they would not have continued up the ramp.

Seven subjects drove by the DO NOT ENTER signs and gave no indication that they would have stopped in the real-life situation. Four of these seven drove past sign 2 and one each of the other three drove past each of the remaining three signs.

Response Measurements.—In addition to the "subjective observations," computations were made of four scores: deceleration time and distance, braking time and distance. Deceleration time is the time in seconds between the first detectable reduction of speed and the reference point (pip) for that event, and braking time is the time in seconds between the onset of brake application and the reference point.

Deceleration and braking distances are defined as above, substituting feet for time. The formula for obtaining reaction distance directly from the ink oscillograph record data (which is in millimeters) was derived from the basic physics formulas for acceleration, $a = (V_t - V_o)/t$, and distance, $s = V_o t + \frac{1}{2} a t^2$, combined with the conversion rates of the oscillograph (mm to common terms as mph time in sec, etc.).* The final working formula is

$$s = \frac{(V_o + V_t)\, t}{k}$$

where

s = distance in feet;
V_o = mm of vehicle speed at the reaction point (braking or deceleration);
V_t = mm of vehicle speed at a reference point;
t = mm between the above points; and
k = 9.0909 which is a conversion factor from ft/mi; sec/hr; mph/mm of vehicle speed; mm/sec of time (oscillograph paper transport rate) and the distortion factor of the simulator speedometer ($\frac{1}{2}$).

In all cases the computations are of either time in seconds or distance in feet relative to one of the landmark pips. This particular pip represents the location of the intersection stop sign (which had been removed). Of those pips which appeared on all records, this is the pip closest to the ramp. (The actual DO NOT ENTER signs were never reached by subjects who stopped or pulled off or slowed substantially.) The distance between this pip and the DO NOT ENTER signs is 130 feet.

Data for the individual signs are given in Tables 2 through 5. It can be concluded that the red-and-white signs were associated with earlier reactions in terms of mean

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*The formula assumes a constant acceleration or deceleration. This is generally true for the short distances measured (8).

TABLE 2

WRONG-WAY RAMP STUDY

		N	Median	Mean	σ	Range	Sk
Deceleration Time (Seconds)	Sign 1	16	-8.60	-10.33	6.90	+2.70 /-23.80	+.75*
	Sign 2	13	-10.05	-8.50	6.41	+5.80 /-16.80	-.73*
	Sign 3	16	-14.30	-15.34	7.55	+1.20 /-25.40	+.41*
	Sign 4	12	-13.00	-11.84	5.93	-4.20 /-23.40	-.59*

TABLE 3

Deceleration Distance (Feet)	Sign 1	16	-165.11	-195.12	134.28	+73.92 /-512.33	+.67*
	Sign 2	13	-187.44	-160.96	131.49	+127.60 /-355.74	-.60*
	Sign 3	16	-281.74	-283.53	144.17	+25.74 /-481.97	+.04*
	Sign 4	12	-224.40	-241.02	124.26	-100.49 /-501.93	+.40*

*Difference between median and mean <u>not</u> significant at $P \leq 0.05$

TABLE 4

WRONG-WAY RAMP STUDY

		N	Median	Mean	σ	Range	Sk
Braking Time (Seconds)	Sign 1	16	-6.00	-5.35	3.85	+4.70 /-11.80	-.51*
	Sign 2	12	-5.40	-5.16	5.46	+5.80 /-14.80	-.13*
	Sign 3	16	-8.50	-7.88	6.21	+1.20 /-22.80	-.30*
	Sign 4	12	-11.50	-6.56	5.54	-3.80 /-14.90	-2.68***

TABLE 5

Braking Distance (Feet)	Sign 1	16	-109.95	-87.12	61.17	+138.20 /-182.49	-1.12**
	Sign 2	12	-77.39	-81.97	99.21	+150.04 /-227.92	+.14*
	Sign 3	16	-163.63	-140.24	111.53	+25.74 /-457.88	-.63*
	Sign 4	12	-143.28	-123.60	115.84	-117.98 /-430.24	-.51*

*Difference between median and mean <u>not</u> significant at $P = 0.05$

**Difference between median and mean significant at $P < 0.05$

***Difference between median and mean significant at $P < 0.01$

TABLE 6

WRONG-WAY RAMP STUDY—MEDIAN TESTS

	Red & Wht	Blk & Wht	
Above	15 (12.74)	12 (14.26)	27
Below	10 (12.26)	16 (13.74)	26
	25	28	53

Deceleration time (Number of cases) expected frequencies in parentheses. $x^2 = 1.548$ with 1 df not significant at $P = 0.05$.

	Red & Wht	Blk & Wht	
Above	19 (15.13)	13 (16.87)	32
Below	7 (10.87)	16 (12.13)	23
	26	29	55

Deceleration distance (Number of cases) expected frequencies in parentheses. $x^2 = 3.406$ with 1 df not significant at $P = 0.05$.

	Red & Wht	Blk & Wht	
Above	14 (11.00)	12 (15.00)	26
Below	8 (11.00)	18 (15.00)	26
	22	30	52

Braking time (Number of cases) expected frequencies in parentheses. $x^2 = 1.470$ (with Yate's correction) with 1 df not significant at $P \leq 0.05$.

	Red & Wht	Blk & Wht	
Above	17 (11.50)	9 (14.50)	26
Below	6 (11.50)	20 (14.50)	26
	23	29	52

Braking distance (Number of cases) expected frequencies in parentheses. $x^2 = 4.796$ (with 1 df significant at $P < 0.01$.

scores. In two cases (sign 4 braking time and sign 1 braking distance) the degree of skewness was significant at the 5 percent level or greater. Median scores (which are not sensitive to skewness) are given in Table 6. For these median scores, only braking distance was significant.

In comparing the signs one against the other (Table 7), the differences in mean time and distance for both deceleration and braking favor sign 3. Table 8 indicates a difference in deceleration distance in favor of the red-and-white vs the black-and-white signs.

There seems to be no question that the red signs (individually as well as combined) were effective both more often and earlier than the black-and-white signs.

Lane-Line Arrowheads

In an initial effort to evaluate the effectiveness of an often suggested remedial measure to alert a wrong-way driver to the fact that he is going the wrong way, a preliminary investigation was made of arrowheads painted on every fourth dashed line of one of the lane markings. These arrowheads were painted (by hand using a stencil) along a one-eighth-mile section of unopened freeway in the Los Angeles area. They were pointed in the direction of normal traffic movement and were placed only on the second (from the median) lane-marking dashed stripe.

TABLE 7

WRONG-WAY RAMP STUDY

Differences between means for deceleration time (dt), deceleration distance (dd), braking time (bt), and braking distance (bd) with longer sign number in parentheses. (Time in seconds and distance in feet.)

	Sign 1	Sign 2	Sign 3
Sign 2	dt(1) 1.83* dd(1) 34.16 bt(1) .19* bd(1) 5.15*		
Sign 3	dt(3) 5.01* dd(3) 88.41* bt(3) 2.53* bd(3) 53.12*	dt(3) 6.84# dd(3) 122.57# bt(3) 2.72* bd(3) 58.27*	
Sign 4	dt(4) 1.51* dd(4) 45.90* bt(4) 1.21* bd(4) 36.48*	dt(4) 3.34* dd(4) 80.06* bt(4) 1.40* bd(4) 41.63*	dt(3) 3.50* dd(3) 42.51* bt(3) 1.32* bd(3) 16.64*

TABLE 8

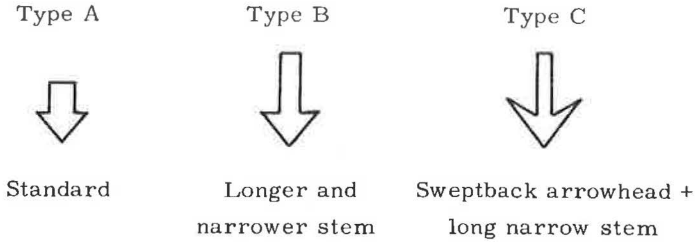
	Black & White
Red & White	dt(R) 3.78* dd(R) 88.61# bt(R) 2.40* bd(R) 53.12*

*Difference between means not significant at $P = 0.05$
#Difference between means significant at $P < 0.05$

Several wrong-way trips were made at speeds of 40, 50 and 60 mph in both the median and the second lane of this four-lane section of freeway. An 8-mm motion picture was made of a portion of this arrow-painted roadway.

Conclusions of those several persons who drove this road were that the arrowheads were very difficult to detect even when it was known when and where to look for them. This same conclusion has been reached by persons viewing the motion picture. Three other impressions are noteworthy:

1. The arrowheads were more noticeable when driving the correct direction than when driving the wrong way. Some drivers (going the correct way) reported the impression that the arrows indicated that those lanes (on either side of the arrowheaded line) were in some way "priority lanes."



2. The driving scene does not appear very unusual or at all disturbing when driving in the wrong direction.

3. The reverse side of some sign panels can be seen when going either in the correct direction or in the wrong direction. Therefore, this possible cue is not as effective as it was thought to be.

Pavement Arrows for Ramps

During the course of this study, a remedial measure was initiated by the California Division of Highways to help alert wrong-way drivers at off-ramps. It was decided to paint pavement marking arrows that would face a driver attempting to enter an off-ramp. Therefore, some consideration was made of the visual impression such arrows would present if the current design of arrow was used.

White paper arrows were cut out according to dimensions currently in use for pavement arrows. This "standard" arrow viewed on a flat black-topped area was rather difficult to discern as an arrow when one was looking toward the point (as a wrong-way driver would). Two modifications improved the "legibility" of the paper arrows: (a) extension and narrowing of the stem, and (b) creating a "sweptback" arrowhead.

Pavement arrows styled along lines similar to type C are therefore recommended when they are intended to be viewed from the pointed end.

PHASE II

Results of Phase I materially influenced the experiment plan for Wrong-Way Study Phase II in which drivers' responses were recorded as they unexpectedly encountered a variety of both "primary" and "secondary" signs at an off-ramp.

Eight films were produced utilizing an on-ramp which was converted to look like an off-ramp. The signs were photographed in 65-mm Eastman color negative using the patented Dimension 150 optical system, and 35-mm reduction prints were made for use in the UCLA driving simulation laboratory. Phase II includes two of the major primary signs from Phase I plus as additional primary not studied before, and five secondary signs with various messages.

The three primary signs each carry the message DO NOT ENTER in the following configurations:

No. 2. Black letters on a white background, two lines, rectangular shape.
No. 4. White letters on a red background with a horizontal white bar, circular shape.
No. 6. Black letters on a white background with white on red DANGER mounted directly above and on the same post.

(Signs No. 2 and No. 4 were used in Phase I.)

The secondary signs (to be placed farther up the ramp) contain the following messages:

A. WRONG WAY GO BACK—white letters on red background, rectangular shape.

B. STOP GO BACK—white letters on red background, rectangular shape.
C. GO BACK YOU ARE GOING WRONG WAY—white letters on red background, rectangular shape.
D. Sign B combined with DANGER directly above and on same post.
E. Sign A combined with DANGER directly above and on same post.

Considerations for Selecting Location of Ramp

The experience with Phase I plus subsequent trial work with various lens systems enabled certain considerations to be set forth for use in selection of the off-ramp for Phase II.

1. A clearly determinable point at which signs suddenly become visible; preferably at about 250- to 300-ft distance from foot of ramp.
2. After signs become visible the approach should be on a tangent section with the ramp curving to the right.
3. The foot of the ramp should be isolated from other traffic and intersections.
4. Ramp should be two-lane at the foot, narrowing to one lane.
5. Sunlight must fall on the face of the signs (both primary and secondary), requiring approach with the camera vehicle from a southerly direction.
6. The freeway and the direction of traffic on it should not be apparent in the films.
7. The approach street scene should be about ¼ to ½ mile in length without any stop signs or other reasons to stop; signalized intersections can appear if they can be kept green or encountered on green.

After selection of the ramp, eight different presentations of these signs were produced on film. Each of the three types of primary signs was combined with one type of the secondary signs to produce three films. Only the secondary signs appeared (without any primary signs) in the five other films.

The combinations of primary and secondary signs used were (1) 2-E; (2) 4-A; and (3) 6-C.

Procedure

A total of 243 drivers have been tested to date on Phase II from two major populations: students from Psychology 1A classes recruited by the circulation of sign-up sheets in the classrooms, and Air Force personnel who were recruited from the four local Air Bases through a joint agreement between the Air Force Office of Ground Safety and the University. None of these drivers can be considered as "volunteers." In addition, a few volunteer UCLA employees are included in the total figure.

For the primary signs, 110 drivers from UCLA were tested as follows: 2-E, 32 drivers; 4-A, 38 drivers; and 6-C, 40 drivers.

In all cases, the wrong-way ramp film was seen as a part of a series of films to which the individuals "drove." The series included two-lane mountain road, freeway or expressway (controlled-access, divided highway) and a "residential area." The latter was the wrong-way film which began in a residential type area, continued along the street for about three minutes, and then curved into the converted off-ramp. The same basic films were shown to all subjects, although the order was different for the Air Force and student groups. Both groups, however, had had the same amount of exposure time in the simulator (approximately 25 minutes of "driving") when the wrong-way film was presented, and each group had driven the mountain road and some controlled-access highway. Employees participating in this study were shown one or the other of the two series previously discussed.

Statistical Analyses

A Brush eight channel oscillograph, standard installation in the Driving Simulation Laboratory, recorded the reactions of the subject as he drove each film. Records obtained included: (a) the subject's driving speed (speedometer reading), (b) accelerator pedal patterns, (c) brake pedal patterns, (d) steering patterns, (e) respiration record, and (f) galvanic skin response (not all cases).

In addition, each driving record was automatically cued from the film for ten locations prior to and passing the wrong-way signs. It was thus possible to reduce the reaction distances for each subject. Reaction times, being dependent on the vehicle speed, cannot be accurately compared and thus were not calculated. Reaction distances, however, include the time modified by the speed.

All reaction distances are interpreted as being the number of feet the subject traveled along the course after passing a specific point and before he reacted to the sign. The specific point, the first of ten location cues, is the beginning of an underpass which precedes the wrong-way signs. At this point, the subject cannot yet see any signs and is not aware that he will be confronted by them. The first sign comes into view as the driver begins to emerge from the underpass and at a time when reactions to the underpass have already occurred. A very definite break point is observable on the oscillograph records since the subjects do not react to the signs until they have left the tunnel (cue 4), and in the majority of cases, the subjects do not react to the underpass except by slowing before entering it.

Deceleration distances (the distance between the first cue pip and the first point of slowing), and braking distances (the distance between the first cue pip and the first point of brake application), were measured by hand from the oscillograph records and these data were then keypunched for analysis by the UCLA computing facility's IBM 7094 computer.

For each of the reaction types (decelerations and braking) records were made in four parts, as follows:

Part I. 0 to 303 ft (303 ft is that point where the secondary signs first come into view—thus no reaction before that point can be attributed to a secondary sign where applicable).

Part II. 304 to 385 ft [385 ft is that point where the driver passes the last primary sign—thus within this category all four signs (right and left primary; right and left secondary) are in view where there is a combination of signs].

Part III. 386 to 555 ft (555 ft is that point where the driver passes the last secondary sign—thus any reaction after that point is not considered in the analyses).

Part IV. Totals (0 to 555 ft)

It seemed logical to categorize the reactions in this way as being:

Part I. To the primary sign only.
Part II. To the combination of primary and secondary signs.
Part III. To the secondary sign only.
Part IV. Total.

For these four parts, means and standard deviations were computed for each sign, and t-tests were made between signs. Tables 9 and 10 give sample sizes, means and sigmas for deceleration and braking distances and Tables 11 through 14 give the t-scores and significance levels for the difference between sign means. A test for skewness showed no evidence of skewed distributions.

It should be understood that the shorter the reaction distance, the sooner is the subject reacting to the sign. Thus it could be interpreted that the shorter the distance, the more effective the sign.

Primary Signs

Looking at the three primaries, it can be seen that in all parts sign 4 has a shorter deceleration and braking distance than sign 2, and that in Part I where the majority of

TABLE 9A

DECELERATION DISTANCE SAMPLE SIZES

	2 - E	4 - A	6 - C
Part I	11.0	18.0	21.0
Part II	12.0	6.0	8.0
Part III	3.0	2.0	1.0
Part IV	26.0	26.0	30.0

TABLE 9B

DECELERATION DISTANCE MEANS

	2 - E	4 - A	6 - C
Part I	290.2	242.9	244.1
Part II	336.7	327.8	341.4
Part III	431.3	431.0	456.0
Part IV	327.9	277.0	277.1

TABLE 9C

DECELERATION DISTANCE STANDARD DEVIATIONS

	2 - E	4 - A	6 - C
Part I	9.5	42.0	37.6
Part II	18.9	29.7	26.6
Part III	24.7	7.1	0.
Part IV	46.8	68.8	64.6

TABLE 10A

BRAKING DISTANCE SAMPLE SIZES

	2 - E	4 - A	6 - C
Part I	7.0	9.0	12.0
Part II	8.0	5.0	9.0
Part III	7.0	7.0	7.0
Part IV	22.0	21.0	28.0

TABLE 10B

BRAKING DISTANCE MEANS

	2 - E	4 - A	6 - C
Part I	288.9	273.9	263.9
Part II	347.9	344.4	346.7
Part III	443.0	439.0	425.0
Part IV	359.4	345.7	330.8

TABLE 10C

BRAKING DISTANCE STANDARD DEVIATIONS

	2 - E	4 - A	6 - C
Part I	8.4	23.5	12.8
Part II	23.2	26.4	24.9
Part III	53.6	50.4	29.6
Part IV	71.1	80.6	69.4

reactions lie, the deceleration difference is significant at a level of confidence greater than one percent. Sign 6 also has significantly shorter deceleration and braking distances (>0.001) than 2, in Part I. There is no significant difference between signs 4 and 6.

Secondary Signs

Additional testing is being conducted to determine if obtained measures are due to differences in the population from which the drivers were selected. There is some evidence that those signs not having the words wrong-way are confusing. Drivers slow but continue on, expecting to see a barricade or some other reason for the sign being there. They do not realize they are going the wrong direction. These results were obtained by questioning some drivers after completion of the testing session.

Interpretation

Experimentation of Phase II of this study substantiates Phase I's conclusion that the red primary sign 4 is either more visible or more meaningful than the white-and-black sign 2. It is believed that the important factor is the color red, and evidence of this is that the addition of the red DANGER sign significantly shortens the reaction time to the basically same black and white sign.

No evidence of difference was found between the European style symbol (sign 4) and the combination of the U. S. standard with a red DANGER sign on the same post. Because of the confusion of sign 4 with the U. S. red STOP sign, it is concluded that the results of this study favor the sign 6 configuration.

TABLE 11

DECELERATION AND BRAKING DIFFERENCES FOR CATEGORY I REACTIONS (PRIMARY SIGNS)

	2 - 4		2 - 6		4 - 6	
	DD	BD	DD	BD	DD	BD
t =	3.646	1.599	3.973	4.593	0.090	1.252
df =	27	14	29	17	37	19
sig. @	> 0.01	ns	> 0.001	> 0.001	ns	ns

TABLE 12

DECELERATION AND BRAKING DIFFERENCES FOR CATEGORY II REACTIONS (PRIMARY SIGNS)

	2 - 4		2 - 6		4 - 6	
	DD	BD	DD	BD	DD	BD
t =	0.774	0.250	0.464	0.103	0.897	0.160
df =	16	11	18	15	12	13
sig. @	ns	ns	ns	ns	ns	ns

TABLE 13

DECELERATION AND BRAKING DIFFERENCES FOR CATEGORY III REACTIONS (PRIMARY SIGNS)

	2 - 4		2 - 6		4 - 6	
	DD	BD	DD	BD	DD	BD
t =	0.018	0.144	0.866	0.778	2.887	0.633
df =	3	12	2	12	1	12
sig. @	ns	ns	ns	ns	ns	ns

TABLE 14

DECELERATION AND BRAKING DIFFERENCES FOR CATEGORY IV REACTIONS (PRIMARY SIGNS)

	2 - 4		2 - 6		4 - 6	
	DD	BD	DD	BD	DD	BD
t =	3.121	0.590	3.324	1.430	0.006	0.695
df =	50	41	54	48	54	47
sig. @	> 0.01	ns	> 0.01	ns	ns	ns

All of the secondary signs are red and white and therefore no color differentiation is possible. The message is the only difference since location and position of the sign were held constant. There is some indication of the need for having the message include the words "wrong-way" in order for the driver to realize why these large red signs have been erected. This finding agrees with results from interviews with six drivers who actually drove past some of these signs at an on-ramp in the Sacramento area. These six were part of thirteen drivers who were (experimentally) instructed to use an on-ramp where they unexpectedly encountered one of these large red signs located on the right-hand side of the ramp.

Obtained differences in deceleration distance and braking distance for the secondary signs are confounded with a difference in the population from which the drivers were selected. Subsequent testing will either confirm the differences obtained or will provide a basis for other conclusions regarding the relative "noticeability" of these signs.

Although several persons did "drive" by the primary and secondary combination of signs without reacting to them at all, there were no statistically significant differences among signs in this respect. The totals for these no measurable reactions were 2-E, 2 drivers; 4-A, 1 driver; and 6-C, 2 drivers.

This indicates that at least in this laboratory environment, these combinations of primary and secondary signs were not effective for all of the drivers tested. The degree to which this lack of complete effectiveness would extend to the actual highway situations is, of course, not known. However, it is reasonable to expect that some older drivers and drunken drivers might not be alerted by these signs. It is therefore recommended that additional remedial techniques be investigated.

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Attitudes of Drivers Toward Alternative Highways and Their Relation to Route Choice

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To determine the factors influencing drivers' choice of alternative routes, a study was conducted in which the attitudes of drivers toward two highways were measured. In addition, traffic characteristics of the routes were measured and the tension generated on each was determined using nine test drivers. The routes employed were 47-mi sections of an expressway-design toll road and parallel rural primary highway. Drivers were sampled entering and exiting on both highways. A summated rating attitude scale was administered to a sample of 3,259 drivers. Also descriptive information was obtained about the driver, his trip, and travel habits. The results indicated that these drivers hold stable attitudes toward the two highways which clearly differentiate between them. It appears that direct measurement of driver attitudes is a better predictor of route choice than descriptive information about the drivers or their driving habits. In addition, the results provide a means of rationalizing the attraction of traffic to an expressway on the basis of drivers seeking to minimize tension in driving. The results suggest that total stress incurred in driving is a more important determinant of route choice than either operating costs or travel time costs. A model of route choice and attraction of traffic is proposed based on tension generation which can be related to travel time data. The results of this research indicate that drivers evaluate alternative highways in a rational, though subjective, fashion. Such evaluation, however, appears quite independent of the usual monetary schemes for rationalizing highway benefits and costs.

•WHEN a driver is provided alternative routes he must make an evaluation of the benefits and costs of each in order to make a choice. If drivers knew nothing about available alternative highways or they did not make an evaluation of them, their choices would be random. Since drivers do not operate in a random manner, it would appear reasonable that they learn the characteristics of the highways and out of this learning develop a basis for evaluation of alternatives. Drivers' choices thus become dependent on the diverse characteristics of the alternatives relative to his trip objectives and it is these which determine stable choice behavior. This behavior is of considerable significance both in determining the use of highway facilities and the benefits drivers derive from them.

Three major factors have been developed to account for the patterns of choice that drivers make among alternative highways: time savings, direct and indirect operating cost savings, and comfort and convenience savings.

BACKGROUND

In general, travel time savings have been the dominant criterion of use of alternative facilities, with the best predictor being the travel time ratio. In both rural (1, 3)

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and urban studies (2, 10) a driver appears to choose routes which provide significant time savings, even though he may have to drive a greater distance. All these studies imply that the driver values time directly and hence scales that variable. From an economic standpoint, a considerable effort has been made to determine the dollar equivalent of this time scale. For passenger car drivers these attempts have not been particularly successful (6).

Relative to operating cost, the relation with choice by passenger car drivers appears to be weak (4). Either drivers do not evaluate operating cost differences or these differences are insignificant. Relative to the total costs of a trip, it may well be that operating cost differences among alternative routes are quite trivial for the passenger car driver.

In addition to these physical measurements, the purely subjective concept of comfort and convenience has been developed. This has generally been described qualitatively as the ease of driving or freedom of movement. Claffey (4) has scaled this factor in terms of the changes in speed imposed on the driver and hence counted the impedances to movement. Michaels (8) has differentiated among highways on the basis of the tension aroused in drivers from traffic and geometric design features. His results indicate that tension reduction is the greatest single saving accruing to a driver choosing an expressway over a parallel non-controlled access highway, and drivers appear to evaluate alternatives subjectively in conformity to the tension induced on each.

Although the research on the whole problem of use of alternatives has described what traffic does, little research has been carried out on drivers preception of alternative routes available to them (2). Further, no attempts have been made to measure on a quantitative scale the evaluations drivers make or their relation to choice of routes. Thus, there is now no reliable way to predict use of facilities except by empirical studies of traffic.

In regard to any benefit analysis of highway facilities it is obvious that drivers evaluate highways on a predominantly subjective basis. No economic determination seems feasible without knowing the scale of value drivers use and its relation, if any, to dollars.

Considering the problem of selection of alternative routes, it seems a reasonable assumption that that choice will be based on what the driver has learned about the alternatives. Either directly or indirectly a driver must develop some stable evaluations; that is, he must have some predisposing views toward the routes or his choices would be random. These predisposing views are, by definition, the attitudes an individual holds toward some object or process. If route choice is rational then a direct measure of a driver's evaluation should be his attitudes toward the alternatives. By determining the intensity of these attitudes toward a pair of highways it should be possible to determine how they relate to the characteristics of the highways and the choices drivers make toward them.

To achieve these objectives, however, it is first necessary to determine whether there is a stable set of attitudes toward highways of different character. Second, it is necessary to determine whether these attitudes depend on the characteristics of the drivers which are relatively permanent, or on the characteristics of a particular trip which would lead to highly variable attitudes. It is in this context that the present study was developed. Its aim was to test the hypothesis that there were significantly different attitudes toward two highways by the drivers on each, and that these attitudes depended on the more enduring characteristics of the routes and the drivers.

Development of the Attitude Scale

The attitude scaling technique employed in this study was the method of summated ratings, which employs a series of direct statements to which the respondent expresses the extent of his agreement. An example of such a statement is "A road with many hills and curves is interesting to drive." The subject then responds in one of five categories ranging from strongly agree to strongly disagree. A score of 0, 1, 2, 3, or 4 is given to his response according to the category chosen with a score of two being neutral. Thus, using a set of such items a total attitude score can be obtained for any subject toward the road under study.

The general procedure for preparing such an attitude battery is described by Edwards (5). In this experiment it was decided to compare attitudes on a toll road and a rural primary, since these are two of the more common choices that a driver has and yet have radically different design characteristics. To develop the final items for the attitude scale, 61 statements were initially prepared. These statements described a variety of characteristics of a rural primary and an expressway both positive and negative. They were presented to a sample of 260 staff members of the Bureau of Public Roads. The instructions that they were given were as follows:

> Place yourself in a hypothetical situation of having the choice of two routes for home to work trips: (1) a limited-access toll road and (2) a parallel free-access primary roadway. The toll on the turnpike is $1.00. The trip is 30 miles on both routes. Assume that the primary route is similar to US 1 between Baltimore and Washington, or between Alexandria and Woodbridge.
>
> The attached questionnaire is designed to elicit attitudes toward these two types of highways. You should respond to each statement in terms of your own personal feelings, checking one of the five categories that range from strongly agree to strongly disagree.

Some basic objective information was obtained about the respondents including age, sex, and the percentage of time they would choose the toll road. Adding the last item allowed an initial check on the validity of the final scale, for it was hypothesized that those responding most positively to expressway items would be most likely to use that facility and vice versa. All items were scored in terms of favorability toward the expressway. The returns were then analyzed according to the standard procedure in which the highest scoring quarter of the sample was compared with the lowest scoring quarter. Well over half the items significantly differentiated the two highways. The final battery was composed of 18 items from the original group of 61 that were found to be the most discriminating between the high and low groups.

A further analysis was done on this pretest group. The attitude scores were correlated with the respondents percentage of choice of the toll road. The two distributions were dichotomized and a phi coefficient computed. The correlation coefficient was + 0.52 between attitudes scores and choice of routes. Thus, it was reasonable to conclude that in this hypothetical situation, there was a stable set of attitudes toward the two types of highways which was significantly related to the choice of routes that the respondents would make.

In addition to the final attitude battery, a questionnaire was included to obtain some basic descriptive information about the respondents' trips so that the attributes of the drivers and their trips could be related to their attitudes. These items were to provide a means for testing the stability of the attitudes and fell in three basic categories: (a) characteristics of the driver and his vehicle which included age, sex, and age of car; (b) characteristics of the trip which included purpose, number of car occupants, and the driving time already completed and that still left to be done; and (c) descriptive information on the driver's estimate of the frequency with which he made this kind of trip and the frequency with which he used the alternative route.

The item on driving time was included because there were no statements in the attitude battery relating to travel time alone. In the sample used to develop the scale, time did not discriminate between the high and low scoring groups. By treating travel time as an independent variable it was possible to relate subjective estimates of driving time to the respondent's attitudes toward the routes. It is obvious that if travel time were a dominant criterion of choice, then there should be a correlation between a driver's attitude toward the route and the duration of trip that he was undertaking. Using this approach an independent test could be made of a driver's choice of routes and of travel time.

Selection of Test Location

In considering a pair of roads of sharply different characteristics between which a driver might choose, the ideal would be a pair which had a common beginning and a

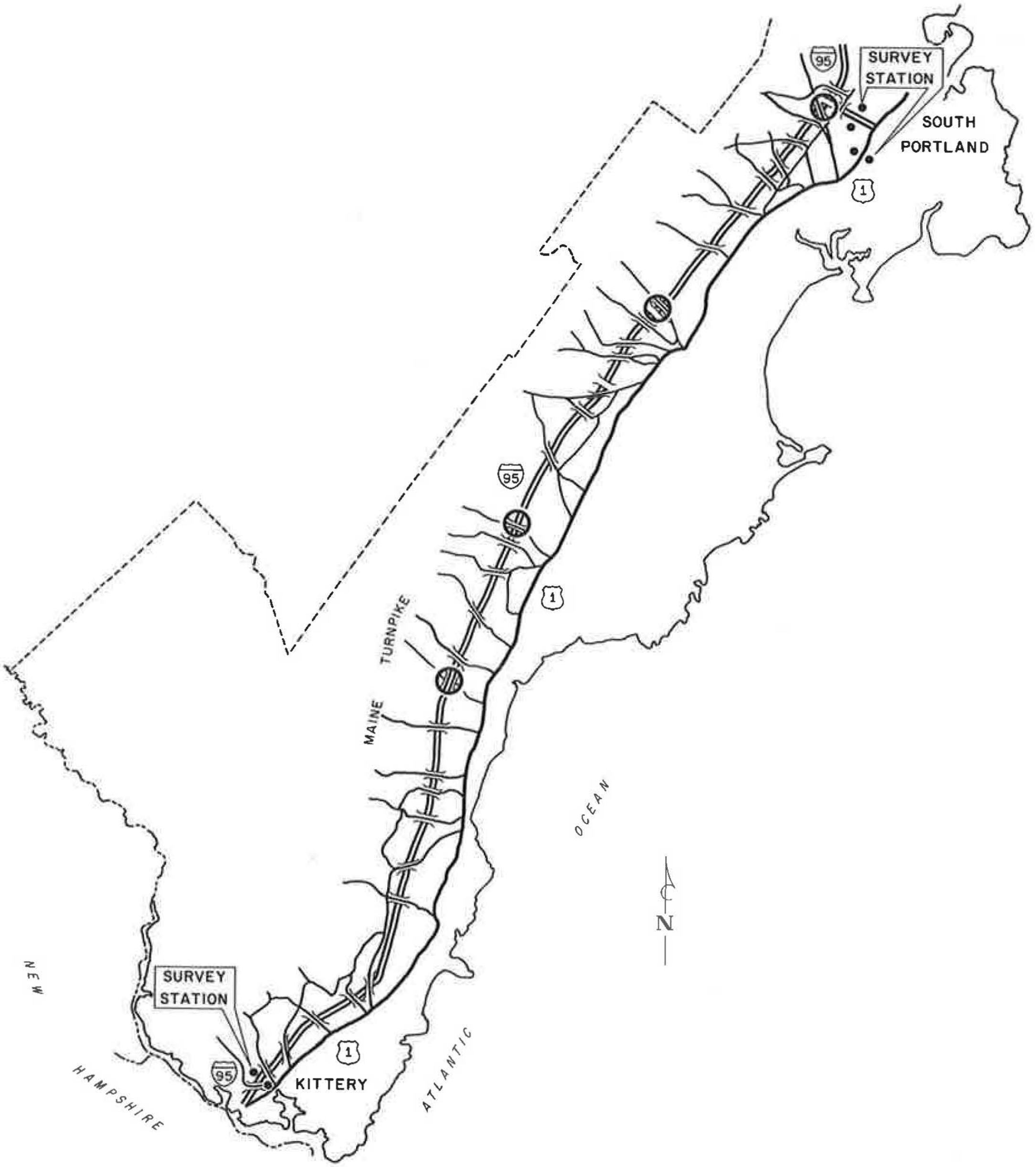

Figure 1. Study routes.

common terminus. In addition, the pair should be long enough to permit a meaningful choice for the drivers. A pair of highways meeting these requirements is the Maine Turnpike between Kittery and South Portland and the parallel rural primary, US 1 which has been studied extensively over the past decade (1, 3). The sections are both approximately 45 miles long. At the Kittery end, the choice of either route is a simple one for the driver for the connection is a Y. At the South Portland end, US 1 and the turnpike join again (Fig. 1).

The characteristics of both routes are quite typical of a modern toll road on the one hand and a rural primary on the other. The turnpike is a four-lane divided highway with interchanges spaced 5 to 15 miles apart and generally built to Interstate design standards. US 1 varies from two to four lanes passing through several small towns as well as undeveloped countryside. There is no control of access and the route has a variety of traffic control devices.

PROCEDURE

A survey team of nine men was used. The sampling schedule was set to run during daylight hours between 8:00 a.m. and 5:00 p.m., with sampling being done at both ends of each highway. For the first 4 hours vehicles were stopped as they entered the test sections. For the next 4 hours vehicles were stopped as they left the test sections. In this fashion samples of drivers were obtained from north and south ends of both routes with drivers never being stopped twice on the same trip. By counterbalancing the order, an approximately equal sample of drivers entering and exiting at both ends of the two highways was obtained.

To obtain the most stable attitudes toward the routes under study, only Maine or New Hampshire drivers were sampled. No fixed procedure was established for stopping a particular vehicle. The complexities of traffic and the limitation of only two interviewers at each station precluded any formal sampling procedure. However, by extending the sampling period over 30 days it was felt that most such biases would be eliminated.

When a driver was stopped, a common set of instructions was given:

> Good morning. We are doing research on why drivers pick particular roads for their trips and would like to enlist your assistance. We have a questionnaire that we would like you to complete which will take about five minutes of your time. If you can spare that time, we would appreciate it.

If the driver agreed, the attitude form was handed to him and the instructions for filling it out were read with him. When the interviewer and the driver were satisfied as to what was to be done, the interviewer withdrew and the driver completed the attitude questionnaire. When finished he handed the form back to the interviewer who then asked the objective questions marking the verbal replies on a coding sheet. The two parts of the form had a common number so that both parts of the survey could be subsequently combined.

Speed and Volume Measurements

In addition to the attitude survey, traffic measures were taken on the two routes. Rather complete volume counts were made daily for both the turnpike and US 1. The latter had volume counters at three locations so that hourly traffic counts were available. On the turnpike, volume was sampled at four separate locations during several different time periods. In addition, daily samples of traffic speed were made on both routes using a radar speed meter. Thus, a fairly complete record of the traffic characteristics on both test sections over the period of the study was obtained.

Tension Measurements

The Galvanic Skin Reflex (GSR) was employed to obtain tension measurements on both the turnpike and US 1. Over the one month study each one of the interviewers was used as a test subject and drove both routes twice in both directions. The procedure outlined in previous reports (7, 8) was employed.

RESULTS

Attitude Survey

During the four weeks of surveying on both routes a total sample of 3,259 different drivers was obtained. No significant differences were found between drivers sampled at the two ends of the test routes. Further, there were no differences between drivers sampled on entering the test sections and those leaving them. Therefore, these data

TABLE 1

ATTITUDES OF DRIVERS TOWARD MAIN TURNPIKE AND US 1

Driver	Turnpike			US 1		
	N	Mean	St. Dev.	N	Mean	St. Dev.
Male	1,138	41.33	9.40	1,039	32.09	9.56
Female	482	38.52	9.54	600	30.20	8.65
Total	1,620			1,639		

TABLE 2

SEX DISTRIBUTION OF DRIVERS

Driver	Turnpike		US 1		Total	
	N	Percent	N	Percent	N	Percent
Male	1,138	70.4	1,039	63.4	2,177	0.667
Female	482	29.6	600	36.6	1,082	0.333
Total	1,620	100.0	1,639	100.0	3,259	0.100

TABLE 3

DISTRIBUTION OF VEHICLES OF DIFFERENT AGE

Vehicle Age	Total Proportion	Turnpike		US 1	
		Male	Female	Male	Female
<1 yr	0.186	0.225	0.221	0.167	0.132
1 to 3 yr	0.393	0.459	0.396	0.342	0.359
4 to 6 yr	0.262	0.201	0.271	0.285	0.328
>6 yr	0.157	0.114	0.111	0.213	0.180

were pooled. Approximately the same number of observations were taken on both routes (Table 1). This, of course, does not represent the distribution of traffic but only the method of sampling on the two highways.

Fourteen percent of the drivers stopped refused to participate in the survey. The percentage was the same on both routes. In addition, approximately 6 percent of the drivers stopped had been interviewed before. As might have been expected the percentage of repeats from first week to the last week increased on US 1 from 1.9 percent at the end of the first week to 5.7 percent in the third week. On the turnpike, it increased from 0.8 percent to 10.3 percent in the third week.

The attitude questionnaires were scored with the turnpike used as a reference for assigning a quantitative score to the responses. Thus, all statements about US 1 that reflected a positive attitude toward that highway were given a 0 score for the category of strongly agree and a score of 4 for the response of strongly disagree. For those

TABLE 4

ANALYSIS OF VARIANCE OF ATTITUDES ON BASIS OF DRIVER AND VEHICLE AGE

Source	Sum of Square	d.f.	Mean Square	F	P(F)
(a) Turnpike Male Drivers					
Driver age	656.53	3	215.51	2.468	<0.05
Vehicle age	996.48	2	498.24	5.706	<0.01
Driver x vehicle	243.35	6	40.56	-	N.S.
Within	99,454.14	1,139	87.32	-	-
Total	101,341.50	1,150	-	-	-
(b) Turnpike Female Drivers					
Driver age	464.30	3	154.80	1.543	N.S.
Vehicle age	263.10	2	131.55	1.312	N.S.
Age x vehicle	418.42	6	69.74	-	N.S.
Within	48,342.20	482	100.30	-	-
Total	49,488.02	493	-	-	-
(c) US 1 Male Drivers					
Driver age	2,532	3	844.0	9.58	<0.01
Vehicle age	629	2	313.5	3.56	<0.05
Age x vehicle	1,390	6	231.7	2.62	<0.05
Within	86,299	980	88.1	-	-
Total	90,850	991	-	-	-
(d) US 1 Female Drivers					
Driver age	1,148	3	382.7	5.50	<0.01
Vehicle age	755	2	377.5	5.42	<0.01
Age x vehicle	722	6	120.3	1.73	N.S.
Within	42,605	604	69.5	-	-
Total	45,230	615	-	-	-

items which were unfavorable statements about US 1, strong agreement was scored as 4 and strong disagreement as 0. Statements about the turnpike were rated in the obvious fashion. Thus, the total score of a respondent was interpreted to reflect his attitude toward the turnpike. The scores on each of the items along with the descriptive information obtained from the interview were placed on punch cards and all of the basic analyses of the attitude sample was done on the computer.

Table 1 summarizes the attitudes of drivers on each route, classified by sex. The higher the score the more positive are the drivers' feelings toward the turnpike. A score of 36 would indicate a neutral attitude toward the turnpike. There were significant differences between the two highways. Drivers on US 1 held a negative attitude toward the turnpike, while turnpike users held a positive attitude toward that facility. The differences between the sexes were also significant. The male turnpike driver was significantly more positive toward the turnpike than the female driver. The US 1 male driver, although still holding a negative attitude toward the turnpike,

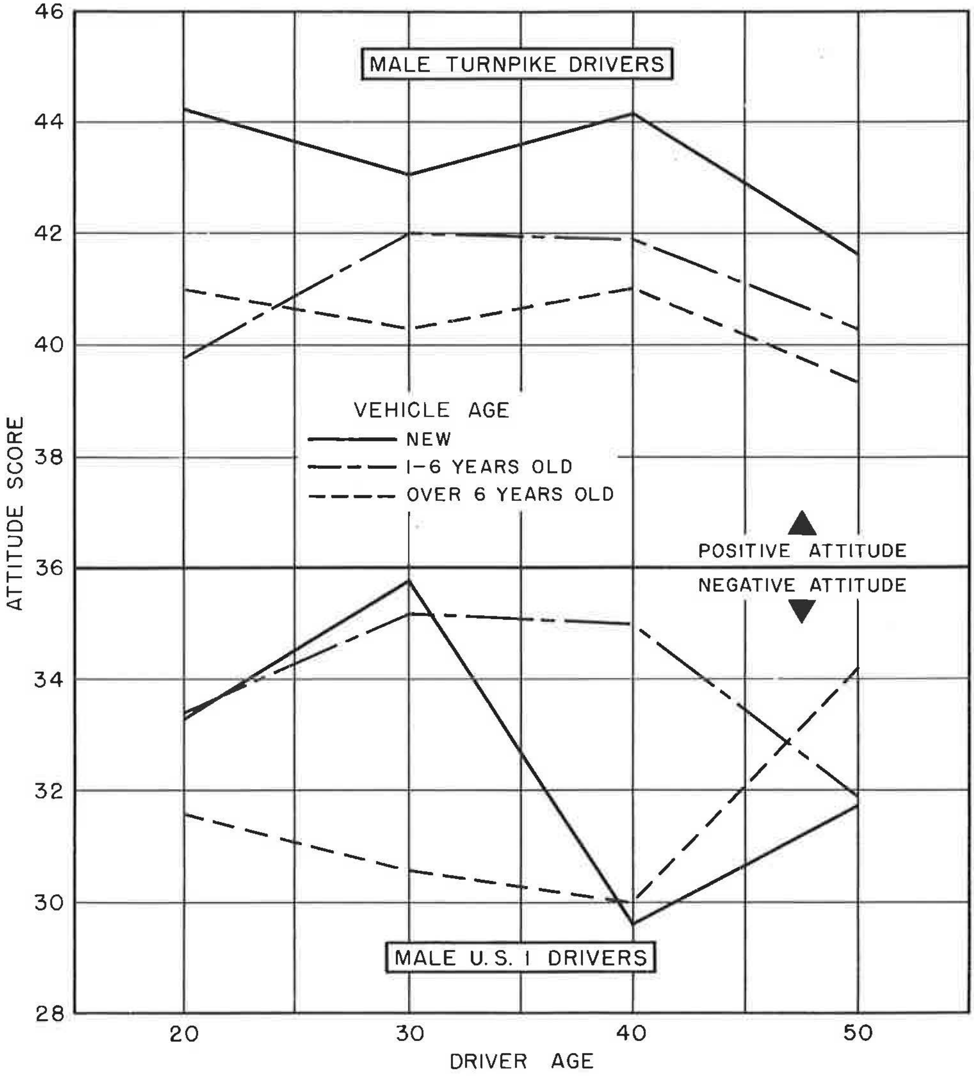

Figure 2. Attitude of male drivers toward turnpike as a function of driver and vehicle age and travel route.

was less negative toward the turnpike than the female driver on US 1. Finally, the attitudes of male and female drivers on both routes were significantly different from neutral. Thus, it is reasonable to conclude that the attitude scale did differentiate between the users of the two highways.

The sex distribution of the drivers on the two routes was analyzed (Table 2). Two-thirds of the total sample were male. More significant, however, is the difference in the proportion of male or female drivers between the two routes. There were significantly more women drivers traveling US 1 than the turnpike. Comparison of this sex distribution with attitudes toward the turnpike from Table 1 indicates a significantly less positive attitude toward the turnpike than for the males. It may be reasonably concluded that there was a correlation between the attitudes that the two sexes held toward the highways and the actual choices they made between them.

The third category under the driver and vehicle characteristics concerns that of vehicle age. Table 3 gives the percentages of vehicles on each route by age and by the sex of the driver. Women drivers in this sample drove older vehicles than the men;

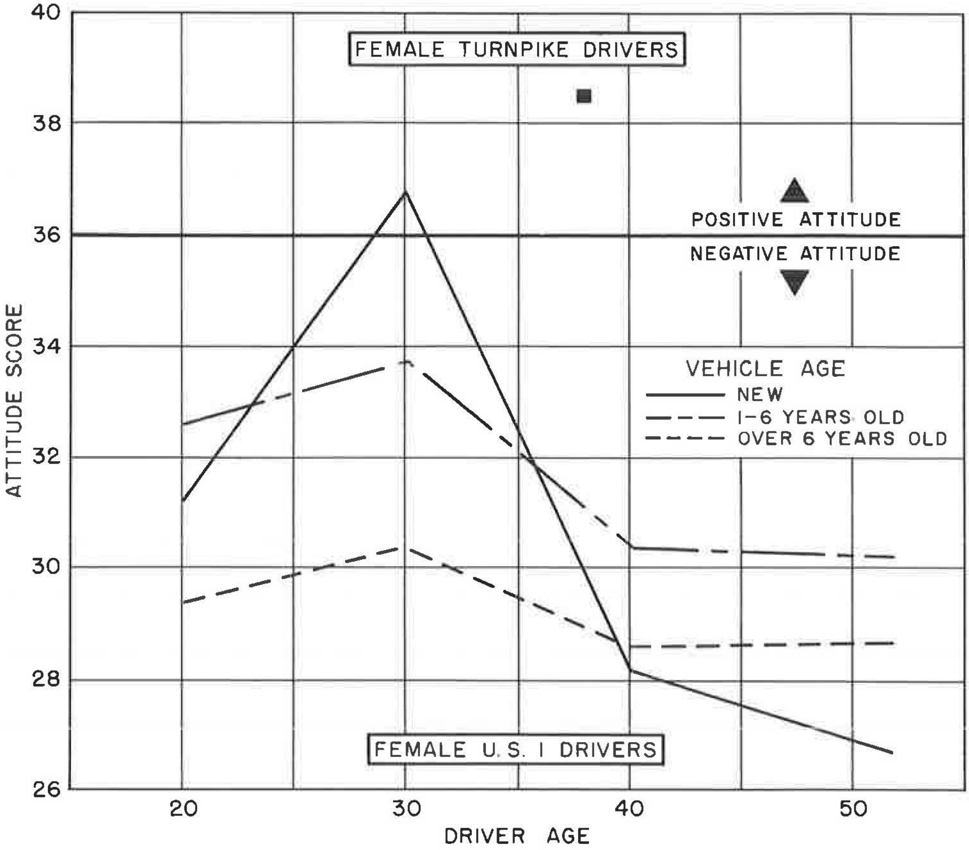

Figure 3. Attitude of female drivers toward turnpike as a function of driver and vehicle age and travel route.

and more significantly, the percentage of older vehicles found on the turnpike was significantly less than that found on US 1.

Drivers in the sample on both routes were compared for age differences. In relation to attitudes toward the two highways, rather clearcut differences exist. An analysis of variance was done for both driver age and vehicle age, the attitude scores being the dependent variable (Table 4). Both driver age and vehicle age are statistically significant for every case but the female turnpike drivers.

The mean attitude scores as a function of age are shown for all conditions (Figs. 2 and 3); vehicle age is the parameter in these curves. For the male drivers, attitudes toward the turnpike became less positive with increasing age. In addition, there is a clear effect of vehicle age on the attitudes toward the turnpike. Thus, the newer the automobile the more positive was the attitude toward the turnpike. In general, the same results follow for the females on US 1; there was a definite ordering of attitudes by vehicle age and by driver age. There appears to be a peak in attitudes toward the turnpike in the age range of 25 to 35, after which driver attitudes become more negative toward the turnpike. There were no significant differences for the female turnpike driver as shown by the single point (Fig. 3). It is reasonable to conclude from these analyses that attitudes toward the alternative highways depended significantly on the stable characteristics of drivers and their vehicles. These results further indicate that drivers' attitudes toward alternative routes were quite stable, evolving partially out of the enduring characteristics of the driver and his vehicle.

TABLE 5

DISTRIBUTION OF DRIVING TIMES

Driving Time Left (min)	Driving Time Completed (min)											
	< 15		15 to 30		31 to 60		61 to 120		>121		Total	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
(a) Drivers on Turnpike												
< 15	55	4	16	8	35	13	31	10	36	12	173	47
15 to 30	12	2	40	23	43	21	44	28	64	23	203	97
31 to 60	45	22	32	15	27	12	33	20	38	22	175	91
61 to 120	35	11	32	24	34	8	59	35	72	32	232	110
>121	68	23	66	25	42	13	85	35	173	64	434	160
Total	215	62	186	95	181	67	252	128	383	153	1,217	505
(b) Drivers on US 1												
< 15	190	136	91	94	41	12	25	7	14	8	361	227
15 to 30	146	96	146	92	51	34	27	20	16	16	386	266
31 to 60	29	17	31	20	12	9	17	7	10	4	99	57
61 to 120	16	4	14	13	11	5	16	8	26	1	83	31
>121	29	7	19	6	14	6	20	3	48	16	130	38
Total	410	260	301	195	129	66	105	53	114	45	1,059	619

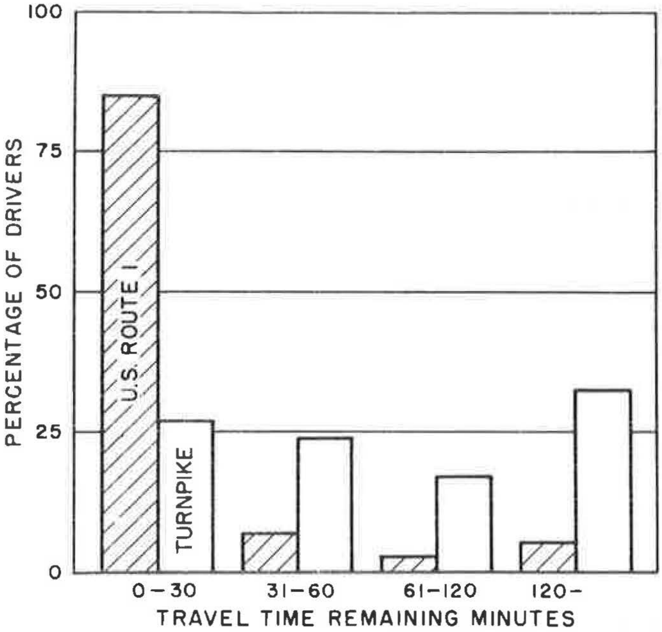

Figure 4. Percentage distribution of trip time remaining for drivers who have been driving less than 30 min.

TABLE 6

MEAN ATTITUDE SCORES FOR MALE DRIVERS HAVING APPROXIMATELY COMMON ORIGINS AND DESTINATIONS

Age	Turnpike	US 1
< 24	—	35.27
25 to 34	42.47	34.22
35 to 44	43.32	33.72
>45	41.73	29.90

Attitudes and Trip Characteristics

The second class of relations with driver attitudes concerns the characteristics of the specific trip during which a driver was sampled. The objective of these analyses was to determine whether attitudes toward the two highways were markedly modified by the purpose of the trip, the number of occupants in the vehicle, and the travel time associated with the trip. Analysis of the data showed that no significant relations existed between either the trip purpose or the number of occupants in the vehicle and the drivers' attitudes toward the turnpike. Similarly, the relation between subjective estimates of trip duration was unrelated to drivers' attitudes toward the turnpike. Thus, the results of this analysis on the characteristics of the specific trip indicate that a driver's attitudes toward the highways among which he could choose were quite independent of the specific trip. This would indicate that the choice among alternatives was made on a basis of stable and pre-existing attitudes toward the different types of highways.

The results relevant to travel time should not be interpreted to mean that there were no differences in the distribution of trip durations on the two highways. Table 5 gives the frequency distributions for the sample. These time values are subjective estimates of the time already spent driving as well as estimates of the amount of time required to complete the trip. The longer the trip, the more likely was it to be done on the turnpike. Thus, approximately 32 percent of all the drivers sampled on the turnpike had been traveling for less than ½ hr and 54 percent had more than 1 hr left to drive. On US 1, 70 percent of the drivers had been driving for less than ½ hr and only 25 percent of the drivers had more than ½ hr more to drive. Figure 4 shows the percentage distribution of remaining trip time for those drivers who had just started their trips. Only 15 percent of all the US 1 drivers expected to be driving for longer than 30 min whereas 71 percent of the drivers just beginning their trips on the turnpike expected to drive more than 30 min. Thus, the longer trip drivers tended to gravitate toward the turnpike.

A clearer picture of the effects of trip time and attitudes results from examining only those travelers on both routes who had approximately common origins and destinations. If only those turnpike drivers who had been traveling less than 30 min and had between 15 min and 1 hr left to travel, are compared with US 1 drivers who also had been traveling less than 30 min but who had between ½ and 2 hr yet to drive, it is obvious that US 1 drivers who made this choice were sacrificing time. The attitudes toward the turnpike for male drivers of different ages were compared (Table 6). For turnpike drivers there were no significant differences among the ages, whereas on US 1 there was a significant decrease in attitudes toward the turnpike as the age of the driver increased. In all cases, however, the US 1 driver held significantly negative attitudes toward the turnpike. Thus, it is reasonable to conclude that for trips having common origin and destination the drivers' choice between the two routes was highly related to their attitudes toward the alternative. In the case of such drivers on US 1, this meant that they chose the rural primary over the expressway even though in so doing it caused a 30 percent increase in travel time.

The sample was also analyzed in relation to the frequency with which drivers make trips between South Portland and Kittery. The trip frequency was defined in three categories: less than 1 trip per year, 1 to 12 trips per year, or more than 1 trip a month. Table 7 gives the percentage of the total sample on each route for each sex and the trip frequency. For the turnpike sample, the majority made the trip more often than once a month. On US 1, however, drivers who made these trips between once a year and once a month predominated. A chi-square test was used to test the differences between the turnpike and US 1 drivers, and the differences between the distributions were significant. When trip frequency increases beyond one trip a month, there is a decrease in the proportion found on US 1, together with an increase in the proportion found on the turnpike. This may indicate that the turnpike exerted an attraction for drivers as the frequency with which they traveled between Kittery and South Portland increased.

The attitudes of drivers toward the two routes were also analyzed as a function of frequency with which they made the trips between South Portland and Kittery (Table 8). Because of the significant differences among driver ages, the data were also separated by that variable. Table 8 indicates that the influence of age is the same as was discussed previously. There is also a consistent and significant increase in the average attitude score toward the turnpike as a function of trip frequency for both male and female drivers sampled on the turnpike. Furthermore, US 1 drivers, although holding negative attitudes toward the turnpike, showed a trend in attitudes approaching neutrality toward the turnpike as trip frequency increased. Thus, there was a general shift toward more positive attitudes toward the turnpike as trip frequency increased. This result offers further evidence that drivers' attitudes toward the two highways developed out of their driving experiences on each of the routes, and from this learning, there was a shift in attitudes toward favoring the expressway-type facility.

The final general analysis concerned the extent of use of the alternative routes by drivers. Each driver sampled was asked what percentage of time he used the other route for his trips (Fig. 5). There were no differences between male and female drivers and all the data were combined. The drivers sampled on the turnpike rarely used US 1: only 12 percent used US 1 for more than half their trips. On the other hand drivers sampled on US 1 frequently used the turnpike: 42 percent for more than 50 percent of their trips. Again, this appears to indicate an attraction of drivers toward the turnpike.

The attitude scale employed in this study was composed of two classes of statements: one was their reference to either the turnpike or US 1; the other was favorable or unfavorable statements. Hence, the items in the attitude scale can be classified in a 2 × 2

TABLE 7

RELATIVE FREQUENCY OF TRIPS OF DRIVERS SAMPLED

Frequency (per yr)	Male		Female	
	Turnpike	US 1	Turnpike	US 1
< 1	0.047	0.073	0.124	0.136
1 to 11	0.441	0.534	0.426	0.473
>12	0.511	0.394	0.451	0.390

matrix. In addition, the total attitude score was arbitrarily scored relative to the turnpike. A negative statement about US 1 with which a respondent agreed was interpreted as favorable toward the turnpike. Conversely, a statement which made positive reference to US 1 and was agreed to by the respondent was interpreted as negative toward the turnpike.

An item analysis of the attitude scale was made to determine the effects of these different kinds of statements. A sample

TABLE 8

AVERAGE ATTITUDE TOWARD TWO HIGHWAYS AS A FUNCTION OF FREQUENCY OF TRIPS BETWEEN SOUTH PORTLAND AND KITTERY

Route	Frequency (per yr)	Driver Age (yr)							
		< 24		25 to 34		35 to 44		>45	
		Male	Female	Male	Female	Male	Female	Male	Female
Turnpike	< 1	-	-	40.07	39.00	41.18	-	36.93	-
	1 to 11	38.92	38.02	40.25	36.87	41.31	38.00	39.13	39.25
	>12	43.21	33.78	43.23	40.33	42.93	41.10	41.77	38.24
US 1	< 1	32.65	28.48	34.54	30.32	32.08	26.33	29.98	27.19
	1 to 11	32.96	31.15	33.05	32.29	31.34	29.63	30.00	28.47
	>12	31.32	31.54	34.97	32.79	33.68	29.12	30.72	30.36

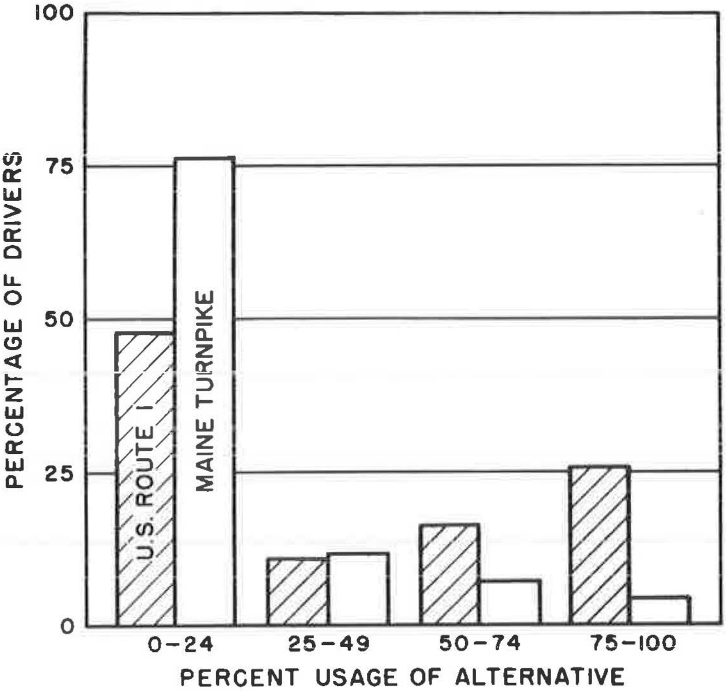

Figure 5. Frequency of use of alternative routes by drivers sampled on Maine Turnpike and US 1.

TABLE 9

AVERAGE ITEM SCORE FOR MALE DRIVERS USING THE TURNPIKE EITHER RARELY OR FREQUENTLY

Use of Turnpike (%)	Favorable		Unfavorable	
	Turnpike Drivers	US 1 Drivers	Turnpike Drivers	US 1 Drivers
(a) Turnpike Statements				
< 24	2.45	2.14	1.71	2.58
>75	2.54	2.44	1.70	1.70
(b) US 1 Statements				
< 25	2.09	2.60	2.46	1.61
>75	2.00	2.20	2.42	2.13

of the respondents was randomly selected on the basis of the percentage of the time they used the alternate. Each item was classified according to whether it referred to the turnpike or US 1 and to whether it was a favorable or unfavorable statement. The score value was determined by the extent of agreement with the item itself by the respondent. Thus, a score value greater than two indicates agreement with the item regardless of whether it is favorable or unfavorable. Conversely, a score value less than two indicates disagreement with the statement.

Regardless of the route on which they were sampled and the percentage of trips in which the turnpike was used, drivers responded positively to favorable statements about the turnpike (Table 9). In response to unfavorable turnpike statements, drivers sampled on the turnpike, regardless of their frequency of use, disagreed with the statements and were thus providing a positive response toward the turnpike. Drivers on US 1, however, strongly agreed with the negative turnpike statements if they were infrequent users of the turnpike, but strongly disagreed if they were frequent users. Thus, there was a significant shift in response to the negative statements by US 1 drivers as a function of the frequency with which they used the turnpike.

Conversely (Table 9), drivers sampled on the turnpike were essentially neutral in their responses to favorable statements about US 1, regardless of whether they were frequent or infrequent users of the turnpike. Drivers sampled on US 1 responded positively to favorable items but less so if they used the turnpike most of the time. On unfavorable US 1 statements there was consistent agreement among drivers sampled on the turnpike which was independent of the frequency with which the turnpike was used. The US 1 driver, however, showed a definite shift from disagreement with unfavorable statements if he was an infrequent user of the turnpike to a positive response if he was a frequent user of the turnpike.

The significant aspect is that drivers sampled on the turnpike made consistent responses to statements about both routes whether they were frequent or infrequent users of the turnpike. For the driver sampled on US 1, however, there were significant shifts in response to both classes of statements depending on whether they were frequent or infrequent users of the turnpike, but the major shift occurred in response to the unfavorable-type statements. These are the ones that appeared to be the most discriminating items in the scale.

These results indicate that drivers who have been sampled on the turnpike show a significant stability in their responses regardless of frequency of turnpike use. The driver sampled on the turnpike consistently agreed with positive statements about the turnpike while disagreeing with unfavorable statements. He also showed significant agreement with statements about the unfavorable characteristics of US 1. Drivers sampled on US 1, however, showed an adaptability to change in their response which was a function of experience with the turnpike. It seems reasonable to conclude that it was the negative characteristics experienced on US 1 relative to the turnpike that caused drivers to shift to the turnpike and that minimized the probability of turnpike drivers shifting back to US 1.

Speed, Volume and Travel Time Results

On the turnpike, speed and volume were determined on a sampling basis. Speed and volume measurements were made at 10-mi intervals both northbound and southbound. A radar speed meter was mounted in the rear of a station wagon which was parked on the shoulder. The speed meter was aimed at the approaching traffic at an angle of about 10 deg. This angle was greater than recommended for the most accurate speed measurements with the result that there is some error in these measurements.

Normally, a sample of 100 vehicles was counted. In addition, the time required for those 100 vehicles to pass the counting station was also determined. Thus, it was possible not only to determine the speed distribution but also to estimate the hourly volume passing that point. The same procedure was followed on US 1.

The cumulative speed distributions for the turnpike are shown in Figure 6. Data was kept separate for the two directions in morning and afternoon sampling periods. The mean speed of these samples is approximately 61.9 mph with a standard deviation of 9.1 mph. The speed distribution is slightly negatively skewed. These values should be viewed cautiously for as has been shown by Shumate and Crowther (9) there is nonhomogeneity among spot-speed samples.

For US 1, the cumulative speed distributions are shown in Figure 7. The mean of this sample is 43.7 mph with a standard derivation of 10.3 mph. The distribution is

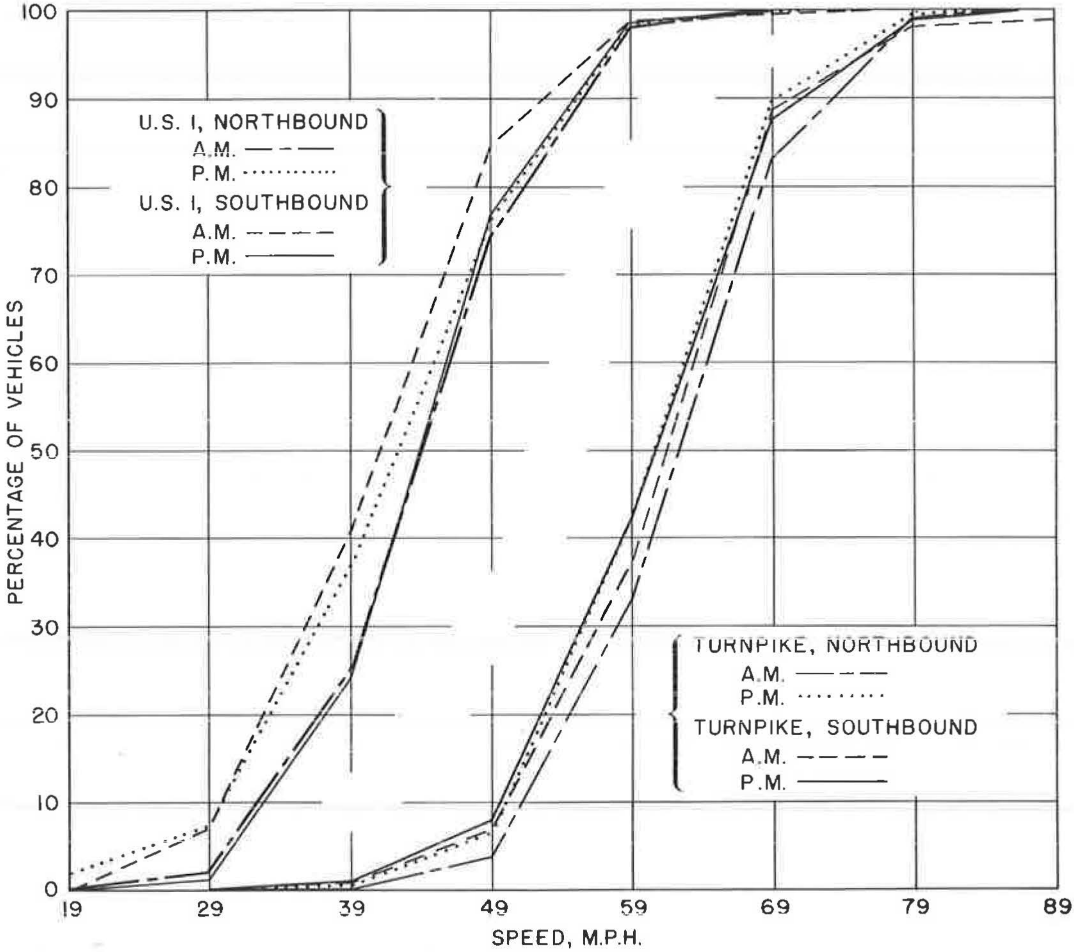

Figure 6. Cumulative distribution of vehicle speeds on Maine Turnpike.

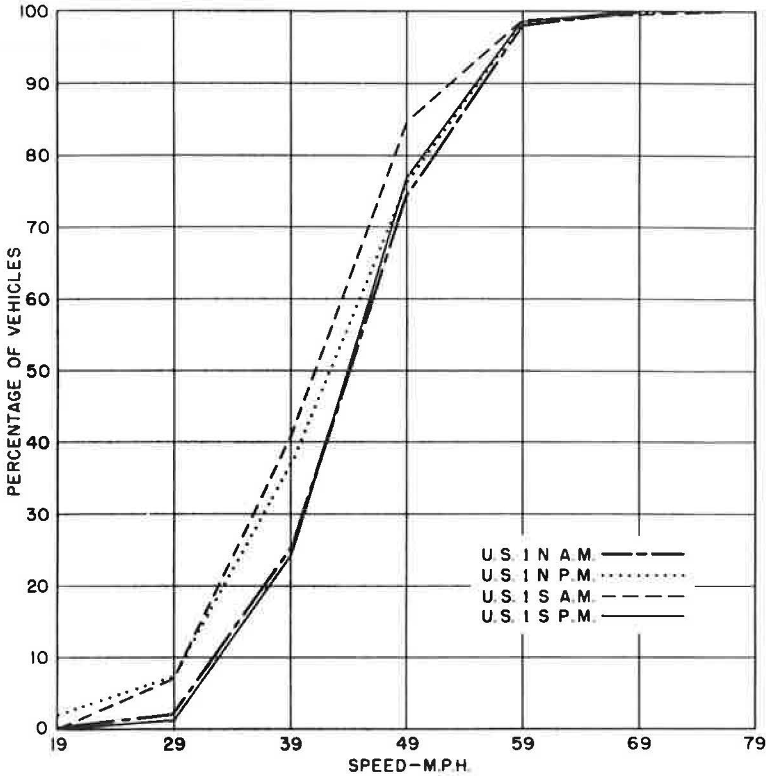

Figure 7. Cumulative distribution of vehicle speeds on US 1.

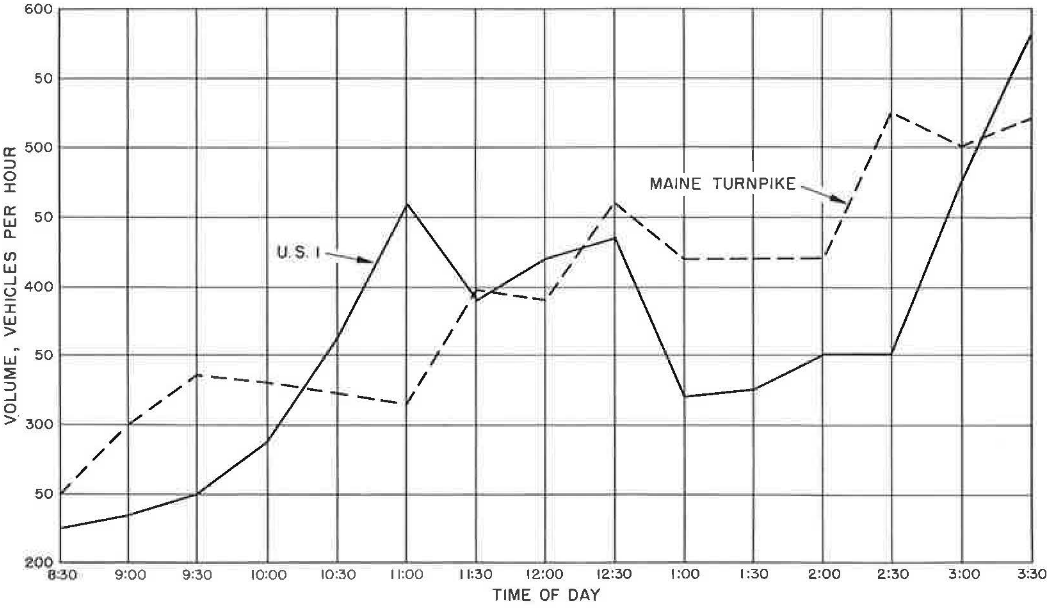

Figure 8. Calculated average hourly volumes on Maine Turnpike and US 1.

TABLE 10

TRAVEL TIMES BETWEEN SOUTH PORTLAND AND KITTERY

Highway	Mean (min)	St. Dev.	95% Conf. Interval
Turnpike	41.1	3.61	±1.25
US 1	63.9	4.31	±1.51

also negatively skewed but not as much as the turnpike. The variability of speeds from sample to sample, as well as in location to location, was far greater on US 1 than on the turnpike. Therefore, the reliability of these summary statistics is in question.

Volumes were calculated for both the turnpike and US 1 on the basis of the same samples of the speed distribution. The average calculated hourly volumes between 8:00 a.m. and 4:00 p.m. are shown for both routes (Fig. 8). The volume on US 1 was not uniform over the entire 47-mi study length, being consistently higher at the more populous northern end. In addition, three counting stations were set up on US 1: one at each end of the study section and a permanent counting station about the middle of the test section. The calculated hourly volumes were approximately the same as those from the counting stations. Finally, the volumes on the two routes were quite comparable, generally paralleling each other in their variations throughout the day.

Travel time data were obtained from the trips made by the 9 test drivers used for the GSR study. In these runs, the drivers were instructed to float with the two highways a total of 4 times. Thus, there were 36 observations of travel time on each route. The summary statistics are given in Table 10 where the standard deviations indicate that on both routes there was a coefficient of variation of 7 percent in travel time. This implies a variation for travel speed of approximately 17 percent on US 1 and 14 percent on the turnpike. Actually, the mean travel time on US 1 agrees quite closely with the travel time predicted from the mean speed of traffic on US 1. On the turnpike, however, the average speed of the test drivers was nearly 7½ mph faster than traffic sampled on the turnpike, indicating that the mean travel time on the turnpike for normal traffic may be up to 4½ min more than given in Table 10. Finally, the maximum range in time savings by selecting the turnpike was calculated on the basis of confidence intervals, and it was found that traveling between South Portland and Kittery a driver would obtain a maximum travel time savings of 35 ± 4 percent by driving the turnpike.

TABLE 11

INTERFERENCES CAUSING GSR IN TEST DRIVERS

No.	Interference
1	Other vehicles traveling in same direction
2	Vehicles merging into driver's path
3	Vehicles turning out of driver's path
4	Traffic control devices
5	Pedestrians on or near driver's path
6	Grades
7	Curves
8	Shoulder objects
9	Opposing vehicles

Tension Measurements

The data for the nine test subjects were analyzed by determining the peak magnitude of GSR for observed interferences (Table 11) which caused the driver to change his speed or position on the roadway. Interference No. 4 (traffic control devices) appears on the turnpike as well as on US 1, because highway maintenance operations were continually performed on the turnpike during this period. Normally advisory speed signs were placed on the highway to protect the maintenance crew and these were included in the definition of traffic control devices.

The magnitude of galvanic skin response per minute which is the defined measure of driver tension was statistically analyzed using the analysis of variance (Table 12). There were significant differences between the routes and subjects but not between directions. These results are similar to

TABLE 12

ANALYSIS OF VARIANCE OF GSR DATA

Source	Sum of Square	d.f.	Mean Square	F	P(F)
Routes	308.65	1	308.65	305.59	<0.01
Subjects	421.11	8	52.64	52.12	<0.01
Direction	0.89	1	0.89	0.89	N.S.
Routes and subjects	62.60	8	7.83	7.75	<0.01
Routes and directions	28.59	1	28.59	28.31	<0.01
Subjects and directions	34.87	8	4.36	4.32	<0.01
Remainder	44.38	44	1.01	—	—
Total	901.14	71	12.69	—	—

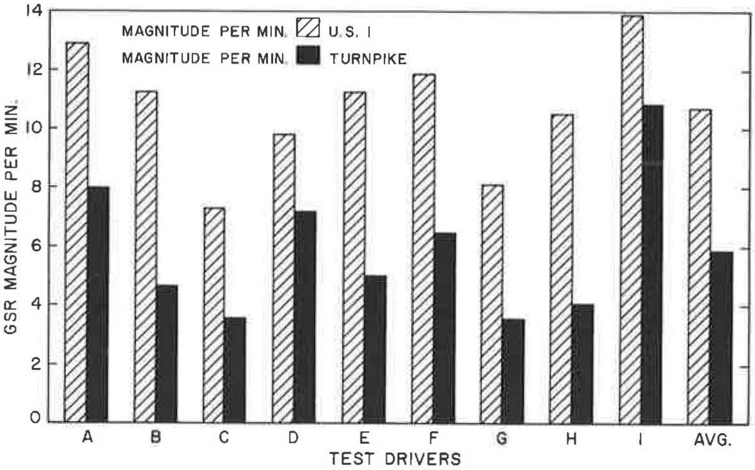

Figure 9. Mean tension generated on Maine Turnpike and US 1.

those reported previously (8). The comparison of tension between the two routes is shown for each subject in Figure 9. The average tension varied considerably between subjects, but in every case US 1 generated significantly more tension than the turnpike. The range of reduction of tension among this group of turnpike subjects was from 22 to 61 percent. The overall average saving of tension by taking the turnpike was 46 percent.

Each route was divided into four 10½-mi sections. The tension data were analyzed to determine whether or not there were differences in tension generation between the sections of the test routes. As expected, there were no significant variations from segment to segment on the turnpike. On US 1 there were also no significant differences between the sections. This finding was unexpected because the highway and traffic from section to section had rather different characteristics. There was also considerable variation in land use adjacent to the highway. One reason for the lack of difference among these sections was because the predominant interference in generating GSR arose directly from other vehicles in the driver's path. Furthermore, when driving through the more complex environments, all drivers reduced their speed and in the process, reduced the probability of unexpected interferences. These compensatory changes may have eliminated any differences between the sections.

INTERPRETATION OF FINDINGS

One of the main objectives of this study was to determine whether there were stable attitudes held by drivers which correlated with their choices between two alternative highways. The results clearly indicate that there were. The attitudes of the users of the one highway differ significantly from the attitudes of the users of the other. Furthermore, the users of the controlled-access highway hold significantly positive attitudes toward that highway, whereas users of the rural primary hold significantly negative attitudes toward the turnpike. On the basis of the results, the likelihood of any sample of drivers holding a positive attitude toward the turnpike actually driving the primary is very small. Furthermore, in the alternative choice situation studied here, an attitude scale appears to be strongly related to choice, much more so than any descriptive information about the characteristics of the drivers or their trips.

This study clearly indicates that drivers do evaluate their experiences on different highways. This organization develops from a variety of elements in the highways they travel. Whether consciously or unconsciously, drivers weigh the various features of highways and combine subjective experiences into an overall evaluation. This evaluation is reflected in attitudes which predispose drivers toward the choice of one highway over another. In fact, these attitudes overwhelm all the specific short-term aspects of a particular trip and dictate which route will be taken.

A third aspect of this study concerns the problem of attraction of traffic to an expressway. In several of the analyses it was quite evident that there was shift in attitudes in favor of the turnpike. The most clear-cut case is the one where the individual items on the scale were analyzed by the route sampled. The significant finding was that the more drivers experience the two highways the more the primary suffers by comparison. The learning experience apparently makes drivers increasingly aware of the negative characteristics of the primary, and hence become more dissatisfied with it. The direct experiences obtained in driving the primary-type highway appear to force drivers onto the turnpike. Thus, the overall problem of the attraction of traffic to an expressway may be considered as arising out of the direct experiences that drivers have in driving it and any alternatives. Because the expressway is perceived by drivers as having fewer negative effects relative to an alternative primary there is a slow shift to the expressway which appears to be motivated by a desire to escape the characteristics of the older design highway.

Three major factors are inherent in this kind of situation which may motivate a shift in favor of an expressway.

1. One factor is the reduction in travel time obtained by choosing the expressway; however, the results of this study show no significant shifts in attitudes as a function of driving time. Drivers feel the same way about both routes whether they are traveling for ¼ hr or more than 2 hr even though, as a proportion of the total trip, savings in time gained from taking the expressway decrease for long trips.
2. The original validation study found that an item concerning the time savings to be obtained from an expressway was non-discriminating; that is, regardless of whether people had positive or negative attitudes toward a turnpike, they all agreed that a time saving was to be obtained on the expressway. Thus, although all drivers knew there was a time saving, it had no influence on their attitudes. Since drivers know this to start with, time savings cannot be the basic cause of the shift in attitudes favoring the expressway. Some more subtle aspect of driving must be the source and it appears most sensitive to the negative characteristics of the primary.
3. The third factor is the direct costs of travel to the user, but it does not appear reasonable, since the shift is in the wrong direction. That is, if cost of travel were a significant determinant of choice, one would find a shift of attitudes away from the turnpike especially as trip frequency increased. However, the results clearly indicate that as the frequency of trips increase there is an increasingly positive attitude toward the turnpike and an even greater likelihood that a driver will choose that highway.

In addition, two items which bear directly on economic evaluation by the driver were added to the scale. These two items were actually the same except that one dealt with direct out-of-pocket cost, whereas the other dealt with cost per vehicle-mile. The two statements read, "I would always travel the turnpike between South Portland and Kittery if the cost were no more than" and the alternatives provided, in one case, increased from \$0.25 to \$4.00, doubling over each of the five categories or, in the other case, from \$0.005 per mile to \$0.08 per mile. It was found, as might be expected, that the cost per mile item was nondiscriminating. Very few drivers have any idea of what the cost per mile is. Estimates on both routes were randomly distributed, with a small proportion of drivers omitting the item.

More surprising was the finding that actual out-of-pocket cost was also nondiscriminating. The reliability on the turnpike was a little higher, possibly because the drivers had just received a toll ticket. Furthermore, drivers sampled on both highways consistently reported to the interviewers that the cost of the turnpike was irrelevant to their choice. This finding may simply mean that most drivers in this sample were quite indifferent to the expense of traveling the turnpike at current cost levels.

Neither time savings nor direct costs appear dominant in determining the attraction of traffic to the turnpike. What appears to be required is something drivers must learn by direct experience and which relates primarily to the negative characteristics of the rural primary-type highway. This leads to the consideration of the stresses arising in driving on the two routes. From the results of the GSR phase of this study, the tension aroused in the test drivers on the expressway is approximately one-half that generated on the primary. This tension is caused by interferences which have purely negative effects. It seems reasonable that shifts in traffic to an expressway-type facility is actually a forcing of drivers away from the primary in order to avoid its stress inducing characteristics. Stated more generally, drivers make choices among routes in order to minimize total stress to which they are subjected in driving. Thus, for the passenger car driver, the basis for scaling the benefits to be obtained from an expressway are neither economic nor time saving but rather stress saving.

The objective of minimizing the stress level in driving may explain two characteristics of the distribution of trips found in this study: (a) the more frequent a trip the more likely were these drivers to take the turnpike, and (b) the longer the duration of a trip the more likely was it to be made on the turnpike.

It is obvious that the total stress experienced on either route is a function of the particular properties of the route and the duration of the trip. That is, the total tension incurred is the integration of the unit stress over the duration of the trip. These tension inducing interferences occur randomly in time with the mean value being greater on the primary highway than on the expressway. Since the variance in rate of occurrence of tension inducing interferences is high, the differences between the stress experienced on two highways in any short time interval will be unpredictable. It will take frequent repetitions or an increased sampling interval, i.e., longer trips, for the driver to detect the difference between the alternatives reliably. By doing either, the likelihood will increase that drivers will detect the differences and thereby modify their choice behavior. The travel time distribution and trip frequency data found in this study conform to this hypothesis.

In simplest terms, the tension generated on any trip is some function of total travel time and the frequency and intensity of stressing interferences. Using a relative measure of tension then, a dimensionless constant is obtained. The relative stress obtained on any trip of a given highway may be defined:

$$S = \frac{T_n}{T_R}(t) \tag{1}$$

where

T_n = magnitude of GSR per minute on highway n;
T_R = magnitude of GSR per minute on reference highway; and
t = trip duration.

Thus, using tension generated on a freeway as a reference, a numerical value of relative stress can be calculated if the type of highway traveled and trip duration are known.

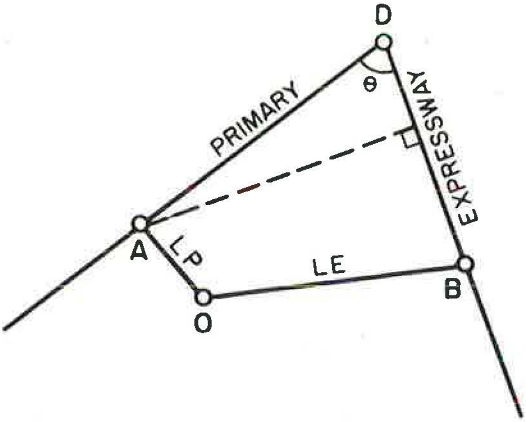

Figure 10. Geometry of diversion situation.

In this and previous studies (7, 8), it was shown that tension generated relative to the controlled-access highway was approximately 1.8 for a primary-type highway and 3.3 for an urban arterial. For a low-volume rural secondary highway, the ratio is probably intermediate, or about 2.5. Similarly, the relative stress for any set of routes may also be computed by summing the stress for the components and the minimum stress route determined.

Concerning the problem of diversion to an expressway this model suggests that drivers will divert to an expressway if the total stress experienced in reaching the expressway and from the expressway to the destination does not exceed that of the trip from origin to the alternative highway and on the alternative to the destination.

A general situation is shown in Figure 10. Assume there is an expressway E and a primary P having a common terminus. Also assume that the origin of a trip is located in the space bounded by the two routes so that there is a direct connection to either by link L. According to the proposed hypothesis a driver will divert to the expressway to reach his destination if the total tension generated on the link L_E and the expressway E is equal to or less than the tension generated on the link L_P and the primary P. If the special case is taken where the origin lies on the primary and L is a perpendicular connection to E (Fig. 10) then an inequality is obtained. The minimum separation between the primary and expressway for which 50 percent diversion will occur is defined

$$K_L \sin\theta + K_E \cos\theta \leq K_P \tag{2}$$

The constants are the relative stress developed on each of the links. The solution of Eq. 2 is simply derived. Solving in terms of the cos θ, a quadratic equation is obtained whose real root is

$$\cos\theta = \frac{\dfrac{T_P}{T_E \cdot V_P \cdot V_E} + \dfrac{T_L}{T_E \cdot V_L} \sqrt{\left(\dfrac{T_L}{T_E \cdot V_L}\right)^2 + \left(\dfrac{1}{V_E}\right)^2 - \left(\dfrac{T_P}{T_E \cdot V_P}\right)^2}}{\left(\dfrac{T_L}{T_E \cdot V_L}\right)^2 + \left(\dfrac{1}{V_E}\right)^2} \tag{3}$$

where

$\frac{T_P}{T_E}$ = ratio of stress developed on a primary-type highway to that developed on an expressway;

$\frac{T_L}{T_E}$ = ratio of stress developed on the link between primary and expressway; and

V = mean speed on appropriate highway, in mph.

It is further possible to define the travel distance ratio and the travel time ratio for this case.

$$\frac{d_L + d_E}{d_P} = \sin\theta + \cos\theta \tag{4}$$

TABLE 13

THEORETICAL SOLUTION OF EXPECTED DIVERSION FROM A PRIMARY HIGHWAY TO AN EXPRESSWAY

Link Type	Separation Between Primary and Expressway (radians)	Trip Distance Ratio	Travel Time Ratio
Primary	0.99	1.39	1.24
Secondary	0.34	1.28	1.12
Arterial	0.13	1.12	1.02

where

d_L = distance on link;
d_E = distance on expressway; and
d_P = distance on primary

and

$$\frac{t_L + t_E}{t_P} = \frac{V_P}{V_L} \sin\theta + \frac{V_P}{V_E} \cos\theta \tag{5}$$

where

t = travel times on each link; and
V = mean travel speed on each link, in mph.

Using the values for relative stress for three different types of highways and the travel speeds, Eqs. 3, 4, and 5 may be solved with the results given in Table 13. The mean travel time ratio decreases consistently as the stress inducing characteristics of the link increase.

Two other aspects may be considered using this model. One is the variance in tension. In this analysis the relative stress is treated as a constant, although it is, of course, a mean value. On the basis of the data in this study the variance of that ratio was 0.42. Using this value and Eqs. 3 and 5, it is possible to calculate the percent of drivers diverting to an expressway (Fig. 11).

The other aspect concerns the volumes that the highways are carrying. As has been shown previously (8), the mean tension on an expressway increases linearly up to about 1,400 vehicles per lane per hour. Beyond that volume tension increases very rapidly. On urban arterials (7), volume appears to have relatively little overall effect on tension generation. For primary-type highways, however, no data are available on the effect of increasing volume. If it is assumed that the effect of volume on the primary type is similar to that on arterials, diversion to an expressway will vary solely with volume on that type of highway. The effect of increasing expressway volume on the travel time ratio for 50 percent diversion is shown for the three types of links in Figure 12, where the travel time ratio for 50 percent diversion decreases until, with volumes exceeding 1,000 vehicles per lane per hour on the expressway, an actual time savings must occur before half the traffic diverts.

The diversion curves developed from this special case do not conform to those developed from origin and destination studies in this corridor (1). The model predicts much more attraction than actually found, partly due to the assumptions about the connection between primary and expressway. The choice points are not very direct for drivers within the Maine Turnpike-US 1 corridor. Furthermore, a significant propor-

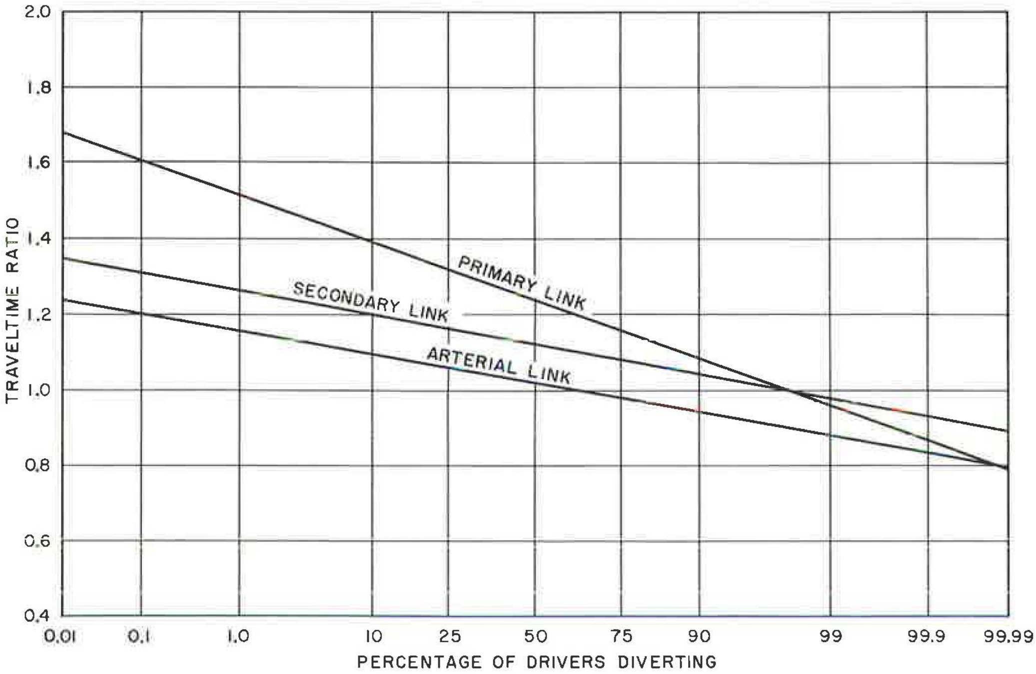

Figure 11. Theoretical diversion distributions for different connections from primary to expressway.

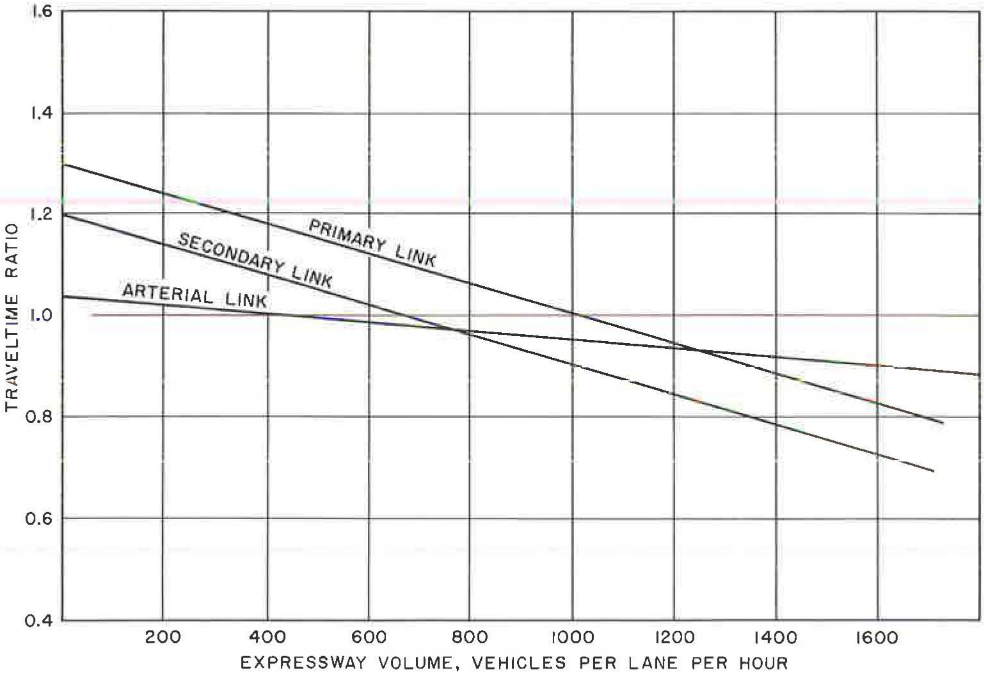

Figure 12. Expected travel time ratio for 50 percent diversion as function of expressway volume.

tion of trips are quite short. For this class of traffic, essentially trapped on US 1, diversion to the turnpike would gain the driver no detectable stress reduction and hence little diversion would be expected.

However, for corridor trips more than ten miles and north-south oriented, considerably more diversion should occur than appears in the general diversion curves. In this respect, Carpenter (3) examined through trips between Wells and Saco and found that 30 percent of the trips diverted to the turnpike. This occurred even though the travel time ratio was approximately 1.22. However, on the basis of the link characteristics, the tension ratio for the alternatives may be calculated and is approximately 1.09. This yields expected diversion of approximately 35 percent of these trips.

It seems reasonable to conclude from this analysis that whenever the alternatives available are equally stress inducing, drivers will always choose the route that takes the least time. Nor is it surprising that most drivers when questioned about choice of route commonly use travel time as a response. Not only is total stress directly related to travel time, but also many of the alternatives available offer no significant stress reduction. Furthermore, such trips are often so short that stress differences are hardly detectable. It is evident from this study, however, that drivers will actually tolerate a time loss as well as a distance loss if the total stress to which they may be subjected is perceptibly reduced.

On the basis of this model, measures that reduce stress should lead to both increases in trip lengths and trip frequency. Since driving is a stressful and energy consuming task, each driver has a tolerance or limit beyond which the subjective cost of driving becomes excessive. The satisfactions to be gained by a trip are less than the energy required to achieve it. If trips are predominantly goal-oriented, the stress imposed on a driver becomes the equivalent of a cost whose value is determined in part by the desirability of the goal. Conversely, reduction of this subjective cost by the addition of improved highways not only makes any given trip easier, but also lower priority goals become attainable, and thus new travel is generated.

It would seem that the value of these subjective costs of driving are determinable experimentally. One way is by subjective scaling of simulated trips which is a variation of game theory techniques. The other is subjective evaluation of actual trips made under defined conditions. However, a significant problem would remain—the measurement of the value a driver places on the goal which motivates a trip. It is this goal desirability, as satisfied through highway transport, which is the measure of the subjective benefits of that system. Apparently, there do exist methods for quantifying the subjective costs of travel but not for subjective benefits. However, it is becoming increasingly clear that even though passenger car drivers make rational evaluations of transportation, their benefit-cost ratio appears to have little in common with the economic criteria normally used in highway transport.

ACKNOWLEDGMENT

The author wishes to express his appreciation to the late Ralph H. Sawyer, Planning and Traffic Engineer of the Maine State Highway Commission, and to the late Williams B. Getchell, Jr., Executive Director of the Maine Turnpike Authority without whose assistance and counsel this research would have been impossible. Also the author is in debt to the field leaders Daniel Bridges and Harold C. Wood, Jr.

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Changes in Driver Performance with Time in Driving

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•DETERIORATION or failure in driving performance with continued time in driving is recognized by traffic and safety engineers to be a major cause of accidents and deaths on the highway. In order to learn more about this change in performance and perhaps ultimately find a way to reduce its hazards, The University of Michigan as a part of its research under a grant from the Ford Motor Company Fund has conducted a study of the changes in driving behavior that occur with increasing time behind the wheel.

The study has been made possible by the development during the last few years of a new research instrument that furnishes a continuous and integrated digital record of driver-vehicle performance.

SOME CONCEPTS

Since there are several concepts or explanations of what happens with increasing time spent in work be it mental or physical it may be fruitful to review some of these concepts before describing the methods used and discussing the results obtained in the present study. Although there has been hesitancy in using the term "driving fatigue" due to its controversial meaning it is under this heading that one must look for an explanation of changes in performance with time.

Captain Robert B. Bennett, Safety Officer, Fighter Interceptor Squadron, (5) states: "Actually, fatigue does not have a specific scientific meaning, nor can it be measured or defined. When we are fatigued we have feelings of tiredness, lassitude, sleepiness, etc., but these are incidental. Fatigue refers to loss of efficiency and skill, and level of anxiety."

The "feeling of tiredness, etc.", is usually defined as (1) subjective, or experiential fatigue; while (2) physiological fatigue is brought about by chemical reaction in the blood. When the amount of glycogen in the blood stream decreases and other by-products of prolonged activity such as lactic acid and carbon dioxide increase, the muscle or nerve tissue loses its ability to function; and (3) objective fatigue—work output or any and all changes in observable behavior. This report is concerned with observable behavior in driving.

Bartley and Chute (1) distinguished the three aspects of fatigue just mentioned, but hold that true fatigue arises in a conflict situation in which the general alignment of the individual is that of aversion. They also argue that fatigue is an experience of the whole person, that such an experience necessitates a science of the person, and that impairment and work output may or may not be related to fatigue. Fatigue (according to Bartley and Chute) is a personal aversive alignment; work output is an observable behavior and work output changes may be brought about by phenomena other than fatigue. Some workers distinguish between experiential, physiological, and behavioral phenomena, but they consider fatigue as somehow composed of all three rather than of just the experiential phenomena. Viteles (14), for example, states that fatigue is "characterized" by phenomena in the three classes. Starch, et al. (21) maintain a distinction between three kinds of fatigue corresponding to the three classes of phenomena. They also emphasize the fact (as do Bartley and Chute) that the three phenomena may have little or no rela-

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Paper sponsored by Committee on Road User Characteristics.

tion with each other, pointing out that subjective fatigue may not occur in highly emotional situations, even though physiological fatigue may be present. Thus, with intense grief, intense concentration on creative work, etc., one may not "pay attention" to fatigue and thus may not experience it. Fatigue feelings, by this view, are a device which warns the individual whenever the waste products in the muscles and blood stream are not released fast enough to maintain a certain energy level, and which may or may not operate, depending upon emotional and other personal factors.

Gilliland, et al. (13) consider the fact that long mental tasks sometimes do not incur feelings of fatigue. They hypothesize, then, that any phenomenon of "mental fatigue" reduces to physical fatigue, reasoning that mental activity sometimes results in holding certain muscles tense, thus producing fatigue feelings. The function of this fatigue feeling is to slow the body in order to allow it to undergo self-repair and regeneration.

Cattell (8) holds to the two-aspect view of fatigue, the physiological and the subjective. In so doing, he makes a statement, quite relevant to the problem of driving "fatigue," to the effect that the greatest decrement in performance occurs after the feeling of weariness passes and a feeling of well-being takes its place. Freeman (12) like Cattell, emphasizes the distinction between fatigue and performance, suggesting that the reason performance level is often maintained despite feelings of fatigue might be a temporary improvement in methods accompanying continuous and prolonged effort in a routine endeavor. Young (27) considers fatigue a motivation factor which he calls "will." By this view, performance level is determined by the extent to which the increments due to "will" off-set the decrements due to fatigue.

Crawford (9), citing Drew (11) and Bartlett (2), mentions three stages of skill fatigue. First the subject's timing is affected; parts of the cycle of operations being occasionally slowed and other parts hurried; second, the subject ignores some of the elements of the task; and at a third stage aches and pains are noticed.

Crawford, referring to Bartlett (3), states that fatigue "may be seen as a progressive widening of the field of stimuli to which response is made, so that the subject's actions lose direction. Insight deteriorates fairly early and standards are lowered. Actions the subject would normally consider hazardous are undertaken with little concern when he is overly fatigued."

Crawford further states that it is difficult to estimate how long it will take for these stages to be reached in driving. He also states that the more the whole being is engaged in a task and consequently the more varied the sources of stress the more gradually will changes take place, the less they will depend on specific physical effort and the harder they will be to detect.

That precise measurements of driving behavior as obtained by the Drivometer might make it possible to detect the effects of fatigue in driving has been demonstrated by Fletcher N. Platt (18), Manager, Traffic Safety and Highway Improvement Department, Ford Motor Company, who made a Pilot Study in 1962. Mr. Platt found that "driver stress and the effects of fatigue can be measured effectively by the Drivometer" and that "quantitatively rating a driver's performance compared to his norm provides a starting point for providing a specific measure of fatigue."

In general, from the findings mentioned, and those of others (see references) one would expect that all phases of driving performance would tend to deteriorate with time, but that motivation (strong emotional drive) could offset this deterioration.

In discussing the findings of this study, let us start with a description of the recordings furnished by the Drivometer—the key to this new study of fatigue. The Drivometer has been described in some detail in other publications. The description presented here is only that necessary for an understanding of the experiment.

THE DRIVOMETER RECORDINGS

The "Drivometer" used in this study records the actions of the driver and the response motions of the vehicle. The counts recorded by the Drivometer include the following:

Steering Wheel Reversals. A count is made each time the steering wheel is reversed by $^3/_8$ in. or more at the rim of the wheel from clockwise to counter-clockwise or in

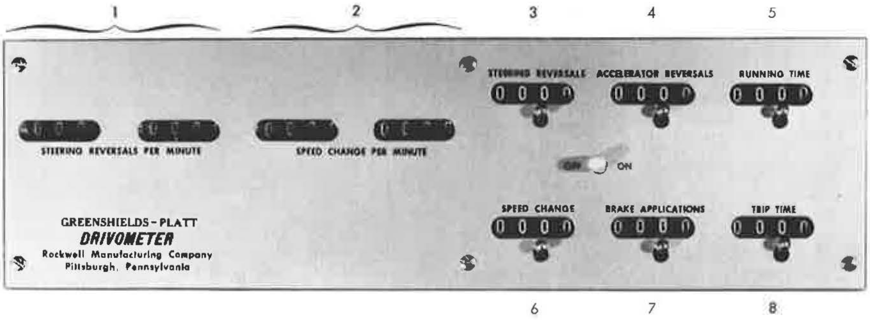


Figure 1.

the opposite direction. Only one count is made no matter how far beyond $^3/_8$ in. the wheel is turned. The steering wheel reversal counts are integrated minute by minute. (Dials No. 1; see Fig. 1).

Acceleration Reversals. A movement of the accelerator approximately $^1/_8$ in. up or down makes a one-half count. Thus, there is a count for each accelerator reversal whether at partial or full throttle.

Brake Applications. There is a count for each brake application.

Speed Change. Speed change is recorded by a one-half count for every two miles per hour increase or decrease in vehicle speed. Thus, the amount of speed change in miles per hour for any time interval may be found by multiplying the dial count by four. Since we are interested in fluctuations in the count rather than the amount, the dial readings are used directly in analysis. The amount of speed change, minute by minute, is shown on the No. 2 dials. The total speed change for a trip is shown on dial No. 6.

The Trip Time and the Running Time are shown by dials No. 8 and 5, respectively. It is obvious that by reading the dials at any time interval, the changes per interval may be obtained by simple subtraction.

PROCEDURE

It was decided to make the "fatigue" runs on an expressway where the physical features of the road would be practically constant. The drivers were all college students. No attempt was made to make sufficient runs to achieve statistical stability. It was anticipated from the findings of others already referred to that there would be little or no consistency in the times at which drivers would show the effects of driving fatigue.

The data from a number of "runs" or trips will be plotted and analyzed to give an indication of the differences in individual driving behavior. The data will then be summarized in tabular form.

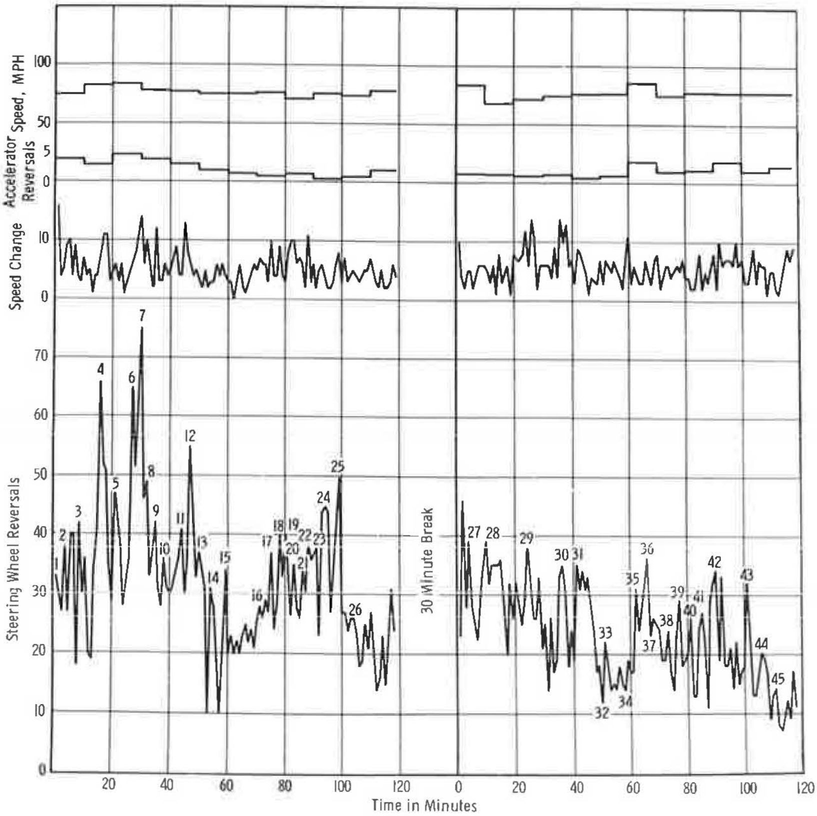
A graphical representation of a typical "fatigue" trip is shown in Figure 2. The physical and mental condition of the driver at the beginning of the run could be described as normal. Each driver at the beginning of a trip filled out a questionnaire giving his own estimate of his condition.

Four variables are shown: (1) the speed in miles per hour for each 10 minutes of driving, (2) the number of accelerator reversals per 10-minute interval, (3) the amount of speed change for each one-minute interval, and (4) the number of steering wheel reversals for each one-minute interval. The number of brake applications was found to be insignificant and was not plotted.

The numbers at the frequency peaks of steering wheel reversals refer to the events that could have caused the fluctuations in the frequency of steering wheel reversals.

List of Events Corresponding to Numbers Shown in Figure 2

1. Adjusted sun visor and car window.
2. Slowed for car in passing lane.
3. Lit cigarette.
4. Used horn—talking.
5. Put out cigarette—slowed for truck.
6. Adjusted heat control.
7. Slowed for car in passing lane.
8. Gestured.



ANN ARBOR, MICHIGAN TO BENTON HARBOR, MICHIGAN AND RETURN, VIA EXPRESSWAY, DRIVER "A"

Figure 2.

9. Talked and gestured.
10. Slowed for one lane traffic.
11. Adjusted heat control.
12. Adjusted heat control.
13. Ate candy.
14. Slowed for truck.
15. Stretched—adjusted heat and vent.
16. Adjusted heat controls.
17. No observed reason.
18. Noted cross winds.
19. Changed to left foot for accelerator.
20. Lit cigarette.
21. Used horn.
22. Slowed for lane traffic.
23. Put out cigarette—adjusted heat.
24. Slowed for truck.
25. Driver stated he was drowsy—noted cross winds.
26. Stretched.
27. Slowed for pedestrian on highway.
28. Gestured.
29. Driver watched counters.
30. Changed back to right foot on accelerator.
31. Put out cigarette.
32. Noted cross wind.
33. Passed two trucks.
34. Road repair zone.
35. Driver seems to be over steering.
36. Changed position of hands on steering wheel.
37. Passing.
38. Changed position of hands on steering wheel.
39. Lit cigarette.
40. Wind from passing truck made car sway.
41. Stretched right foot.
42. Seemed to be over steering.
43. Changing grade.
44. Changing grade.
45. Changed position of hands on steering wheel.
46. Applied brakes to avoid slow car in passing.
47. Burning car on roadside.
48. Changed hands on steering wheel.
49. Again changed hands on steering wheel.

ANALYSIS OF GRAPH

An examination of Figure 2 reveals that the accelerator reversals per 10-minute period decrease in frequency at about the end of the first hour and then increase at about the end of the third hour.

The minute by minute amount of speed change is much more variable than the number of acceleration actions. This is to be expected for the speed change depends on the topography of the road and the varying position of the accelerator, not just the up and down movements of the accelerator.

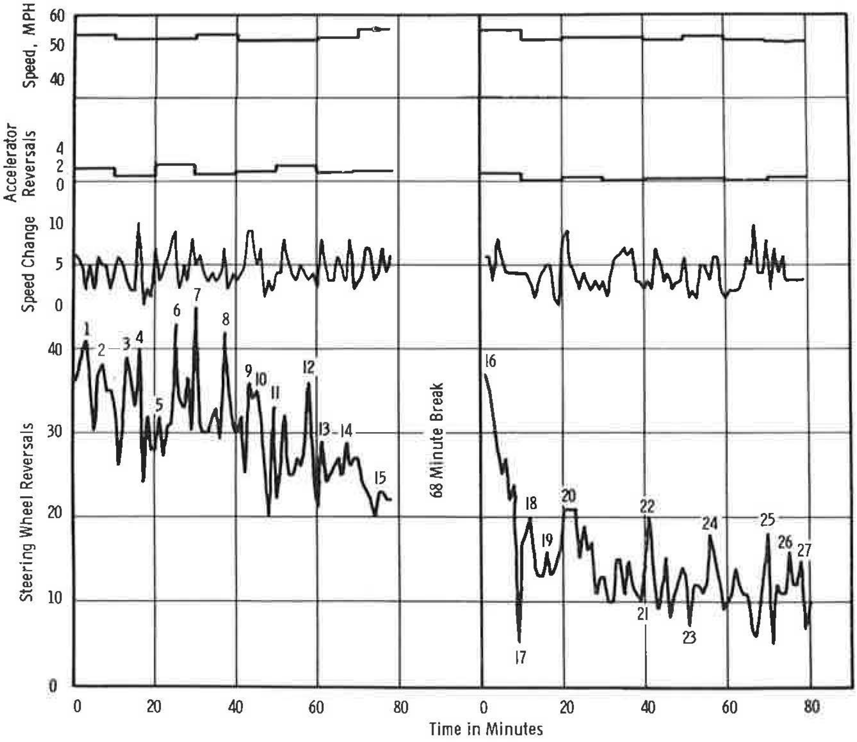
The speed change in both amount and variability decreases at about the end of the first hour and then increases but drops off again at about the end of the second hour.

After the 30-minute time break, the speed change starts, after the first minute, at a relatively low level, then after about a half hour increases, and then decreases to a fairly constant rate.

The numbers of steering wheel reversals per minute show a decrease in both amount and variability. There is also found to be a roughly defined rhythm in the number of steering wheel reversals. First, there is a rise, then a decrease at about the end of the first hour, then again a rise, followed by a decrease.

After the 30-minute break the reversals decrease for the first hour, then increase for a short time but not to as high a level, after which they decrease to a low point at the end of the four-hour drive.

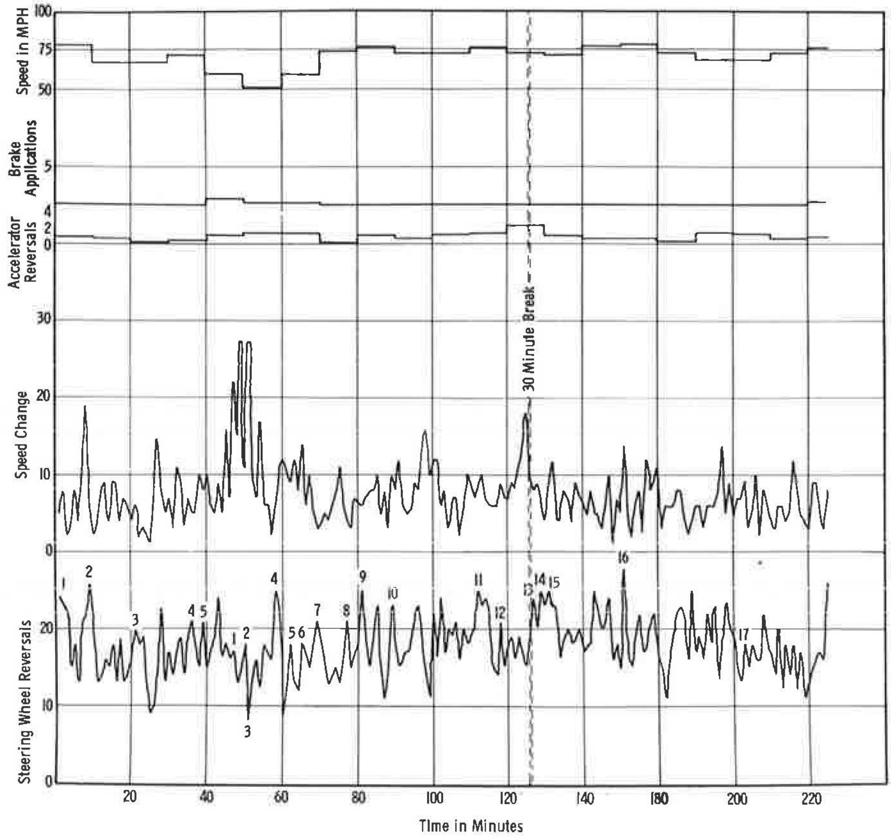
The variation in the number of steering wheel reversals is more pronounced than other driving actions. But this is judging from only one trip, so let us turn to another drive by the same person.



ANN ARBOR, MICHIGAN TO MARSHALL, MICHIGAN AND RETURN. DRIVER "A"

VIA EXPRESSWAY. SPEED TO BE CONSTANT 50 MPH, CAREFUL TRACKING IN LANE

Figure 3.



CHICAGO TO ANN ARBOR VIA EXPRESSWAY DRIVER "B"

Figure 4.

In the next run (Fig. 3), the time is shorter but the driving task has been made more difficult. The driver was requested to maintain a constant speed and tracking position on the pavement.

List of Events Corresponding to Numbers Shown in Figure 3

1. Cross wind.
2. Lit cigarette—turned on heater.
3. Cross wind.
4. Put out cigarette.
5. Closed air vent.
6. Passed car.
7. Passed truck and car—talked.
8. Telling story.
9. Cross wind.
10. Slowed and passed truck.
11. No explanation.
12. Stretched.
13. Lit cigarette—opened vent.
14. Turned off heat—turned off dome light.
15. Slowed—cross wind.
16. Passed truck—increased speed.
17. No explanation.
18. Put out cigarette.
19. Driver checked speed.
20. Talking—no specific subject.
21. Talking.
22. Passed car.
23. Driver stated that he was very tired—having hallucinations.
24. Checking speed.
25. No explanation.
26. Lit cigarette—talking.
27. Closed vent—turned heat down.

The driving pattern for driver "B" (Fig. 4) is distinctly different from that of driver "A." The amount of speed change is slightly greater while the number of steering wheel reversals is less. There seems to be no decrease in the frequency of the steering wheel reversals as was experienced by Driver "A." Driver "B" stated that he was fresh and alert at the beginning of the trip. But other trips by driver "B" showed a similar pattern even though he was tired at the start.

List of Events Corresponding to Numbers Shown in Figure 4

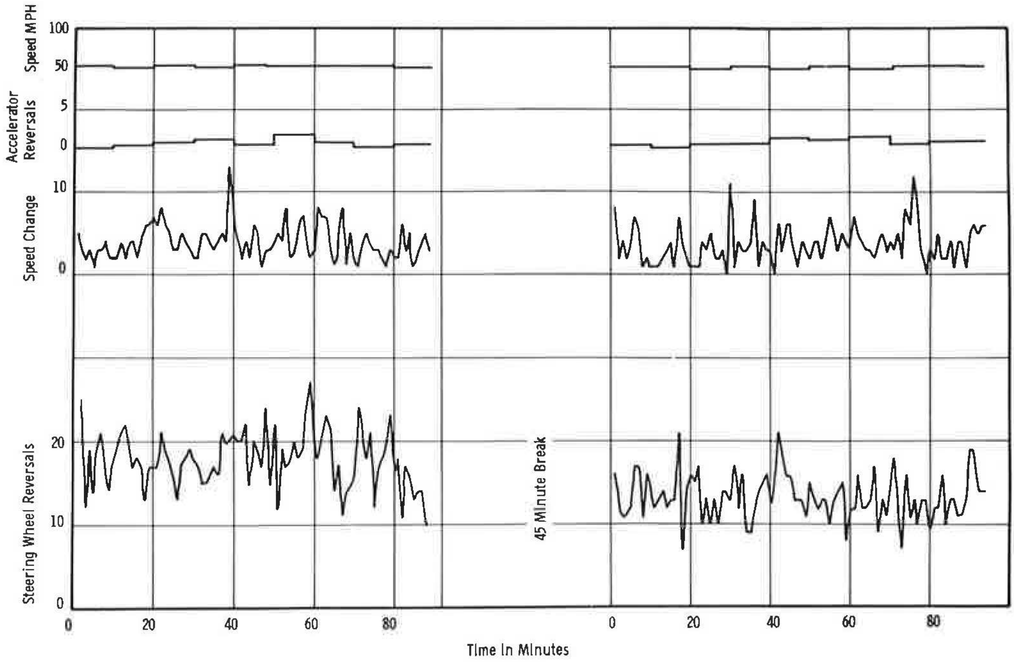
1. Strong cross wind.
2. Slowed—toll gate.
3. Left toll gate.
4. Cross wind.
5. Heavy traffic.
6. Toll gate.
7. Traffic backed up for traffic light.
8. Braked twice.
9. Stopped for light—speeded up.
10. Stop light.
11. Beginning to snow.
12. Adjusted seat—lit cigarette.
13. Rough pavement.
14. Barricade—one lane traffic.
15. Wheel off edge of pavement.
16. Snowing—pavement wet.
17. Traffic and weather conditions improved.

The driving patterns for driver "C" are shown in Figure 5. In this trip the driver was attempting to maintain a constant speed of 50 miles per hour.

It may be noted that the number of steering wheel reversals at about $1\frac{1}{2}$ hours dropped from an average of about 16.6 per minute to a rate of about 12.6 and then remained fairly constant.

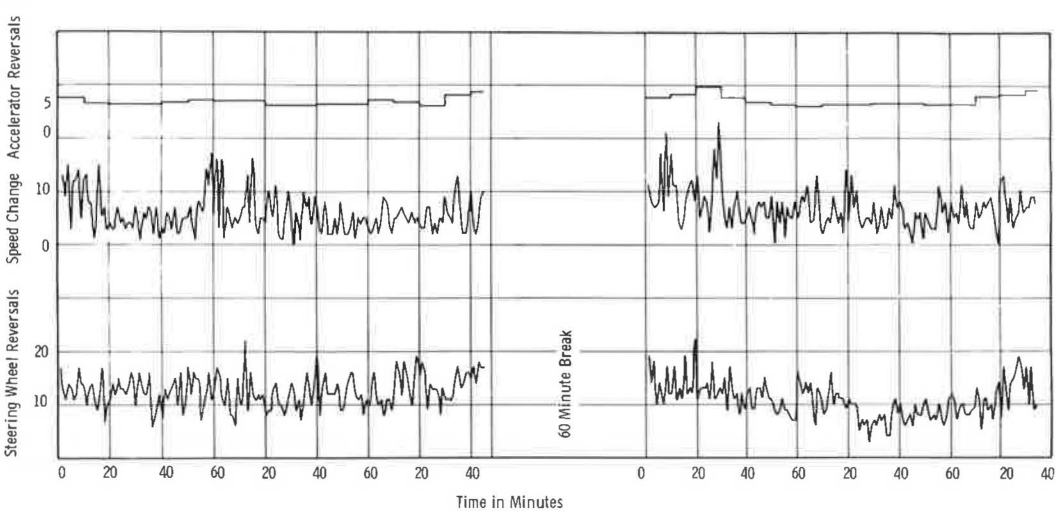
Another trip by driver "C" (Fig. 6) shows a similar driving profile. In this longer trip the rate of steering wheel reversals reached a low point after about $5\frac{1}{4}$ hours of driving.

Driver "E" (Fig. 7) displays a driving profile different from driver "A" when driver "A" was attempting to drive at a constant speed. Driver "A"'s steering reversal rate



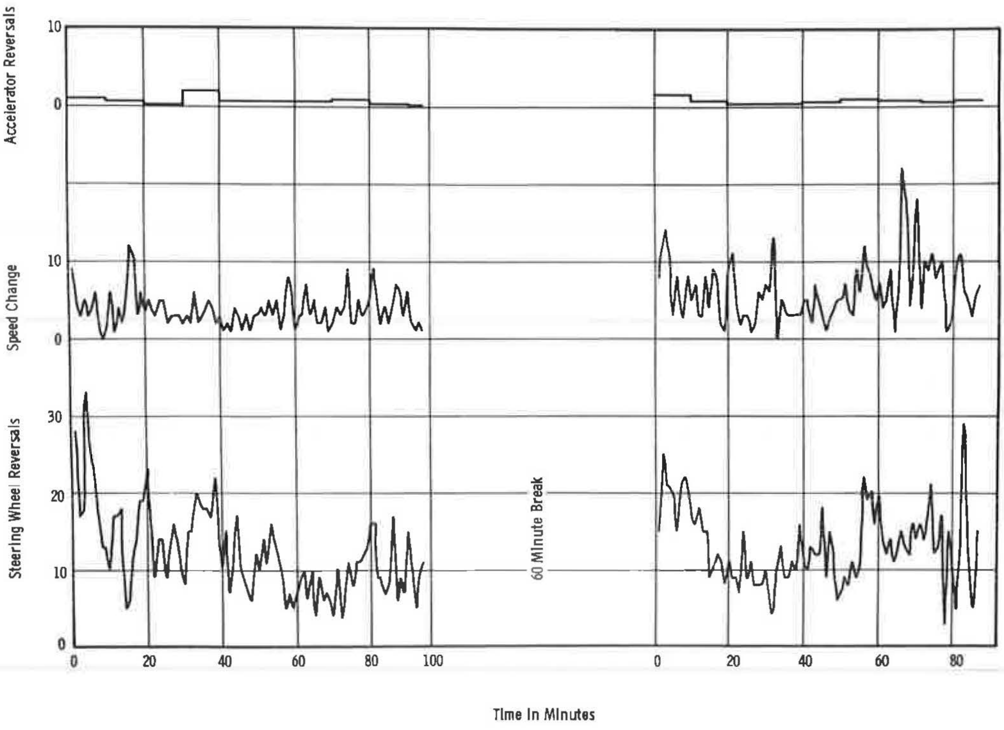
ANN ARBOR, MICHIGAN TO BATTLE CREEK, MICHIGAN AND RETURN VIA EXPRESSWAY. DRIVER "C"

Figure 5.



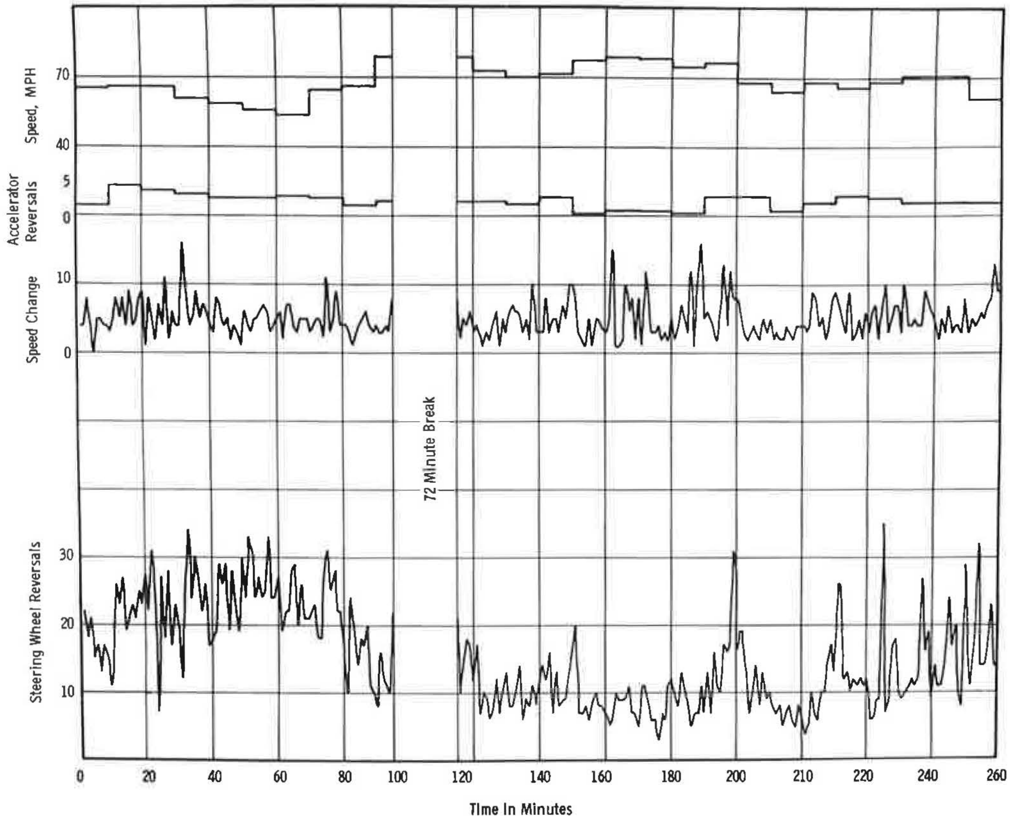
ANN ARBOR, MICHIGAN TO MUSKEGAN, MICHIGAN AND RETURN VIA EXPRESSWAY. DRIVER "C"

Figure 6.



ANN ARBOR, MICHIGAN TO KALAMAZOO, MICHIGAN AND RETURN VIA EXPRESSWAY. DRIVER "E", CONSTANT 60 MPH SPEED.

Figure 7.



MACKINAW CITY, MICHIGAN TO ANN ARBOR, MICHIGAN VIA EXPRESSWAY. DRIVER "A"

Figure 8.

shows a fairly constant decrease throughout the trip. Driver "E" reaches a low point after about 1 hour and 10 minutes of driving and then his rate increases and shows much more variation.

In Figure 8 there is shown a driving pattern for Driver "A" that appears to be quite different from the two previously shown driving patterns for "A." This figure shows the last part of about a 9-hour drive. At the beginning of the chart shown in Figure 8, "A" had been driving for about 3 hours. The low point in the frequency of steering wheel reversals was reached after about 6 hours of driving and about 1 hour and 20 minutes after a stop period. Both the rate of speed change and rate of steering wheel reversals were increasing at the end of the drive. This was quite different from the experience shown in Figure 4.

This phenomenon shown in Figure 8 may be compared to the finding of Herbert and Jaynes (15) who found an improvement in performance after 9 hours as compared to 7 hours. They state that one explanation may be that a gradual but unconscious buildup of fatigue occurs over several hours of driving. "Once the condition becomes obvious to the operator, a conscious effort is made to compensate and thus effect a return to a higher skill level."

All of the runs taken were plotted as shown in the examples given but to show all these would add little if anything to the report. The data for the other runs are summarized in Table 1—"Changes in Driver Behavior with Time Behind the Wheel." The items listed in the table are as follows:

TABLE 1

CHANGES IN DRIVER PERFORMANCE WITH TIME BEHIND THE WHEEL

Type of Run	Driver	Condition of Driver	Date	Time	Steering Wheel Reversals			Speed Change			Accelerator Reversals			Speed M.P.H.		
					N. Rate	Rate	Avg.	N. Rate	Rate	Avg.	N. Rate	Rate	Avg.	Events Obsvd.	Hwy.	Per.
Av.	A	Normal	11/25/62	20'-30'	12	11.8		4.0	3.8		1	5		78	4	
Av.		Normal	2/1/63	20'-30'		11.3			3.6			0.9		65.0	1	
Av.		Normal	12/9/62	20'-30'		15.3			4.2			1.1		76.0		1
Av.		Normal	12/22/62	20'-30'		15.5			5.7			0.2		67	1	
CS/TR		Sleepy	3/16/63	20'-30'		15.3			5.3			1.4		60	2	
CS		Tired	11/13/62	20'-30'		12.3	13.6		5.0	4.7		0.6	0.78	71.0	2	
CS	B	Tired	1/20/63	20'-30'	32	34.1			4.5			2.0		53.0	1	1
CS		Normal	1/22/63	20'-30'		27.7			3.8			2.7		45.1	1	1
Av.		Tired-Sleepy	12/4/62	20'-30'		47.5	30.6		6.5	5.04		4.6	3.1	82.1	1	2
CS	C	Normal	2/5/63	20'-30'	13.0	13.0		5.5	3.7		2.0	1.5		61.8		2
CS		Normal	2/7/63	20'-30'		16.8			10.0			2.9		65.0	3	2
Av.		Tired	2/4/63	20'-30'		17.5			3.7			1.0		53.0	1	0
CS		Normal	2/12/63	20'-30'		12.8	15.02		4.8	5.54		1.9	1.82	71	0	0
Av.	D	Normal	11/23/62	20'-30'	9	10.0		3.9	4.5		1	0.2		65	1	2
Av.		Fresh	11/20/62	20'-30'		14.8			5.3			0.9		71.0	1	2
Av.		Tired	11/25/62	20'-30'		9.8			3.7			2.3		74.0	1	2
		Tired	12/21/62	20'-30'		6.5			4.4			1.2		69.0	1	1
		Tired	12/18/62	20'-30'		10.4			4.7			.1		74.0	2	0
		Normal	1/31/63	20'-30'		11.7			4.0			.5		67.0	0	2
		Tired	12/16/62	20'-30'		6.1	10.53		4.0	4.44		.2	1.04	72.0	0	0
CS/TR	E		4/10/63	20'-30'	20	12.3		4.0	3.5			0.3		62.4	1	
Av.	F	Fresh	11/19/62	20'-30'	25.0	26.6		4.0	4.8		2.0	1.4		71.0	0	2
Av.	A		11/25/62	50'-60'		12.5			4.5			0.9		79.0	2	0
Av.			2/1/63	50'-60'		9.6			4.2			1.0		62.0	0	0
Av.			12/9/62	50'-60'		19.1			4.8			1.2		71.0	1	1
CS			12/27/62	50'-60'		15.4			10.9			1.4		51.0	3	
CS			3/16/63	50'-60'		12.5			3.7			1.1		60.0	0	0
			11/13/62	50'-60'		14.0	13.85		5.8	5.65		0.8	1.06	72.0	1	1
CS	B		1/20/63	50'-60'		25.8			3.8			1.8		52.0		1
50 mph			1/22/63	50'-60'		29.0			4.9			2.6		50.5		2
45-50			12/4/62	50'-60'		23.7	26.16		3.8	4.17		1.8	2.07	75.0	0	0
	C		2/5/63	50'-60'		12.7			5.7			2.2		60.3	1	1
			2/7/63	50'-60'		16.5			7.7			3.1		64.5	0	0
			2/4/63	50'-60'		19.0			3.9			1.9		52.0		1
			2/12/63	50'-60'		9.9	14.52		4.8	5.52		2.2	2.35	70.0	0	0
	D		11/20/62	50'-60'		17.7			7.1			0.4		74.0	2	4
			11/25/62	50'-60'		15.9			15.6			3.3		48.0	3	1
			12/21/62	50'-60'		5.1			5.9			.5		76.0	0	0
			12/18/62	50'-60'		8.9			2.9			.2		76.0	2	3
			1/31/63	50'-60'		9.3			3.3			.3		60.0	0	1
			12/16/62	50'-60'		7.4	10.41		3.9	6.4		.5	.86	74.0	1	0
	E		4/10/63	50'-60'		10.1			3.8			0.7		50.4	2	
	F		11/19/62	50'-60'		22.0			3.2			1.9		68.0	0	1
	A		11/25/62	80'-90'		12.5			3.5			0.5		78	2	
			2/1/63	80'-90'		11.9			3.9			0.5		65.0	1	
			12/9/62	80'-90'		23.5			6.2			2.7		66.0	2	
			12/22/62	80'-90'		18.3			6.3			1.1		77.0		2
			3/16/63	80'-90'		10.2			3.9			1.1		61.0	3	
			11/13/62	80'-90'		14.5	13.48		3.8	4.61		0.8	1.11	75.0		4
	B		1/20/63	80'-90'		25.0			4.6			.9		55.0	1	1
			1/22/63	89'-90'		25.5			5.2			1.4		59.0	1	2
			12/4/62	80'-90'		32.4	27.66		6.9	5.57		1.3	1.2	71.0	2	3
	C		2/5/63	80'-90'		10.4			5.2			1.2		63.0	2	3
			2/7/62	80'-90'		16.1			7.8			4.2		64.0		1
			2/4/63	80'-90'		13.3			2.8			.8		52.0	0	0
			2/12/63	80'-90'		10.1	12.47		5.5	5.33		1.9	2.02	67.0	1	0
	D		11/20/62	80'-90'		17.8			7.4			2.5		60.0	1	4
			11/25/62	80'-90'		9.9			4.1			2.1		73.0	1	0
			12/21/62	80'-90'		6.0			5.4			1.6		67.0	2	0
			12/18/62	80'-90'		7.2			3.3			.2		75.0	0	0
			1/31/63	80'-90'		8.6			5.3			.6		63	0	2
			12/16/62	80'-90'		7.6	9.51		5.5	5.16		1.3	1.38	63.0	1	0
	E		4/10/63	80'-90'		10.4			4.8			0.4		65.0	1	0
	F		11/19/62	80'-90'		22.1			4.9			2.8		68.0	2	1
	A		11/25/62	110'-120'		12.2			5.5			1.3			1	0
			2/1/63	110'-120'		10.6			4.4			.9		61.0	1	
			12/9/62	110'-120'		17.7			7.9			2.4		63.0	1	0
			12/22/62	110'-120'		19.5			6.1			1.4		77.0	0	0
			3/16/63	110'-120'		12.3			10.2			1.3		60.0	0	0

			2/7/63	110'-120'		12.7		7.0		2.5		64.0	0	0
			2/4/63	110'-120'		12.8		3.1		.8		51.0	0	0
			2/12/63	110'-120'		10.3	11.90	6.8	4.97	2.1	1.70	68.0	0	0
	D		11/20/62	110'-129'		18.3		6.4		1.2		75.0	0	0
			11/25/62	110'-120'		9.6		3.9		2.3		72.0	1	3
			12/21/62	110'-120'		4.6		3.3		.7		66.0	0	0
			12/18/62	110'-120'		8.9		5.0		1.2		78.0	1	1
			1/31/63	110'-120'		8.9		2.8		.6		65.5	0	0
			12/16/62	110'-120'		5.4	8.28	3.5	4.31	.6	1.1	81.0	0	0
	E		4/10/63	110'-120'		9.4		4.5		0.5		64.0	0	0
	A		11/25/62	140'-150'	12									
			12/9/62	140'-150'		17.9		5.3		2.0		75.0	0	0
			12/22/62	140'-150'		19.3		4.8		0.7		78.0	0	0
			3/16/63	140'-150'		12.8		3.8		1.7		60.0	1	4
			11/13/62	140'-150'		11.9	15.48	4.2	4.53	0.7	1.28	78.0	1	2
	B		1/20/63	140'-150'		10.9		4.0		2.0		54	10	4
			1/22/63	140'-150'		17.1		3.7		0.7		68	1	1
			12/4/62	140'-150'		28.3	18.8	7.9	5.2	1.2	1.3	71.0	2	0
	C		2/5/63	140'-150'		12.6		3.8		1.2		61.8	0	2
			2/7/63	140'-150'		14.9		7.7		1.3		63.0	2	0
			2/4/63	140'-150'		12.3		3.8		1.4		53.0	0	0
			2/12/63	140'-150'		10.0	12.46	5.8	5.27	1.9	1.45	68.5	1	0
	D		11/20/62	140'-150'		14.8		7.3		1.3		70.0	0	2
			11/25/62	140'-150'		11.5		9.2		5.3		73.0	2	1
			12/21/62	140'-150'		8.3		13.3		2.8		48.0	3	0
			12/18/62	140'-150'		7.1		5.5		.5		77.0	0	1
			1/31/63	140'-150'		8.6		2.5		.4		61.0	0	0
			12/16/62	140'-150'		7.2		7.8		1.8		81.0	1	1
	E		4/10/63	140'-150'		14.5	10.28	7.0	7.51	1.0	1.87	59.0	1	0
	A		12/9/62	170'-180'		9.9		3.9		0.5		82.0	0	0
			12/22/62	170'-180'		19.3		6.2		1.4		68.5	0	0
			3/16/63	170'-180'		12.9		2.6		1.7		59.0	1	0
			11/13/62	170'-180'		11.0	13.24	2.5	3.80	1.0	1.15	78.0	0	0
	B		1/22/63	170'-180'		20.6		4.8		1.3		68.0	1	0
			12/4/62	170'-180'		16.6	18.6	5.8	5.3	1.2	1.25	77	2	0
	C		2/5/63	170'-180'		13.9		8.2		3.2		65.0	0	0
			2/7/63	170'-180'		14.9		5.8		1.9		65.0	0	1
			2/4/63	170'-180'		12.6		2.4		1.1		53.0	0	0
			2/12/63	170'-180'		6.8	12.05	6.2	5.65	3.0	2.30	68.5	0	0
	D		11/20/62	170'-180'		14.6		5.2		0.7		68.0	1	3
			11/25/62	170'-180'		9.7		4.4		5.0		80.0	2	0
			12/21/62	170'-180'		8.1	13.13	7.6	5.17	.7	2.36	60.0	0	0
			1/31/63	170'-180'		7.0		3.5		.7		63.0	1	0
	E		4/10/63	170'-180'		13.8		6.8		0.7		64.0	1	0
	B		1/22/63	200'-210'		14.0		4.2		1.4		58	0	1
			12/4/62	200'-210'		23.0	18.5	4.5	4.35	2.2	1.8	78.0	1	0
	C		2/5/63	200'-210'		11.6		6.0		1.7		65.0	0	0
			2/12/63	200'-210'		9.0	10.3	9.5	7.75	2.4	2.05	68.5	1	0
	D		11/23/62	200'-210'		13.0		4.8		0.6		62.0	1	2
			11/25/62	200'-210'		14.5		8.5		5.7		75.0	0	0
			12/21/62	200'-210'		12.0		7.9		2.0		63.0	1	0
			1/31/63	200'-210'		6.1	15.2	4.3	8.3	1.6	3.3	62.0	0	0
	B		1/22/63	230'-240'		22.0		5.6		3.8		64.0	3	1
			12/4/62	230'-240'		11.0	16.50	5.4	5.55	2.9	3.35	77.0	0	0
	C		2/5/63	230'-240'		11.0		5.2		1.2		66.0	0	1
			2/12/63	230'-240'		11.7	11.35	5.6	5.4	3.9	2.55	68.0	0	0
	B		1/22/63	260'-270'		26.5		7.3		3.2		65.0	3	0
	C		2/5/63	260'-270'		7.8		4.8		1.3		64.0	0	0
	B		1/22/63	290'-300'		16.5		4.9		1.5		61.0	0	0
	C		2/5/63	290'-300'		9.9		6.7		2.9		64.0	10	0
	B		1/22/63	320'-330'		23.3		6.1		3.2		58.0	0	0
	B		1/22/63	350'-360'		22.6		4.0		2.9		51.5	0	0
	B		1/22/63	380'-390'		13.7		3.6		2.1		71.0	0	0
	B		1/22/63	410'-420'		11.8		5.6		2.8		66.0	1	0
Av.	B	Normal	1/22/63	440'-450'		7.9		3.5		0.8		72.0	0	1
	B		1/22/63	470'-480'		12.2		3.0		2.8		63.0	0	1
	B		1/22/63	500'-510'		14.2		3.8		3.1		63.0	1	0
	B		1/22/63	530'-540'		15.4		4.1		2.1		66.0	1	0

1. Column 1 indicates the type of run, such as "N" meaning normal with no instructions as to speed or tracking, or "C.S." for maintaining constant speed and position in lane.
2. Column 2 designates the driver making the run.
3. Column 3 shows the condition of the driver at the start of the trip.
4. Column 4 gives the date of the trip in order that the trip may be identified.
5. Column 5 gives the time after starting the trip, thus 20'-30' indicates that the time interval was that from 20 to 30 minutes after the beginning of the run.
6. Columns 6, 7 and 8 have to do with the number of steering wheel reversals per minute. Column 6 gives the normal rate as determined from several runs. These normal rates are characteristic for each individual and tend to be constant. Column 7 gives the average rate for the 10 minute period designated in Column 5. Column 8 gives the average rate for all the trips for the driver designated in Column 2.
9. Columns 9, 10 and 11 refer to the amount of speed change. Column 9 gives the normal amount of speed change per minute period, Column 10, the rate for the 10-minute period, and Column 11, the average rate for all the runs by the driver given in Column 2.
12. Columns 12, 13 and 14 similarly to speed change, give the normal rate, the rate and the average rate.
16. Columns 16 and 17 list the events. Column 16 gives the highway and traffic events external to the car, while Column 17 gives those occurring in the car, such as actions of the driver. Compare with the events listed in connection with the graphs of driving patterns.

CONCLUSIONS

An examination of the graphic charts of the individual "fatigue" runs and of the summary table showing the changes in driving patterns at half hour intervals plus other findings from Drivometer tests leads to several conclusions.

The Drivometer is sensitive enough to monitor the changes in driving behavior that occur with time behind-the-wheel. The most pronounced measurement is the frequency of the steering wheel reversals. The amount of speed change is less pronounced than the steering wheel reversal rate. The accelerator reversals seem to mean little as a measure of driving change and the number of brake applications is even less significant.

Each driver, according to tests not included in this report, seems to have an individual rhythm or rate of steering wheel reversals that he tends to maintain. It is the rate at which the driver tends to be comfortable. If a driver's rate is twenty steering wheel reversals per minute and he has been driving on an open highway, he will on encountering urban conditions lower his speed but maintain his steering reversal rate. This would indicate that a change in rate may be due to a change in the driver's condition, and not to driving environment.

A driver may, as shown in Figure 3, display a steering wheel reversal rate that decreases in amount and variation with time behind the wheel. The steering wheel reversal rate as shown, drops from a norm of about 32 per minute to about 15 at the end of the trip. But most drivers do not show such a well defined change in performance with time.

For some drivers, with the passage of time, there may be less response to events. For example, for the first four trips for drivers "A", "B" and "C" listed in the table, the number of events responded to in the time interval 20 to 30 minutes after starting were respectively 7, 8, and 11, while in the interval 170-180 the responses were 1, 1, and 7.

As shown in Figure 4, the change in performance is greater if the difficulty of the driving task is increased. In this instance the driver was attempting to maintain constant speed and tracking.

Perhaps the most important attribute of driving "fatigue" is its variability. Either the "will" or the messages of "fatigue" may be in the ascendancy. An emotional urge may overcome the physical effects of fatigue to such an extent that fatigue is simply not experienced.

But with long continued driving the effects of "fatigue" can become operative and accidents often result. The writer has never fallen asleep on the highway but he recalls that twice while teaching an evening class at the end of a day that began at 9 A.M. and ended at 11 P.M., with about 6 hours of lectures plus laboratory periods, he found that he had "blacked-out" in front of a class. Such a black-out of only four or five seconds in front of a class may only be humorous; but on a highway it can be fatal.

It is recalled that after rather intensive investigation, the writer being one of the investigating engineers, it was decided (by the court) that Pasquale Tomasette, died on Aug. 16, 1950 because he went to sleep and not because of a "ghost" hole in the shoulder of the road. According to a newspaper account the accident involved the biggest damage suit against the state of New York up to that time.

The tests performed in the present study were not conducted to the point of failure but it could be that the effects of "fatigue" on driving performance may be detected by a monitoring device before the driver is aware of the change in his performance. A monitoring device could actuate a warning bell.

Testing to the point of failure could perhaps best be done by use of a simulator, but it may be mentioned that all test runs in this study were made with dual brake controls for the observer. It is hoped that this pilot study will lead to further and more extensive investigations.

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Ability of Drivers to Make Critical Passing Judgments

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•ONE of the key skills required by the operator of a motor vehicle is the ability to make safe and accurate judgments required in the overtaking and passing of another vehicle. As pointed out by Lauer (2) "Every time one passes he must get on the wrong side of the road; he must face oncoming vehicles; and he must take chances in getting out and back into his lane of traffic."

Possibly one of the most critical elements involved in passing behavior is the ability of the driver of the overtaking vehicle to estimate what Forbes (1) has called clearance time. Forbes defined clearance time as the time allowed by the passing driver between the completion of his own pass and the arrival of the oncoming car abreast of him. The purpose of the present investigation was to determine how accurately drivers are able to estimate clearance time.

METHODS

Subjects

Nineteen male college students, whose ages ranged from 18 to 23 yr, were paid to participate in the study. All subjects had several years driving experience, and had served in previous laboratory investigations in which they had been screened for visual defects.

Procedures

Preliminary training.—A subject was picked up at his residence by one of the experimenters in the test vehicle (1959 Mercury). The subject immediately assumed control of the car with the experimenter sharing the front seat. Each subject was allowed approximately 15 min of familiarization driving to become acquainted with the characteristics of the car. This was conducted on a relatively traffic free road where the subject could accelerate, brake, etc., and, in general, become familiar with the vehicle. At the end of this period the subject was directed to a point where a rendezvous was made with an automobile operated by the second experimenter.

The second phase of the preliminary training took place on the site where the actual investigation was conducted. This was a section of S.D. 50, which is a moderately traveled state road constructed of concrete. The section consists of approximately 4 mi where long sight distances were available.

The subject followed about four car lengths behind the lead car which was maintained at 60/mph by the second experimenter. During this phase of preliminary training, the subject practiced passing the lead car. A subject was instructed to pass as rapidly as possible without endangering either vehicle. The experimenter obtained the time, in seconds, from the moment the subject began his pass (at which time the subject had been instructed to say "now") until he had completed the pass and was again in the proper lane of traffic. Each subject completed a number of practice passes before the beginning of the actual test session.

After completion of the preliminary training, both vehicles pulled over to the side of the road and the following instructions were read to the subject:

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> You will follow the lead car which will be traveling at 60 miles per hour. However, you will not pass it. Instead, when you see an approaching car you will estimate what you consider to be the last safe moment for passing the car ahead of you and let me know by saying "now." By safe, I mean allowing yourself enough time or "room" to pass without causing the oncoming car to reduce its speed or take any other precautionary measures. Your saying "now" is intended to indicate to me the amount of distance between your car and the approaching car that allows just enough room to pass safely. You should say "now" when you feel the distance between you and the approaching car has decreased to a distance just long enough for you to safely pass the lead car. Remember, do not actually attempt to pass—just say "now."

The instructions were repeated if the subject indicated that he was not clear on the procedure.

Test Condition.—The subject followed the lead car and each time another vehicle approached estimated what he considered to be the last safe instant for passing. When the subject indicated this by saying "now" the experimenter activated a timer. When the approaching car came abreast of the lead car, the experimenter stopped the timer. This period of time was considered as the subject's estimate of the minimum passing time or clearance time. This was repeated 10 times for each subject so that a total of 190 clearance estimates were obtained.

Clearance Time Estimates.—Each subject made 10 estimates of what he considered to be the minimum clearance time in which he could pass the lead car with sufficient time allowed so that an approaching car would not be forced to take any evasive action. For purposes of analysis, the mean passing time based on the practice passes completed in the preliminary training session was obtained for each subject. This was used as a correction factor and subtracted from each clearance time estimate made by the subject. For example, if a subject had made a clearance time estimate of 14 sec, i.e., 14 sec elapsed between the time he said "now" and the approaching car came abreast of the lead car, the mean passing time was subtracted from this figure. Thus if the mean passing time were 10 sec, the subject's clearance time estimate was considered as an overestimate of 4 sec. On the other hand, if his clearance time estimate was only 8 sec he had an underestimate of 2 sec.

RESULTS

Table 1 indicates the number of underestimates and overestimates made by the subjects and the magnitude, in seconds, of the estimates. The number of estimations in each of the two categories are quite similar and their distribution, in terms of magnitude of error, is likewise quite similar.

There was considerable variation among the subjects in their ability to make the required clearance time estimates (Table 2). Concerning the algebraic means of the individual subjects, each mean is based on the 10 estimates made by each subject with the mean passing time subtracted from the estimated clearance time previously described. Table 2 also gives the standard deviations as computed for the estimates of each subject, the ranges of the estimates, and the number of over and under estimates made by each subject.

TABLE 1

NUMBER OF UNDER AND OVERESTIMATIONS AND MAGNITUDE OF ERROR

Error (sec)	Under-estimates	Over-estimates
0 - .9	23	24
1.0-1.9	24	20
2.0-2.9	14	15
3.0-3.9	14	13
4.0-4.9	10	12
5.0-5.9	6	5
6.0-6.9	0	1
7.0-7.9	2	0
8.0-8.9	0	2
9.0-9.9	0	0
10.0 and over	0	5

TABLE 2

PERFORMANCE DATA OF INDIVIDUAL SUBJECTS

Subject	Mean	S. D.	Range		No. Estimates	
			High	Low	Under	Over
1	0.93	2.349	+4.70	-1.30	5	5
2	0.34	1.897	+4.17	-2.33	3	7
3	0.98	2.700	+4.80	-4.00	3	7
4	0.10	1.512	+2.84	-2.66	6	4
5	-3.01	1.840	-0.30	-5.40	10	0
6	-3.48	2.518	+1.70	-7.30	9	1
7	1.12	2.074	+4.20	-2.70	2	8
8	-0.59	1.569	+3.09	-2.51	7	3
9	1.83	3.180	+8.20	-3.30	3	7
10	3.55	2.847	+8.70	-1.30	2	8
11	2.58	1.866	+6.65	-0.15	1	9
12	8.15	5.667	+18.70	+0.70	0	10
13	-1.29	2.572	+3.50	-3.90	7	3
14	-2.39	1.311	+0.60	-4.10	9	1
15	0.79	1.873	+3.20	-2.30	4	6
16	-3.60	2.039	+0.40	-7.20	9	1
17	0.24	2.393	+4.20	-3.30	5	5
18	0.27	2.313	+4.00	-4.30	4	6
19	1.02	2.207	+5.70	-1.30	4	6

The results of this investigation can be considered from two points of view. If the investigation had been concerned with only the ability of an individual to deal with the various variables involved in the situation and to make a judgment of closure time based on his evaluation of these variables, it could be said that the subjects were capable of making this type judgment with a relatively high degree of accuracy. Thus the estimates, when plotted in terms of magnitude of error, form a normal distribution. With zero considered as a perfect judgment, under the conditions involved, 25 percent of the judgments fell within a ± 1-sec interval, and nearly 50 percent of the judgments fell within a ± 2-sec interval.

In viewing the results, however, the instructions to the subjects should be kept in mind. They were not asked to estimate closure time, rather they were instructed to estimate the last safe moment for passing the car ahead of them without causing the approaching vehicle to take any evasive action. In this context it would appear that many subjects are not capable of accurately making this judgment. Whereas an overestimate would be considered as a safe estimate, an underestimate would have resulted, in actual driving, in a situation where the subject would not have had time to pass the lead car. Nearly 50 percent of the judgments made were underestimates.

The nature of the investigation was such that subjects were required to make what might be termed critical judgments of clearance time. The primary concern in the study was with the ability of drivers to estimate as closely as possible the last safe moment for passing a vehicle with another car approaching. The typical driver is not frequently called on to make a decision of this type when operating a vehicle. However, the present investigation would suggest that when a judgment of this type is made, the average driver is not capable of making it with any degree of accuracy.

On the basis of timings taken by the experimenter, it was possible to determine whether the driver could actually have passed the lead car safely (overestimate) or whether he would not have had adequate time to complete the pass (underestimate). It was found that out of a total of 190 estimates, 97 were overestimates and 93 were underestimates.

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Effects of Fatigue on Performance in a Driving Device

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ABRIDGMENT

It is commonly though that after a number of hours of operating a vehicle, certain physiological and mental changes occur in the driver which collectively constitute driver fatigue. However, there is little evidence to support the view that driver fatigue results in a performance decrement. The present investigation was designed to determine the effects of fatigue on several performance tasks required in the operation of a driving simulator.

Sixty male subjects (paid undergraduates, average age 19) were randomly assigned to one of six experimental conditions and were tested in a driving device patterned after the AAA device. Measures of tracking error, speed maintenance, and reaction time were obtained for each subject. Test sessions involved either 4 or 6 hr. In the 4A condition, subjects operated the device for 4 hr but were required to perform all the tasks only during the first and last hour. During the second and third hour the only requirement imposed was that the subject perform the tracking task. In condition 4B, subjects operated the device for the first and last hour of the 4-hr session and were excused during the second and third hour. In condition 4C, subjects operated the device for the entire session and were required to perform all tasks during the session. Conditions 6A, 6B, and 6C were similar except a 6-hr session was involved. In the case of subjects in the 6A condition, the device was operated for the entire session, but only the tracking task was performed during the second through the fifth hour. Subjects in 6B were excused during the second through the fifth hour, whereas subjects in the 6C condition operated the device for the entire period and performed all tasks during the session.

Performance decrements were obtained in the tracking task for subjects in several conditions. The most obvious decrements occurred in the 6-hr conditions (6A and 6C) where performance during the first hour was significantly better than that shown during the last hour. In the speed maintenance task, performance during the first hour also tended to be superior to performance during the last hour. In only the 6C condition were these differences significant, however. Surprisingly, subjects showed a decrease in reaction time during the driving sessions. In each condition, reaction time was faster during the last hour than during the first hour of the task. These differences were significant in the 4C and 6A conditions.

The present investigation tends to indicate that there may be considerable differences between tasks in their demonstrated sensitivity to fatigue. Some tasks required of the operator showed a performance decrement, others showed no decrement, whereas a definite improvement in performance was shown on other tasks. In addition, the results suggest that subjects adjust their effort to the expected duration of the task, since subjects in the long sessions did not perform as well as subjects in the shorter conditions during the initial periods. This was the case for all of the performance tasks. Therefore, motivational factors may be of considerable importance in determining the performance of subjects on tasks such as those used in the present investigation.

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Velocity Thresholds in Car-Following at Night

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•CAR-FOLLOWING is defined as that phenomenon in which a vehicle follows a lead vehicle which is traveling at an arbitrary speed. If the velocity of the lead vehicle is designated by v_1 and the rear vehicle velocity by v_2, then the relative velocity, v, is defined as the difference v_1-v_2. It is the threshold of this velocity that has been investigated. Here velocity threshold is defined as that relative velocity which the driver of the rear vehicle can detect with a 50 percent probability at a given headway for a given presentation time. The headway is taken as the distance from the driver's eyes to the rear bumper of the lead vehicle.

This study is concerned with the determination of velocity thresholds under night driving conditions, and is based on the premise that the information available to the driver of the following car concerning the state of the lead car, is primarily provided by the taillights of the lead car. When a relative velocity exists between the two cars, this visual information appears as a change in the visual angle subtended by the two taillights of the lead car and apparent changes in the brightness and area of the taillights. For the presentation times of relative velocity used in this study, the changes in headway were so small that it was assumed taillight brightness and area could be taken as fixed. Hence, velocity thresholds were obtained by considering only the change in visual angle. This, of course, may not be the only cue of consequence in detecting relative velocities, but it is almost certainly a major one.

Velocity thresholds for daytime driving were obtained in a previous study (1) in which an automobile simulator was also used.

SIMULATION

It was decided to determine the velocity thresholds using an automobile simulator since experimentation on an actual highway presents many problems as far as experimental control and variable measurement are concerned. A block diagram of the simulator is shown in Figure 1. For each given increment of relative velocity v, the switch S_1 is closed by the timer for a time interval T_p, thereby causing the integrator to

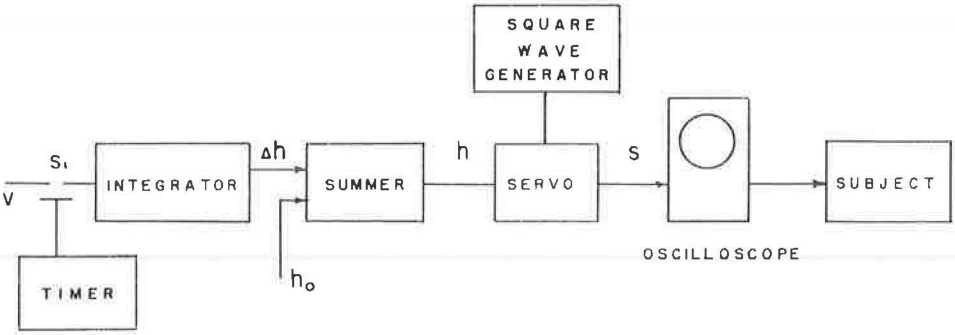

Figure 1. Simulator block diagram.

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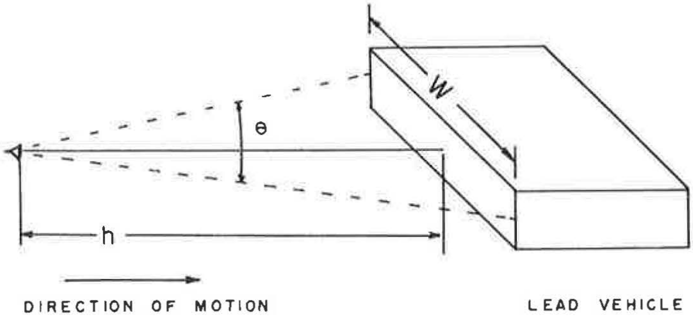

Figure 2. Ray diagram of car-following situation.

integrate v. On integration, v becomes Δh (the change in headway over the time interval T_p), which is added to the initial headway, h_0, to give the instantaneous headway, h. The signal h controls a servomechanism, the output of which is a square wave whose amplitude (S) is inversely proportional to h. However, the horizontal visual angle (θ) subtended by the taillights of the lead vehicle is also inversely proportional to h as $\theta = w/h$ where w is the distance between the taillights of the lead vehicle—w = 7 ft (Fig. 2). Consequently, S is directly proportional to the horizontal visual angle, θ. This signal is then fed into the horizontal input of the oscilloscope which causes 2 spots to appear on the oscilloscope face, representing the taillights of the lead vehicle. Defocusing of the spots was necessary to give a spot whose diameter was equivalent to a taillight diameter of 5.8 in. at h = 71 ft. The diameter of each spot was $^{13}/_{64}$ in. while spot luminance was 4.15 ft lamberts at a contrast of 1.9 percent. The spot size was not varied as the headway changed and the spots were displayed on a 5BPI type cathode ray tube. Lastly, the subject viewed the oscilloscope face from a distance of 30 in. while a headrest was used to insure that his head was always in the same position.

DESCRIPTION OF EXPERIMENT

The subject was presented with a view of only the taillights of a vehicle. The separation of the taillights was initially set to correspond to some real world constant headway, representing the real situation of a lead vehicle being followed by a rear vehicle at some constant headway (i.e., both vehicles' speeds are identical and v = 0). The relative velocity was then changed from 0 to v. This change causes a proportional change in the spot separation, either an increase or a decrease depending on whether v is negative or positive. The subject observes the simulated taillights and reports whether he perceived an increase, decrease, or no change in the spot separation.

Three male subjects with normal vision were used in the experiment. All subjects had driving experience and ranged in age from 24 to 30 yr. The experiment was performed in a dark room and a visual adaptation time of 15 min was required before experimentation began. Communication between the experimenter and subject was maintained by a telephone headset.

PROCEDURE

The taillight separation was initially set to correspond to some real world headway. The subject was then instructed to observe the oscilloscope when the command "observe" was given. A fraction of a second later a signal corresponding to a step change in relative velocity, v, of duration equal to T_p was fed into the simulator. After this presentation the subject was given the command, "report." On this command he reported whether or not he had detected any motion of the taillights. If he had detected motion during the interval T_p, he was also to report the sense of the motion (i.e., did the taillights separate or draw closer together). After the subject had reported his observation, the taillights were removed from the oscilloscope screen and the taillight separation reset to its initial value. Then the spots were restored on the oscilloscope

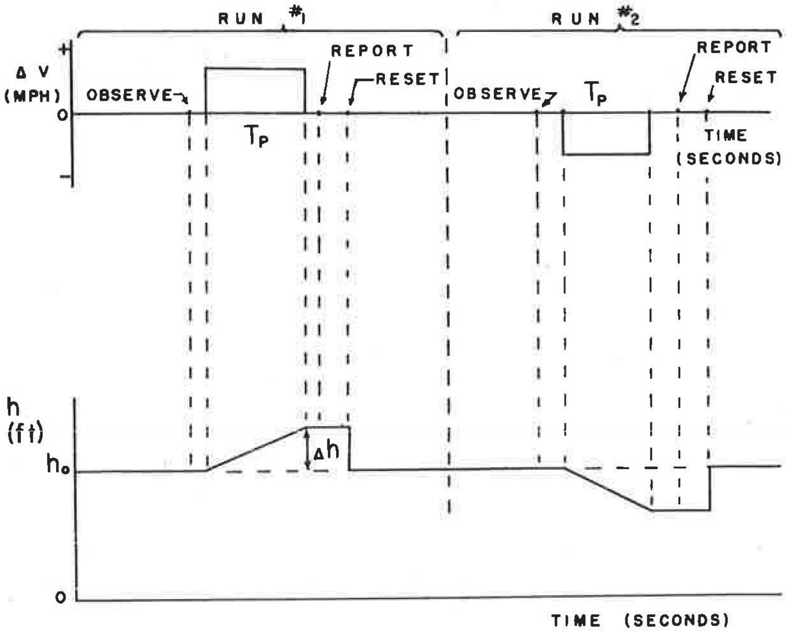

Figure 3. Event diagram of experimental procedure.

and another run made. The sequence of events as well as the behavior of the variables v and h are shown in Figure 3. Fifty such runs were made at one setting. For the presentation times used, this took about 15 min. After a reset period of 5 min another 50 runs were made and so on until a total of 200 runs were completed. The rest periods were found necessary to minimize fatigue.

The subjects were presented with 9 different incremental velocities, v, for a given set of steady-state conditions. These velocities had positive, negative, and zero magnitudes and were presented to the driver in a random sequence. Two hundred runs per subject were made for each combination of steady state headway h_0 and presentation time T_p. Headways of 71, 129, 188, and 276 ft were used and the presentation times T_p were 0.3, 1.0, 2.0, 3.0, and 5.0 sec.

RESULTS

Velocity Perception Curve

Each set of 200 runs was used to plot a velocity perception curve which is a plot of the probability of velocity detection vs the incremental velocity, v. The probability of velocity detection for a given velocity increment was determined by dividing the total number of runs in which the subject detected motion correctly (i.e., the subject had to not only determine if motion had taken place but also the sense of the motion) by the total number of runs at that velocity increment and expressing the result as a percentage. Figure 4 shows the average velocity perception curve obtained when the three subjects' velocity perception curves are summed and averaged for a given h_0 and T_p. The other values of h_0 and T_p used, yielded similar curves.

Threshold Velocity Characteristics

The relative velocity threshold is dependent on both the headway and presentation time of the relative velocity stimulus. For each value of headway and presentation time, there exists both a positive and negative threshold velocity.

The dependence of threshold velocity on headway was first determined. Figure 5 shows the relation between the positive threshold velocity, v_t, and the headway, h,

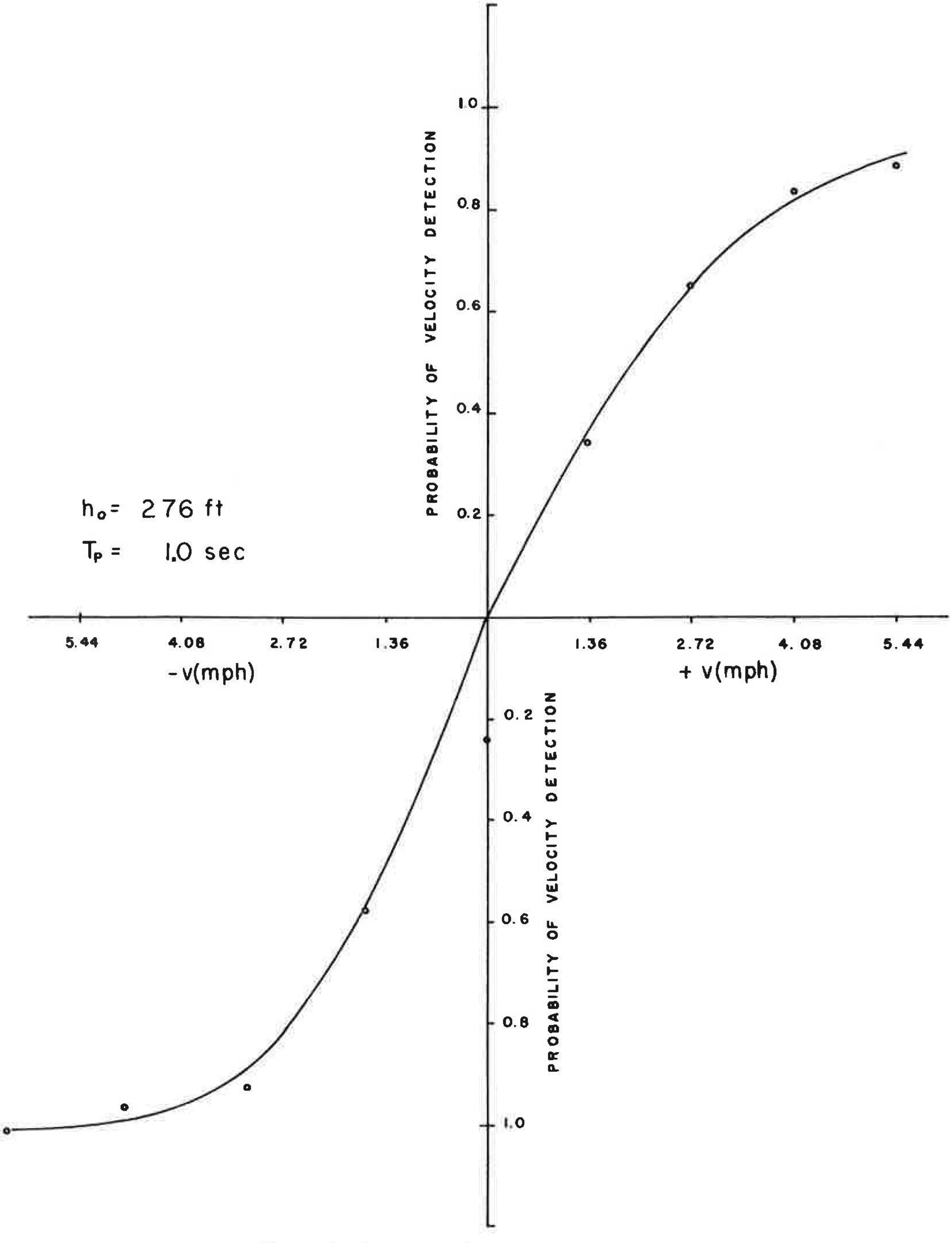

Figure 4. Average velocity perception curve.

where T_p is a parameter. The method of least squares was used to obtain the best linear approximation to the data points for each headway. The equations of these curves have the general form $v_t = Kh^n$ where the parameters K and n are dependent on T_p and have the values given in Table 1.

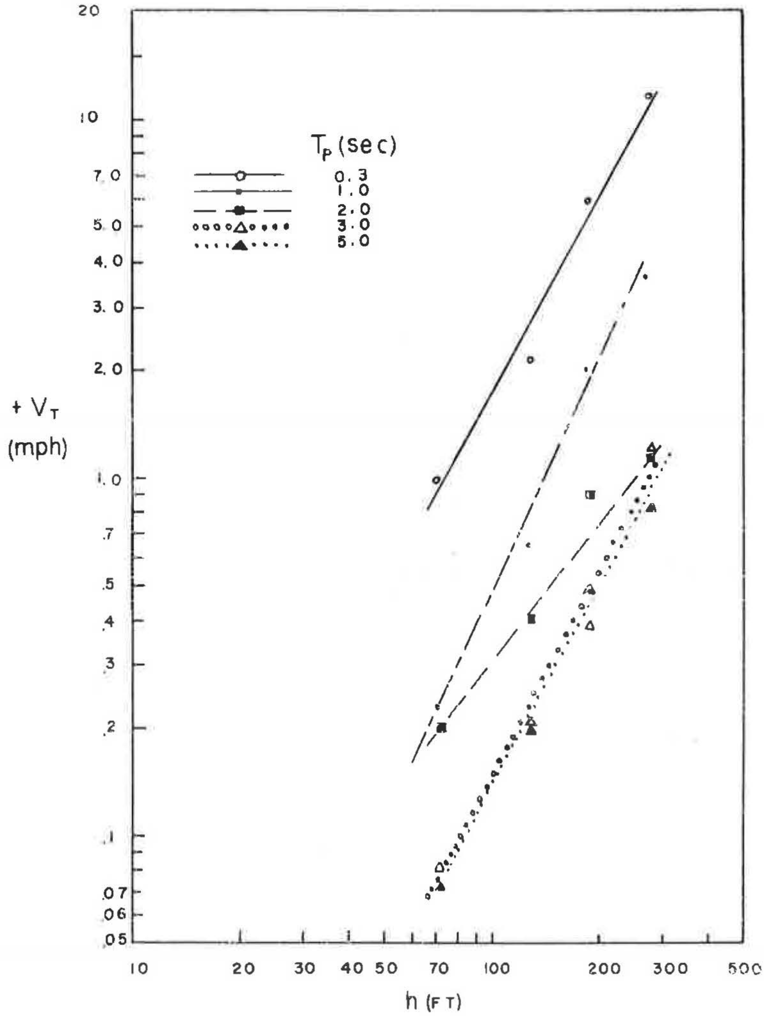

Figure 5. Positive velocity threshold characteristics for simulated nighttime driving.

TABLE 1

Dependence of K and n on T_p.

T_p (sec)	K (mph)	n
0.3	3.16×10^{-4}	1.86
1.0	2.82×10^{-4}	2.10
2.0	6.73×10^{-4}	1.34
3.0	2.17×10^{-5}	1.91
5.0	2.87×10^{-5}	1.84

Figure 6 shows the relation between the negative velocity threshold, v_t, and the headway h where T_p is a parameter. Again the curves have the general form $v_t = K_1 h^m$ where K_1 and m are dependent on T_p and have the values given in Table 2.

These velocity threshold characteristics hold only for simulated night driving. In a previous work (1) the velocity threshold characteristics were determined for simulated day driving (Figs. 7 and 8). Comparing Figures 5 and 6 with Figures 7 and 8, the night and day characteristics are

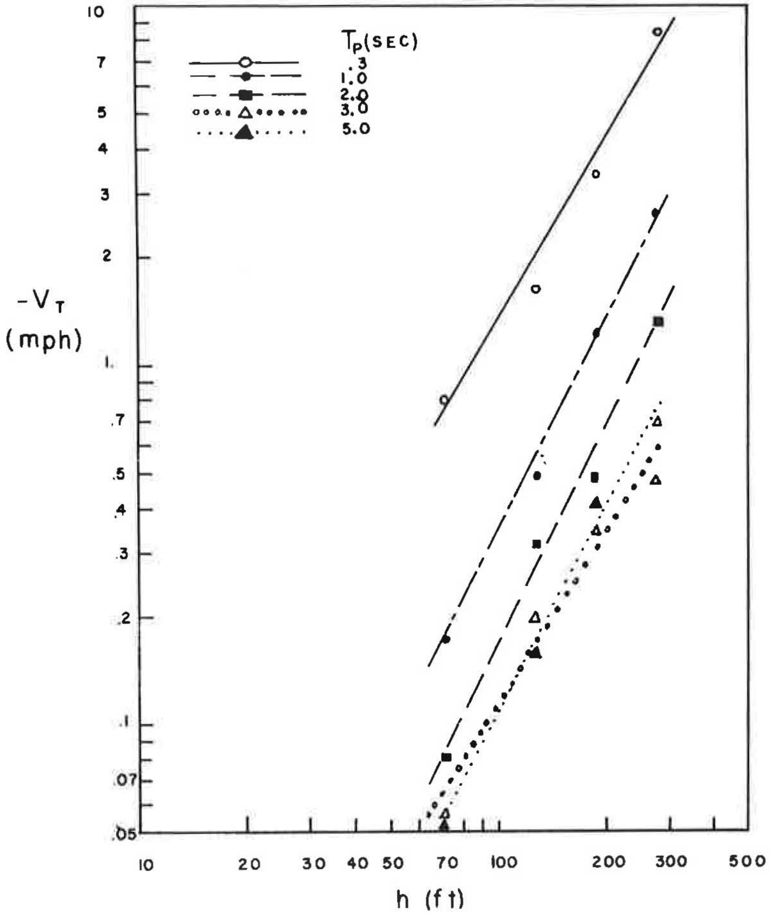

Figure 6. Negative velocity threshold characteristics for simulated nighttime driving.

TABLE 2

Dependence of K_1 and m on T_p

T_p (sec.)	K_1 (mph)	m
0.3	4.73×10^{-4}	1.72
1.0	2.72×10^{-6}	2.04
2.0	1.71×10^{-5}	1.99
3.0	6.98×10^{-6}	1.60
5.0	1.37×10^{-5}	1.94

similar. The only significant difference between the two types of thresholds is that the night velocity threshold is generally smaller than the day velocity threshold. This difference is quite possibly because the observer was presented with fewer extraneous visual stimuli at night than during the day; however, it may be a consequence of the environment in which the experiment was performed. In any event, it appears that the process of relative velocity detection was the same in both experiments.

General Velocity Threshold Equations

In the determination of the day velocity threshold it was found that two equations could be used to interrelate accurately the velocity threshold with the variables of headway and presentation time (1). The same approach was applied to the night velocity threshold. Figures 9 and $\overline{10}$ show plots of plus and minus v_t vs T_p on log-log graph

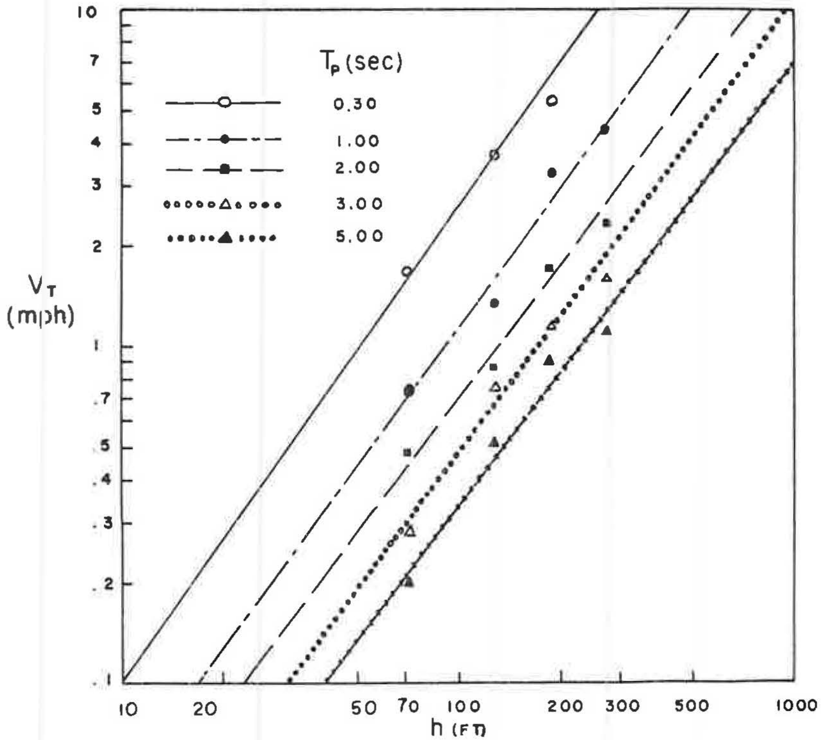

Figure 7. Positive velocity threshold characteristics for simulated daytime driving.

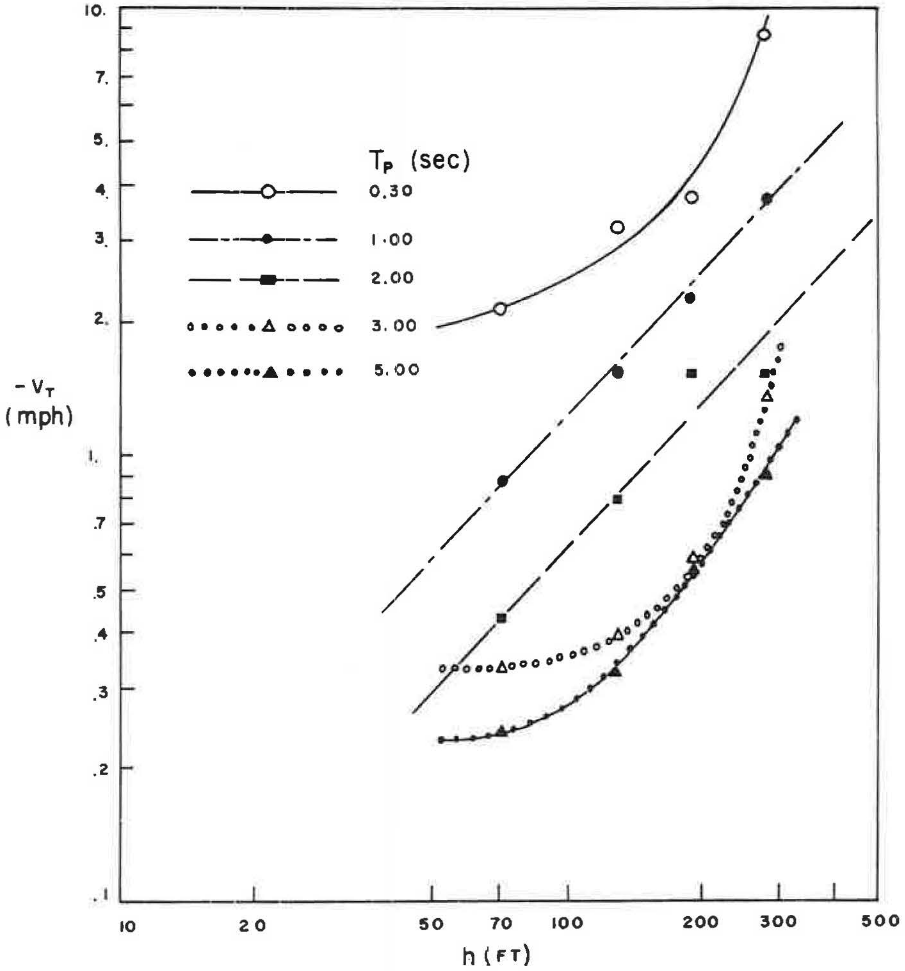

Figure 8. Negative velocity threshold characteristic for simulated daytime driving.

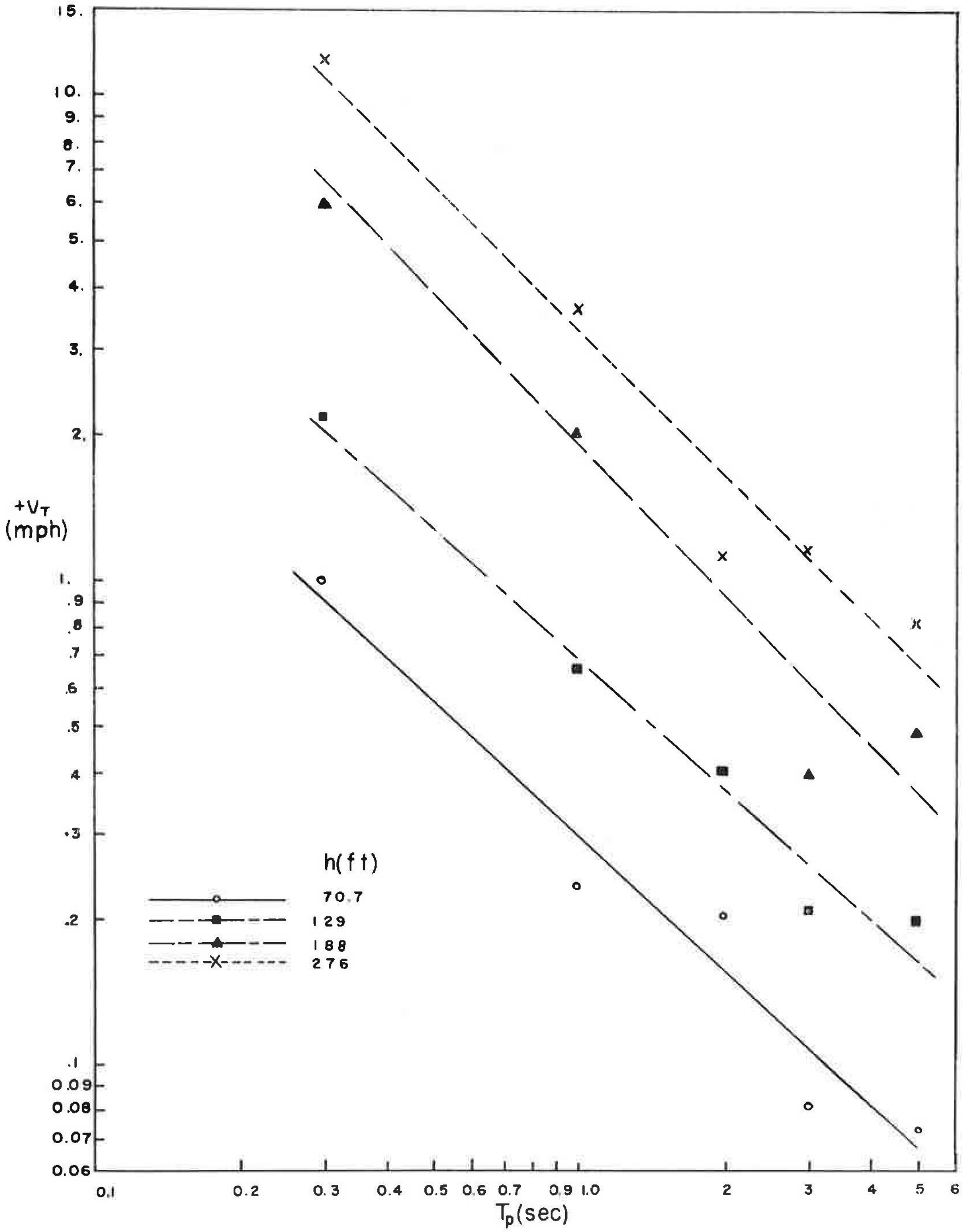

Figure 9. Positive velocity threshold characteristics (v_t vs T_p).

paper. The method of least squares was used to obtain the best linear approximation to the data points for each headway. It is evident from the curves that the describing equations are of the form $v_t = K_2(h)\, T_p^{-n}$. Evaluation of the constants yields the following two invariant threshold equations:

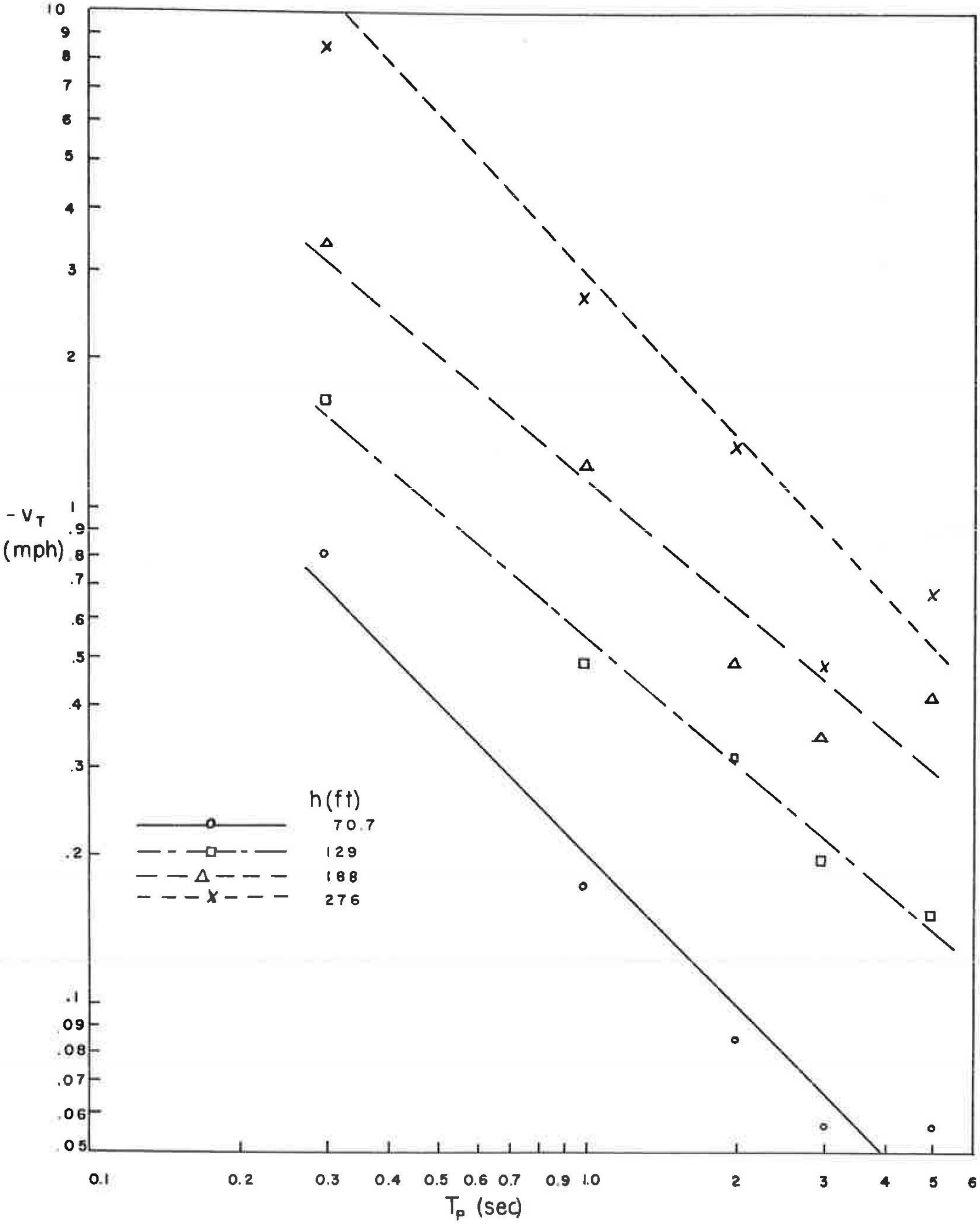

Figure 10. Negative velocity threshold characteristics ($-v_t$ vs T_p).

v_t positive $\quad v_t T_p^{0.963} h^{-1.85} = 1.065 \times 10^{-4}$ (1)

v_t negative $\quad v_t T_p^{0.946} h^{-1.96} = 4.375 \times 10^{-5}$ (2)

where h is in feet, T_p in seconds, and v_t in miles per hour. Eqs. 1 and 2 are valid only for the following range of variable values:

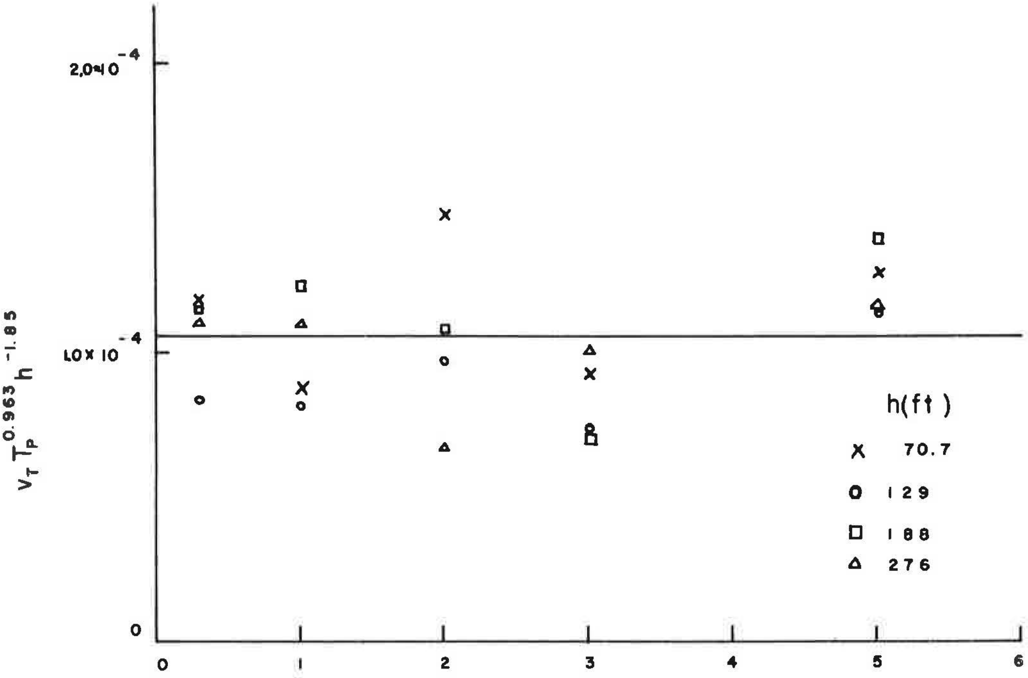

Figure 11. Dependence of the positive velocity threshold on T_p.

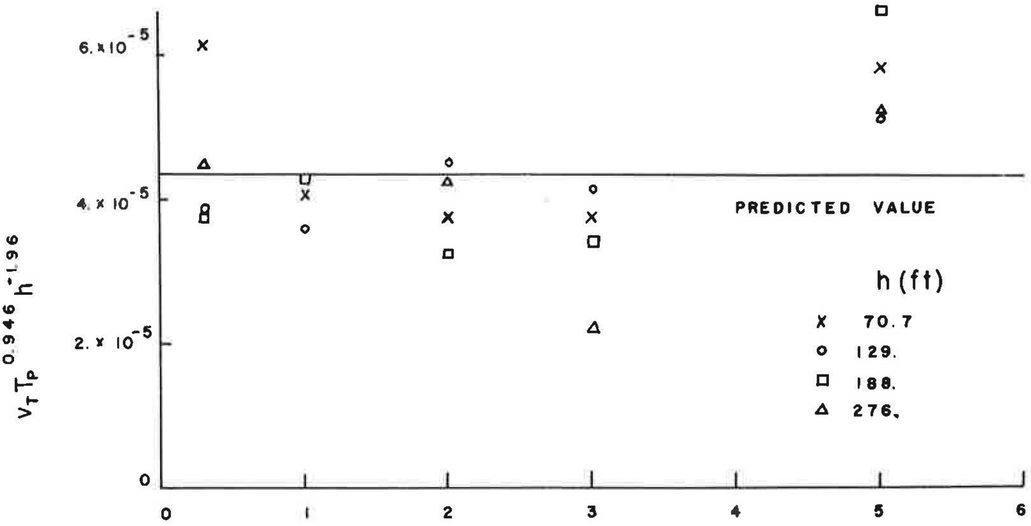

Figure 12. Dependence of the negative velocity threshold equation on T_p.

$$\begin{aligned} 0.07\text{ mph} &\leq +v_t \leq 11.7\text{ mph} \\ 0.05\text{ mph} &\leq |-v_t| \leq 8.5\text{ mph} \\ 0.3\text{ sec} &\leq T_p \leq 5\text{ sec} \\ 71\text{ ft} &\leq h \leq 276\text{ ft} \end{aligned}$$

The same test for invariance of the general velocity threshold equations was made as before (1). That is, the left-hand portions were calculated on the experimental data and the result plotted as a function of T_p (Figs. 11 and 12). These plots show that the general velocity threshold equations are, in fact, almost invariant in that there is no consistent trend of the data points with T_p.

CONCLUSIONS

This experimental investigation of the driver's night velocity threshold, using a simulator, has yielded the driver's velocity threshold as a function of headway and presentation time of the relative velocity. Two general velocity threshold equations were derived which interrelate the velocity threshold with the presentation time and headway for the simulated situation. It is simple to calculate the positive and negative night velocity thresholds if the headway and presentation time are known. A comparison was made between day and night velocity thresholds, both obtained from automobile simulator experiments, with the result that the night velocity threshold is generally smaller than the corresponding day velocity threshold. This deviation is due, of course, to the modification of the environment. In one case the complete vehicle and roadway are observed on the TV screen, whereas in the night driving case only the two spots are visible.

REFERENCE

1. Todosiev, E. P. Velocity Thresholds in Car-Following. Presented at 43rd Annual Mtg. of the Highway Research Board, 1964.