HIGHWAY RESEARCH RECORD

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Foreword

Study of man's performance in his driving environment will probably never be fully accomplished, but the growing body of research is giving us considerably more insight into that most interesting subject—man as a driver. Concentration of research effort is being made on all three elements of the transportation problem—the road, the vehicle and the driver—and their interrelationships. The seven papers in this RECORD portray interesting aspects of man as a driver. Developed almost entirely by professional researchers, the papers show to some extent how far we have gone in ascertaining behavior, and also how far we have yet to go. The latent interest in this subject has, of course, been brought more to the surface by the national interest in safety and increased research effort throughout the world. All those concerned with driver improvement and training will find this RECORD to be of extreme interest; fellow researchers will likewise find much to their liking and those that are just simply intrigued with driving will also wish to acquaint themselves with the presentations.

In the first paper, four California researchers have studied aspects of short individual driver improvement hearing sessions upon driving records. It was found that attendance at such hearings did not serve to reduce accidents or point counts against the records of drivers but that they did serve to reduce court convictions for the year following the hearing and to a lesser extent for the second year following the hearing.

Five New England researchers have studied driver information processing in a unique manner, as reported in the second paper. By limiting the amount of time that the road and surroundings were observed, parameters for a mathematical modeling simulating the driving task were developed. The preliminary research indicated fairly good approximations to actual driving behavior.

Two Arizona researchers have studied variations in driver characteristics at intersections. Using time-lapse photography, the gap acceptance and headway characteristics of both in-state and out-of-state vehicles were measured to see what differences might exist. For left-turning vehicles no significant differences were found between the two categories. However, out-of-state vehicles were found to have longer headways when they were located at beginnings or ends of queues than when they were in the middle portions.

The next report, by two Franklin Institute researchers, gives results of car-passing studies when several degrees of varying knowledge of the oncoming car situation were made available to the car attempting the passing. The research indicated that passing performance was linked to the degree of knowledge of the speed characteristics of the oncoming car—the greater the knowledge, the lesser the variance in driver performance in the maneuver.

The fifth study is by a Bureau of Public Roads researcher and reports on the ability of drivers to estimate velocity of their vehicles. It was found that peripheral vision stimulation produced more accurate velocity estimates than did frontal

stimulation. The author suggests that fixation of the frontal field of vision could be a factor in highway hypnosis. The degree of knowledge of velocity needed to adequately perform steering and multiple car maneuvers is pointed out.

Two Kansas researchers investigated a new system for braking automobiles, using the left foot for braking and the right for acceleration. A braking system incorporated into the steering wheel was also tested. Using a range of subjects in the study, it was found that significant reductions in braking time were achieved with the unique braking system. This has interesting implications concerning safety as shorter stopping distances are thus achieved.

The last paper, by two Massachusetts researchers, describes a mathematical model developed to describe a vehicle's path in an emergency. Comparisons with both TV simulation and actual roadway conditions were made in the research.

Above all, the research in this RECORD serves to point out the difficulties connected with fruitful study of the driving task and its implications and the many-faceted approaches that are being used by researchers to accomplish their various objectives in extending the frontiers of knowledge.

Contents

The Effectiveness of Short Individual Driver Improvement Sessions*

R. S. COPPIN, R. C. PECK, A. LEW, and W. C. MARSH
Research and Statistics Section, California Department of Motor Vehicles

The study's main purpose was to evaluate the effects of short individual driver improvement sessions on the subsequent driving records of negligent operators. Also investigated was the influence of age on the effectiveness of these sessions. The report concludes that (a) those requested to attend a hearing had significantly fewer convictions during the first 12-month period following such a scheduled hearing than did a control group; (b) these effects appeared to shrink during the second 12-month period to a point where differences between experimental and control groups were not statistically significant; (c) accident frequency did not appear to be reduced as a consequence of the driver improvement hearing; (d) the hearing did not reduce the point count of the negligent operator during a one-year follow-up to that of the "average" driver; and (e) the effects of the hearing were constant at all age levels. Among other topics discussed are the effects of attending a hearing vs merely receiving a hearing notice and certain limitations in the findings and research design.

•THE control of licensed drivers is currently one of the major problems confronting driver licensing officials. Although the majority of the licensed driving population does not accrue a large number of violations and accidents, there is at any given point in time a small proportion of the population who violate traffic laws and are involved in accidents to such an extent that they become at least a potential hazard to the safety and welfare of the general public and themselves. Any means of effectively controlling the behavior of such drivers would represent an important contribution to the prevention of needless death and injury.

It is the basic objective of the Driver Improvement Program of the California Department of Motor Vehicles to improve the driving habits and performance of such drivers who, because of traffic law violations and/or accident involvement, are legally classed as negligent operators. According to statute, a prima facie negligent operator is any person whose driving record shows a violation point count of 4 or more points in 12 months, 6 or more points in 24 months, or 8 or more points in 36 months.

One means presently employed to obtain the objective of post-licensing control is the Negligent Operator Informal Hearing, whereby the negligent operator is informed of his record and is allowed to state his case. Such hearings generally consist of a 30-40 minute contact between the subject and a departmental driver improvement analyst, during which the subject's record is discussed, and various suggestions for improvement are made by the analyst. Consistent with the legalistic, social-control orientation of the program, the hearing process is not therapeutically structured, and, as a consequence, the driver improvement analyst (i.e., hearing referee) does not follow or receive training in contemporary counseling techniques. All driver improvement analysts must have at least one year's experience as drivers license examiners and, in addition, all are

*The original report contained extensive statistical analyses and related material in appendixes which are not included herein.

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given specialized in-service training in the form of a six-week course. College training is not required, except for those entering the drivers license examiner series with no prior experience. This latter group must have a B. A. (in any field) from a recognized college or university.

The analyst's basic role is to impress upon the subject the importance of safe driving habits and of the ramifications of continued traffic law violations and accidents. At the end of the hearing, the analyst informs the subject that a final decision as to the department's course of action will be made by headquarters, and the subject is then dismissed. His case is later reviewed, and he is informed by mail of the action taken. Typically, an initial action is to place the subject on probation for a minimum of one year, which was by far the predominant form of action taken in this study. Occasionally, however, the record and prognosis for improvement indicates that a more severe action is needed, such as suspension or revocation of the subject's driving privilege. In arriving at these determinations, the analyst considers the various aspects of the driver's record, including the severity of the record and the attitude of the subject during the hearing. The action indicated by the hearing analyst is in the form of a recommendation to headquarters, with the final decision resting with a review analyst. In the present study, the review analyst concurred with the initial recommendation in 84.2 percent of the cases sampled. One hundred and forty-one cases (14.6 percent) received a less severe action than was recommended, compared with 12 cases (1.2 percent) who received a more stringent action. However, the rationale and effectiveness of the review changes were not within the scope of the research design employed in this study and could therefore not be evaluated. Further particulars regarding the hearing process and philosophy can be obtained elsewhere (6).

Insofar as possible, the present analysis was limited to first-time negligent operators—those who had no prior contact with the department beyond receipt of a warning letter. The reasons for this restriction are twofold. First, the obtainment of a control group of "hard-core" negligent drivers presented administrative and technical difficulties which could not be surmounted. Second, the precedures for handling the hard-core negligent operator are varied, depending on the history of departmental actions with respect to each hard-core subject. An evaluation of the effects of a single hearing session on such a heterogeneous group was not felt to be a particularly meaningful or fruitful enterprise.

It is the department's philosophy that progress in the area of post-licensing control can be best achieved in conjuction with a thorough, ongoing, empirical validation of present and future programs. Only in this way can the effectiveness of a given program be evaluated with any degree of confidence and scientific rigor. Such evaluation allows one to progress toward the development of optimally effective programs by precipitating refinements in current programs and suggesting or exploring alternative approaches. Toward this end, the current study is just one of several efforts by this department in the general area of individual and group driver improvement techniques.

The authors feel that the findings reported here represent a definite contribution to the area of post-licensing driver control, especially when viewed in relation to the department's (and others') overall research efforts in this area. It will be our specific purpose here to describe and evaluate the effectiveness of the department's individual hearing process in reducing the accident and citation frequencies of negligent drivers. By so doing, we do not wish to imply that an empirically demonstrable citation or accident reduction is the only meaningful criteron for evaluating the negligent operator hearing process. The program may have subtle indirect effects which would not be reflected in an analysis of comparative accident and citation frequencies. One such effect might be the influence which the existence of the program has on the overall public. In other words, mere awareness of the existence of a driver control program may have a deterrent effect on the overall driving population, but not on drivers so extreme as to be classified as negligent operators.

In addition, the hearing program serves another important function—that of providing due process in connection with the social control obligation of the Department of Motor Vehicles. Since the department has a role in maintaining adherence to traffic laws, it is sometimes necessary that these prescribed norms be reinforced by with-

drawing the driving privilege of habitual violators without regard to the improvement possibilities of the program. The hearing process fulfills the due process requirement inherent in taking restrictive legal action against any citizen of the state. In short, it is the department's objective that the Driver Improvement Program achieve the maximum in rehabilitative power while fulfilling the important requirement of due process.

METHODOLOGY

Research Design

As originally conceived, the experimental design of the study was a conventional two-group model, in which one group received some form of "treatment" (experimental condition) and a comparison group received no "treatment" (control condition). In the present study, the "treatment" or experimental condition was the department's conventional negligent operator hearing; the group of subjects who initially received such hearings will henceforth be referred to as hearing subjects or the "hearing group," whereas those who did not receive an initial hearing will be referred to as control subjects or the "control group." Since the subjects were not assigned to the groups at random, it was necessary to adopt a matching design, in which relevant data on a large number of subjects from each group were collected and used in obtaining two groups who matched each other with respect to all available relevant variables (age, sex, marital status, prior accidents and prior traffic citations). These were selected on the basis of known driver record relationships within the overall driving population. The extent of these relationships within the California negligent operator population was not known at the time of the study. By controlling the effects of the relevant variables, significant differences between the two groups on subsequent measures (dependent variables) can be attributed to the effects of the treatment (i.e., hearing). In this study, the dependent variable used to evaluate the effects of the hearing was the subsequent two-year driving performance of the groups, as measured by departmental records of reported accidents and traffic citations (abstracts of court convictions).

This description should suffice to give the reader a general understanding of the research design employed in the present study. A more detailed and comprehensive discussion of the more salient design aspects of the study will be reserved for later.

Data Collection Procedures

Of the approximately 18,000 first contact hearings held in 1961, a pool of 9,000 subjects was identified as having received a hearing during the first eight months of that year. Slightly more than 3,500 of these cases were selected for coding and subsequent keypunching. (All 9,000 cases were initially screened on the basis of the accumulated number of negligent operator points in the 12-month period prior to hearing, and those with point counts in excess of five were eliminated. This was done because no control subjects with point counts in excess of five were available for comparison.) A control or comparison group of 2,000 subjects who also had no prior departmental contact and who had attained negligent operator status during the summer of 1961 was also identified for subsequent coding and keypunching.

Between February and September of 1964, the relevant data were transcribed from driver records to code sheets for the selected subjects. The coding was done in accordance with instructions delineated in a coding manual designed specifically for this study. For the hearing group, the coded categories can be conveniently divided into four general areas: (a) biographical and miscellaneous data available from drivers license application; (b) biographical and miscellaneous data from hearing form (mileage, type of action, etc.); (c) prior (to hearing) 12-month driver record; and (d) subsequent two-year driving record (e.g., court abstracts of traffic citations and reported accidents).

The items for the control group can be categorized in a similar manner with the exception of the data from the hearing form, which did not exist for the control subjects. Instead of a hearing date, the control assignment date was coded for the control group. It is around these dates—the hearing date and control assignment date—that the one-year prior and two-year subsequent driving record was resolved.

The coding of the two groups (hearing and control) was consistently alternated throughout the data collection period, in order that any temporally related biases or distortions in coding precision and judgement would be counterbalanced (i. e., affect each group equally). In addition, the coders were alternated between groups in order to counterbalance any bias which might have resulted from differing sets and idiosyncracies among the coders.

All coders were thoroughly trained, and a complete accuracy check was made on all coding during the initial phases of the project. Afterwards, systematic spot checks were made on each coder's accuracy to insure against coding deterioration over time. Based on an ongoing tally of spot checks, the coding error on the driver record categories was estimated at about one percent—one error per every 100 coded driver record categories. Errors on the non-driving record portion were almost nonexistent. Although some driver categories were coded incorrectly more often than others, there was no evidence of differential coding errors between the control and hearing group.

In order to further verify the coding accuracy, a correlational analysis was done by coder and item on a random subsample of 50 records—25 control and 25 hearing cases. The codes assigned to each of the items by the raters were correlated with those assigned by two professional analysts. High correlations between coder and judge reflect a high degree of accuracy and concurrence, whereas low correlations are indicative of inaccuracy and non-concurrence. The overall accuracy was very high for most item categories. However, three items were considered deficient in accuracy and therefore removed from any analytical interpretation.

After all cases had been coded, the data were scanned, punched into card format and subsequently converted to tape. Detailed machine edit checks were performed and any detected inconsistencies were corrected. At this point, the matching of subjects was ready to commence.

Derivation of Matched Samples

In order to determine whether any selective bias had occurred in the assignment of subjects to the two groups, preliminary distributions were derived on the entire coded pool with respect to the variables of age, sex, marital status and prior driver record. Statistically significant differences were found between the hearing and control group on each variable, indicating that the two groups were not representative of the same underlying population of negligent operators and, therefore, not comparable. It was therefore necessary, as mentioned earlier, to resort to a matching design, in which the coded pool of subjects comprising the two groups were matched on age, sex, marital status, and number of accidents and countable traffic citations in the 12-month period prior to hearing or control assignment, including Failure to Appear stops (FTA's) for moving violations. FTA's represent traffic citations for which the cited subject has not appeared in court as promised.

In addition, it was decided to split the experimental group by season of hearing assignment—non-summer (January-May) and summer (June-August). This was done to control for the possible influence of seasonal effects, since the control subjects could only be drawn from the summer months. Because the possible influence of season would only be controlled for the summer-hearing matches, it was decided to utilize them in deriving the matched control sample, and afterwards to match as many non-summer hearing subjects to the matched control sample as possible. Thus, the goal was to match two hearing subjects—one summer and one non-summer—to each control subject. In this way, the summer and non-summer hearing subjects would be matched to each other, as well as to the control subjects. (This goal was not quite attained since a non-summer hearing match could not be found for 35 of the control subjects.)

Since the number of exact matches derived through the collating procedure was disappointingly small, it was decided to relax the matching requirements slightly by allowing subjects to match who were no more than two years apart in age, but who were identical with respect to all other matching variables. Of the summer matches, 322 were exact, 179 inexact; of the non-summer matches, 304 were exact, 162 inexact.

A total of 501 summer hearing matches and 466 non-summer hearing matches was

derived from the original pool of 3,500 hearing subjects and 2,000 control subjects. Since only the 501 control subjects who matched summer hearing subjects were used in deriving the non-summer hearing sample, the control subjects in each group are largely the same subjects, minus the difference between them. In other words, all 466 of the controls who matched a non-summer hearing subject are also among the 501 who matched the summer hearing subjects. Further details concerning the matching outcome are given later.

Limitations of Data

Before commencing with a description and analysis of the results, certain limiting facets of the data should be made clear since they place qualifications on the inferences one can draw from the findings. Although implicit in any study of this nature, it should be emphasized that the driving performance criteria are those events (accidents and citations) contained on the departmental record. It is known that many accidents and violations are not reported to the department. In order to generalize the treatment effects (hearing) from departmental records to actual driving behavior, one must assume the events to be linearly correlated. This assumption permeates all studies of this type and to the authors' knowledge, no data are available to either support or refute it. However, it is felt that the assumption is a reasonable one.

A second limiting factor concerns the generality of the data. The hearing sample, strictly speaking, is only representative of the population of hearings from which it was drawn—in this case, 1961 hearings. Consequently, any changes in the hearing program subsequent to sample selection would not be reflected in the sample selected for this study. Also, to the extent that the matching procedure produced samples which were not representative of the overall negligent operator population on variables such as age or prior driver record, any generalization of sample findings to such a population must rest on the assumption that the hearing effects are relatively homogeneous with respect to these attributes.

A further assumption which must be made is that there was no appreciable difference between the two groups with respect to the types and temporal spacing of citations in the prior 12-month driver record period. If either of these assumptions were false, subsequent driver record comparisons could be distorted. A similar assumption concerns the exposure and socioeconomic variables. Since these variables were not available for the control group, the groups could not be matched on them. It seems reasonable to assume, however, that these variables would vary at random between the two groups, especially in view of the between-group homogeneity introduced by the matching procedure. This is particularly true for variables such as mileage and occupation, which were not available at the time of hearing-control assignment, and which therefore could not be utilized selectively in assigning subjects to the treatment groups.

Probably the most trenchant limitation to the study concerns the confounding of the hearing and control conditions as a result of differential treatment in the subsequent-to-assignment periods. Since a subsequent hands-off policy could not be adopted at the time this study was initiated, subjects in both the control and hearing groups were scheduled for hearings if they continued to violate subsequent to the initial assignment. Although not optimal, such a procedure is permissible from a design standpoint as long as the criterion for assigning subsequent treatments is the same for both groups. In the present study, however, the control group subjects were assigned subsequent hearings much more readily than the initial hearing group subjects, thereby confounding the initial distinction between the two groups. Fortunately, the direction of the findings was such that relatively definitive conclusions could still be derived concerning the intital treatment effects. This factor will be explored more comprehensively in the next section.

RESULTS AND FINDINGS

Adequacy of Matching and Composition of Groups

Hearing-Control Comparisons—It will be recalled that the hearing and control groups were matched on five variables—age, sex, marital status, number of prior accidents,

and number of prior citations. In all cases the matching between control and hearing subjects was very satisfactory. In fact, an exact match was obtained on all variables except age, where only negligible deviations occurred. Statistical tests indicated all age differences to be the result of chance occurrences.

Since area of residence within the state is known to be related to driving record, the reader may question why this was not included as a matching variable. To avoid further reduction of sample size, the authors decided to allow area to vary between groups on the assumption that its effects would be randomized. This proved to be the case. Statistical tests of significance on the area distribution proved to be non-significant, as were differences in the overall citation and accident rates derived from the various areas of the state. Thus it can be concluded that the hearing and control groups represent the same underlying population with regard to all three area variables.

Summer and Non-Summer Hearing Comparisons—It was pointed out earlier that the hearing group was subdivided into two categories—those who had received their initial hearing during the summer months, and those who had received their initial hearing in the non-summer months. This dichotomy was necessitated by the fact that control subjects were available for only the summer months, and the effects of season of hearing upon subsequent driving record were not known. Because the non-summer hearings and summer controls were selected from different periods of time, the possibility that subtle differences might exist in the composition of the two groups must be considered. Such differences could occur either as a result of true differences between groups who met the negligent operator definition at different times of the year or they could be artifacts produced by subtle differences in selection and scheduling procedures. Also it must be remembered that the prior and subsequent records between two groups selected at different points in time are not perfectly parallel. It was therefore decided to split the hearing group by season and to obtain the maximum number of matched control subjects for each hearing group. Such a procedure has the advantage of allowing for separate analyses within season of hearing, thereby isolating any distortion due to seasonal variation.

Before undertaking any hearing-control (treatment) comparisons, the summer and non-summer hearing groups were cross-compared with respect to a number of biographical and driver record variables. Statistical tests of significance indicated a significant difference between the hearing groups with respect to only one variable, area citation index. Thus, we have some evidence in support of our initial speculation—namely, that summer and non-summer hearing cases may not represent an identical population of negligent drivers. Such a speculation is also consistent with the fact that the subsequent driving records of the two groups were consistently different. Whether such differences were a result of pre-existing differences in the composition of the groups or temporal changes in the hearing structure and its effectiveness could not be determined from this analysis. Fortunately, comparisons between the hearing and control group within season of hearing produced the same decision with respect to hearing effectiveness, so that the issue has no bearing on the basic hypotheses which the study was designed to test.

Since the matching controls for the non-summer hearings were selected entirely from the summer months, subsequent driver record comparisons between these two groups (non-summer hearing vs summer controls) may be slightly biased. Driver record analyses with respect to treatment effects should therefore be considered more accurate in the case of the summer hearing vs summer control comparisons. In the pages which follow, emphasis will be placed on the latter comparisons, especially when evaluating the magnitude of the hearing effects.

Composition of Hearings by Response Categories—Based on the outcome of the hearing notice, the hearing groups can be divided into three "response" categories: (a) appeared—subjects who attended the hearing; (b) non-appeared—subjects who did not attend and whose notices were not returned "unclaimed"; and (c) notice returned—subjects who did not attend and whose notices were returned "unclaimed," indicating that these subjects were possibly no longer residing at the address. The breakdown of the summer and non-summer hearing groups in terms of the delineated response categories

showed that, of the summer hearings group, 420 appeared, 57 did not appear, and 24 had the notices returned. Of the non-summer group, 417 appeared, 38 did not appear, and 11 had the notices returned.

Although a detailed analysis of the comparative driving records of these groups will be reserved for later, some general comments concerning the implications which these response categories have with respect to the present research design should be included at this point. In order to construct valid treatment comparisons from which unbiased inferences may be derived, it is necessary that the entire hearing group ("appeared," "did not appear" and "notice returned") be included when making comparisons with the control group. Such a procedure is dictated by the fact that those persons who did appear may differ in a number of respects from those who did not appear, and that these differences may be related to driving record. Therefore, if we were to limit our treatment comparisons to the appeared group, the outcome could be biased since the control group could not be given the same "opportunity" to have subjects (potential "did not appear" and "notice returned" cases) removed.

Subsequent Driving Record by Type of Treatment

In this section, the effects of the hearing program are evaluated with respect to the following driving record criteria variables:

1. Citation reduction in the first and second year subsequent to hearing-control assignment;
2. Accident reduction in the first and second year subsequent to hearing-control assignment;
3. Months till first citation subsequent to hearing-control assignment;
4. Months till first accident subsequent to hearing-control assignment; and
5. Net months till first incident (accident or violation) subsequent to hearing-control assignment.

All comparisons will be between the control and hearing groups by age within season of hearing. Because there were so few females in the sample, the analyses will be confined to the combined male and female samples.

Subsequent Citation Frequency—The mean number of subsequent citations by treatment (control vs hearing) within season of hearing are as follows:

Season of Hearing	First-Year Record		Second-Year Record	
	Hearing	Control	Hearing	Control
Summer	1.06	1.43	0.93	1.01
Non-summer	1.21	1.44	0.99	1.02

In the first subsequent year, both hearing groups have significantly fewer citations than their respective control groups. Thus, one can be confident that the hearings resulted in a real (non-chance) reduction in citation frequency during the initial one-year subsequent period. The most dramatic difference occurred with respect to the summer hearing comparison, and for reasons discussed earlier, the latter comparisons probably represent the more accurate reflection of the magnitude of the hearing effects. In terms of percentage difference, the summer hearing group had 35 percent fewer citations in the first subsequent year than did their control counterparts. For the non-summer hearing, a citation reduction of approximately 19 percent was noted. An analysis of the second-year differences indicates that the hearing effects shrank dramatically over time. In fact, the second-year citation differences, though favoring the hearing groups, are not statistically significant. In other words, one cannot be confident that the latter differences are anything but random sampling variations (chance). For reasons which will be discussed later, there are grounds for suspecting that the full hearing effects have been suppressed, especially with regard to second subsequent year comparisons.

In order to determine whether the hearings were differentially effective by age, the treatment comparisons with respect to subsequent citation frequency were split into four age groups. Although there appeared to be a tendency for the hearing effects (on citation frequency) to decrease with increasing age, statistical tests of the age by treatment interaction did not reach significance. We therefore cannot conclude that the various age groups are affected in different degrees by the hearing process.

Subsequent Accident Frequency—The comparative performance of the hearing and control groups relative to subsequent accident frequency are as follows:

Season of Hearing	First-Year Record		Second-Year Record	
	Hearing	Control	Hearing	Control
Summer	0.25	0.24	0.18	0.16
Non-summer	0.25	0.23	0.19	0.17

It is immediately apparent from these figures that the situation relative to subsequent accident frequency deviates considerably from the outcome encountered with respect to subsequent citations. With accidents, there is practically no difference between any of the hearing and control accident means, and in each instance the direction of the difference is in favor of the controls. Statistical tests confirm that all differences reflected in the subsequent accident data can be attributed to chance. Although there is a theoretical possibility that contaminations in the research design could have suppressed subsequent accident reduction, the findings relative to subsequent accident frequency present a disappointing picture of the accident-reducing power of the individual hearing program, at least as the program was constituted in 1961.

Months Till First Citation—Another method of evaluating hearing effectiveness is to determine whether the hearing delayed the onset of violation behavior in the subsequent-to-treatment period. This was accomplished by coding the number of months till first subsequent citation for each subject in the study and employing statistical tests of significance on the tabulated results. The mean number of months till first citation by treatment and season for all those who received at least one countable citation in the two year subsequent driver record period are as follows:

Season of Hearing	Mean No. of Months Till First Citation (Citation-Free Drivers Excluded)	
	Hearing	Control
Summer	7.31	5.57
Non-summer	7.08	5.50

It can be seen from these data that all comparisons favored the hearing group. A statistical test indicated that the hearing did produce a real delay in the receipt of initial citations in the subsequent-to-treatment period. The amount of the delay for the summer comparisons was 1.7 months. Thus, coupled with the earlier finding that the hearing process reduced the subsequent frequency of traffic citations, it can also be concluded that the hearing process produced an initial delay in committing traffic violations.

Months Till First Accident—An identical analysis was performed with respect to delay of an initial subsequent accident. The descriptive details are as follows:

Season of Hearing	Mean No. of Months Till First Subsequent Accident (Accident-Free Drivers Excluded)	
	Hearing	Control
Summer	9.70	8.18
Non-summer	9.92	8.27

Although the comparison tends slightly to favor the hearing group, it is not statistically significant and could therefore be attributed to chance variation. Thus, it cannot be concluded with any assurance that the hearing delayed the occurrence of reported accidents. In direct contrast to subsequent citation incidence, there is no evidence that the hearing either delayed or reduced the occurrence of accidents in the subsequent driver record intervals.

Net Months Till First Incident—Because some of the hearing subjects received initial suspensions and also had a greater likelihood of receiving subsequent suspensions, it was anticipated that the months of net temporal exposure for the hearing group would be less than that of the control group. A statistical test on the net temporal exposure variable indicated that the hearing group did, in fact, have significantly less net temporal exposure subsequent to treatment than did the control. Because of this, one could speculate that the comparative reduction in subsequent citation frquency for the hearing group could possibly be attributed to reduction in exposure. To test this hypothesis, the authors formulated a "net months till first incident" variable; this variable consisted of the number of months accrued by each subject between treatment assignment and his initial subsequent incident (citation or accident) minus the number of months each subject was suspended during this interval. The means for all those with at least one incident on their record are as follows:

Season of Hearing	Mean No. of Net Months Till First Subsequent Incident (Incident-Free Drivers Excluded)	
	Hearing	Control
Summer	6.61	5.15
Non-summer	6.34	5.12

As can be seen, all comparisons still favor the hearing groups and the margin of the differences does not appear to have been appreciably affected by holding net temporal exposure constant. A statistical test on the data indicated that the hearing resulted in significant net delay in the occurrence of initial incidents during the 24-month period subsequent to hearing-control assignment. It would appear from this analysis that the hearing effects are relatively independent of net temporal exposure. To the authors' knowledge, this is the first successful attempt at analyzing this factor.

Subsequent Driving Record by Response Category

In order to make driving record comparisons within the hearing group by response category, the summer and non-summer hearings were combined into one group and their prior and subsequent driving records tabulated for analysis. The analysis of variance

employed on the prior driver comparisons indicated that the three response categories did not differ significantly with regard to prior number of citations and accidents:

Variable	Response Category		
	Appeared	Did Not Appear	Notice Returned
Accidents	0.26	0.18	0.20
Citations	1.14	0.91	1.34

Inspection of the first subsequent year's driving records of the groups proved to be considerably more interesting. In every case, the non-appeared group was found to have the superior subsequent record, with the appeared group occupying the intermediate position. Although statistical tests of the citation and accident differences failed to reach significance, the direction and consistency of the differences is notable. This finding cannot be interpreted as indicating that the overall hearing process (including receipt of hearing notice) is ineffective, but it does serve to reinforce suspicions concerning the effects of the hearing contact per se. In other words, one is tempted to speculate that the primary source of the hearing program's effectiveness lies in communicating to the subject the possibility of impending action, rather than the face-to-face interaction with the hearing analyst. Another possibility is suggested in the response category by net temporal exposure comparisons:

Variable	Response Category		
	Appeared	Did Not Appear	Notice Returned
First subsequent year	11.26	9.43	10.34
Second subsequent year	11.15	9.97	11.00

The numbers represent the average number of months which the subjects in each response category could legally drive during the subsequent 12-month interval. From this it can be seen that the driving of the "did not appear" group was the most restricted in the first one-year subsequent-to-hearing period. In other words, this group was suspended more than any other, thereby reducing their legally permissible temporal exposure below that of the other two groups. Statistical tests indicate that these exposure differences are real and not attributable to chance sampling variations. If the "did not appear" group actually adhered to their suspensions by not driving, then this reduced exposure could have decreased their incidence of accidents and citations subsequent to hearing. Another possibility is that the more severe action (increased suspensions) imposed on the "did not appear" group resulted in increased improvement. Finally, it can be argued that persons who refuse to appear for their scheduled hearings are, at the very outset, different from those who do appear, and that any subsequent difference could be a function of these pre-existing differences. More will be said about these response category findings in the next section.

DISCUSSION AND CONCLUSIONS

This section will relate certain of the study's research design qualifications to the findings in the previous section and will provide an overall interpretation of the data. Based on this interpretation, recommendations will be made as to future research needs and the direction of program development relative to control of the negligent driver.

Biased Nature of Driver Record Comparisons

It will be recalled from the discussion of research design and methodology that the two groups—hearing and control—were not treated equivalently in the period subsequent to treatment assignment. In verification of this statement, the following table shows that the control group received subsequent actions to a much greater extent than did the hearing group:

Season of Hearing	No. of Actions per Negligent Operator Point in Subsequent Two-Year Period		Months Till First Action	
	Hearing	Control	Hearing	Control
Summer	0.13	0.18	10.7	5.1
Non-summer	0.14	0.19	9.5	5.2

Thus, not only was the control group "treated" with hearings subsequent to control assignment, but they were treated to a much greater extent than was the hearing group. Apparently, the fact that the control group did not initially receive an action made it more likely that they would be called in for a hearing or action soon after violating in the subsequent period. In the hearing group, on the other hand, the mere presence of a hearing form on record delayed scheduling for subsequent hearings, despite continued traffic involvements.

The implications of this factor are very far-reaching and important. Since the control group received more actions per subsequent negligent operator point count than the hearing group, any effect which the initial hearing may have had would be obscured by the greater likelihood of a subsequent hearing for the control group. In effect, then, each time this happened the "pureness" of the control group was lessened. The question thus raised is how the findings are affected by such a bias. In view of the fact that the hearing group still received significantly fewer citations than the control group, we can be even more confident that the hearing reduced the number of subsequent citations. In other words, had the control group remained "pure," larger differences would probably have occurred. However, the accident comparisons were not significant, and we have no way of knowing whether a reduction would have occurred had the groups received equal treatment subsequent to hearing or control assignment. One thing seems certain, however; if the hearing process does have an effect on accident frequency, it must be a small one, detectable by only the purest of measures.

Comparison With Overall Driving Population

How does the subsequent one-year record of the hearing group compare with that of a similarly stratified (re. age, sex, marital status composition) group selected from the overall population of California drivers? By utilizing data from the 1964 California Driver Record Study (8), and adjusting it to the age, sex, and marital status composition of the hearing group, mean accident and citation rates of 0.14 and 0.58, respectively, are derived. Compared with the respective values for the combined summer-non-summer hearing group of 0.25 and 1.13, it can be seen that the hearing group still has almost twice the accident and citation incidence subsequent to hearing as does the adjusted overall California driving population. A previous study by Coppin and Van Oldenbeek (7) produced a similar finding. It is quite apparent, then, that the hearing program does not reduce the count level of negligent drivers to the average level of all California drivers.

Effects of Attending a Hearing

As indicated by our results relative to the response category comparisons, there is no evidence that it is the face-to-face contact with a hearing analyst which results in an improved subsequent record. In view of the finding that the "did not appear" group had a record that was as good, if not better, than the "appeared" group, it is quite possible that a large amount of the hearing program's effectiveness is a result of receiving the hearing notice.

However, it should not be inferred from this speculation that a mere warning letter would necessarily have the same impact as the overall individual negligent operator hearing program. In the hearing notice, the subject is requested, with threat of penalty, to appear at the hearing. A mere warning letter, no matter how severe, may not carry the same impact as notice of a legally constituted hearing scheduled on the subject's behalf.

Generality of Findings

As mentioned earlier, the matching restrictions rather severely reduced the heterogeneity of the hearing group with respect to variables such as age and prior driver record. In fact, not one subject in the study had a prior negligent operator count in excess of 5 points at the time of selection. The question is then raised as to how far the findings can be extrapolated beyond the population which is represented by the matched samples. The authors are of the opinion that the generality of the findings has not been excessively restricted, except possibly with respect to sex and prior driver record. In other words, since negligent operators at the more extreme count levels (6, 7 and above) were not included in the samples, and females were included to a very limited degree, the findings cannot be legitimately generalized beyond male 5-count subjects, unless one assumes that the effects of the hearing are homogeneous with respect to prior count level and sex.

Unresolved Issues

The authors wish to emphasize that the present research sheds little light on the actual mode by which the individual hearing is effective. Does the hearing actually change the attitudinal process of drivers, or is the improvement merely a function of the authoritarian aspects of departmental contact? What types of psychological makeups are most affected and least affected by this hearing process? Can any of the hearing effects be attributed to possible subsequent exposure reduction? Is the improvement which results from the present program the maximum which can be expected from any treatment? To what extent have the improvement and its duration been suppressed by the previously mentioned design contaminations? Are some analysts more effective than others in bringing about improvement? Are some types of actions more effective than others? Why does the hearing reduce violations, but (apparently) not accidents? Can accident frequency be reduced by any treatment short of completely removing the negligent driver from our roads and highways?

The answers to these questions can only be derived through more extensive research in the area of the negligent driver and treatment techniques. Toward resolving at least some of these issues, the department has undertaken a massive, rigorously controlled, multi-treatment research project in which subjects are assigned at random to one of a variety of control and experimental conditions. This multi-treatment study, combined with the results from the present study and a former study on group techniques (5), should go a long way toward developing an empirically based approach to the effective treatment and rehabilitation of the negligent driver.

SUMMARY

Analysis of the subsequent-to-treatment driving records of the hearing and control subjects indicated the following:

1. The hearing groups had significantly fewer citations in the first subsequent year than the control groups. No significant differences were found between the hearing and control groups with respect to citation frequency in the second subsequent year. However, because of research design contaminations which could theoretically have suppressed the full hearing effects—especially in the second year—it could not be concluded with assurance that the hearing effects diminished completely after one year.

2. No significant differences were found between the hearing and control groups with respect to subsequent accident frequency in either the first or second subsequent year. However, because of the previously mentioned design contaminations, it could not be concluded with complete assurance that the hearing program was completely ineffective as a reducer of accidents.

3. The various age groups did not appear to have been differentially affected by the hearing process. In other words, there was no evidence that the hearing was more (or less) effective with one age group than another.

4. The hearing significantly delayed receipt of intital citations in the subsequent-to-treatment interval, and the magnitude of the delay was too large to be attributed to the reduced net temporal exposure of the hearing groups. No significant difference in the onset of subsequent initial accident involvement was noted between the groups. In other words, it could not be concluded that the hearing program delayed the receipt of initial accidents in the subsequent-to-treatment period.

5. The subsequent citation and accident frequencies of those who attended their scheduled hearing were not significantly different from the frequencies of those who did not attend. Thus, it could not be concluded that it was the face-to-face contact with the hearing analyst which effected the subsequent reduction in citations for the hearing group.

6. The subsequent accident and citation frequencies of the combined hearing groups were approximately twice as high as a similarly stratified sample from the overall California driving population, indicating that the hearing did not reduce the point count of the negligent driver to the state average.

The authors propose the following speculative interpretation of the above findings:

1. The overall individual hearing program is an effective means of reducing subsequent citation frequency, but the effects probably diminish with time.

2. The overall hearing program, at least as constituted in 1961, either does not reduce subsequent accident involvement or reduces it to such a small extent that the reduction can only be detected with the purest of research designs, employed on very large samples.

3. Receipt of the hearing notice and/or initial action probably constitutes an important source of the hearing program effects, apart from face-to-face interaction with a hearing analyst.

Recognizing the study's limitations and findings, the department has initiated one comprehensive, multi-treatment approach, in which a variety of rehabilitative techniques will be compared within the structure of a definitive research design. This latter approach should provide answers to many of the unanswered questions raised by the presently completed study.

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The Attentional Demand of Automobile Driving

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A theoretical analysis and an experimental investigation of certain aspects of automobile driver information processing were undertaken. The theoretical analysis was the result of an effort to avoid difficulties associated with a servomechanistic approach to the automobile driving problem. The analysis is predicated on the assumption that a driver's attention is, in general, not continuously but only intermittently directed to the road. Between observations, uncertainty about both the position of his own vehicle on the road and the possible presence of other vehicles or obstacles increases until it exceeds a threshold. At that moment in time, the driver looks again at the road. This simple model appears to be a useful analog of the driving process. The analysis makes specific predictions about the form of the functional relationship between intervals between observations and vehicle speed.

The experimental program had two goals. One was the empirical investigation of the relation between amount of interruption of vision and driving speed. The other was the determination for various drivers and various roads of the values of some of the parameters in the mathematical model. This report presents the results of the theoretical and experimental investigation. In general, the model is a fair approximation of actual behavior and it remains for future work to determine whether this approximation is good enough to be useful for the specification of vehicle, highway, and user characteristics.

•ALL of us who drive are aware that at times we do not seem to pay very much attention to what we are doing. Drivers tune radios and light cigarettes; they blink and talk to passengers; they listen to news or music. It is said that drivers become "road hypnotized"—staring without seeing at the scene ahead. They look into rearview mirrors and scan for traffic police; they read advertising signs and search for turnoffs. Some of these activities are legitimate parts of the driving task; most are not. All of them constitute a diversion of attention away from the primary task of controlling a vehicle along a highway in accord with law and custom.

Driving is, in one sense, an error-free performance. No normal driver deliberately undertakes to get into an accident or into a collision. Collisions are (with some exceptions stemming from psychopathological origins) involuntary and accidental. For most driving situations, then, we can say that the driver accomplishes about what he intends to accomplish. The problems of analyzing error-free systems are great. In particular, where the system is a road, an automobile, and its driver—for whom a preview of the path ahead is directly available—it is difficult to use the techniques of simple linear servo-analysis. The output of the system is easily measured and easily understood, but it is extremely difficult to specify what the input is which results in the observed output.

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Prior attempts have been made by other investigators to determine those elements in the complex visual world of road and traffic which elicit the driver's responses. Gordon (1) used the technique of restricting the driver's view in order to enforce head movements. Then a head-mounted camera photographed what the driver fixated upon, permitting the investigator to identify the important and salient features of the visual environment. Sheridan et al (2), rather than limiting the field of view by artificial "tunnel vision," limited the forward field of view in two other ways. One way was to present everything out to a distance, d; the other was to present only the segment of road from d to $d + \Delta$. The distance ahead that the driver can see, d, was controlled as the chief experimental variable, and his performance measured.

Our approach is to treat the driver as an information processing device. He takes in information visually through the windshield by observation of the entire road ahead, and transmits information by manipulations of the steering wheel, brakes, etc. Using this as a conceptual model, we have indulged in some speculation about the information processing task, and have erected a not too complicated mathematical theory of how information flows into the driver and is processed.

Some of our theoretical notions arose from some personal observations made by the senior author while driving on a straight road with little oncoming traffic. A heavy rain resulted in the windshield wipers' being able to clear only a small sector of about 20 degrees behind the blade, so that visual conditions for the driver were somewhat analogous to those which would be presented by a radar sweep. The wiping speed was independent of the speed of the car. The driver became aware of a "psychological speed limit." Up to that speed, there was no anxiety; above that speed the driver became anxious and had to slow down.

This observation suggested a parallel between the sampling of a time function (in which the minimum sampling rate for signal reconstruction is related to the bandwidth of the signal) and the sampling of a road (a space function), where the minimum sampling rate is related to the characteristics of the road and to the velocity at which it is traversed. One might imagine that the road had a certain information rate built into it—that is, there were so many bits per mile. The faster one traverses a portion of the road, the more bits per unit of time must be processed. Were the driver to see a road only at fixed intervals, he would develop uncertainty about what might have appeared on the road since his last observation, and about where he is on the road. If the intervals between observations were very long, then the accumulated uncertainty and the amount of information to be absorbed on the next observation would be greater. If the observation time itself were very short, the driver would be unable to completely reduce his uncertainty by absorbing the required amount of information.

The analogy leads to a parallel between information flow rate and some "equivalent bandwidth" of the road. The equivalence, of course, would be established by the driver's selection of a speed at which he traverses the road. Given a fixed sampling rate, then, if a driver were to traverse a road at his "maximum" speed, one might argue backwards that the speed/sampling-rate combination would permit estimation of the equivalent bandwidth of the road and of the information density of the road.

There are a number of factors which can influence the selection of a driving speed. One would be the wiggliness of the road—that is, the frequency with which the road deviates from a straight path by enough to require corrective action. Another factor would be the overall density of significant obstacles in the road. Still another might be related to how accurately the vehicle can be steered and the degree to which, without attention, it maintains the desired path. Less easily quantified is the driver's estimate of the probability that some new object will enter the road or the probability that opposing traffic will deviate into the path of his vehicle between observations. In general, all of these factors can be reduced to an uncertainty estimate per unit length of road.

We have considered two experimental situations. In one the sampling rate is fixed and the driver modifies his speed according to the road, traffic, etc. The alternate is to cause the vehicle to travel at a constant speed and allow the driver to control the interval between observations at will. Thus, if the vehicle is very stable it does not need to be attended to as often as if it were very unstable; and if the uncertainty of

steering is small, the driver does not have to look as often as he would if it were large. Similarly, objects at a distance produce less uncertainty than objects close at hand. One would expect that as opposing traffic approaches, the driver must attend more often. If there are many side streets, driveways, and the like, then the probability of cross traffic is high and the driver has to pay more attention.

Naturally, the rate at which one would look would not ordinarily be constant. Instead, it would be a continuous variable function of the instantaneous state of affairs. For example, if one were traversing a road at a constant speed and entered a populated area so that the probability of animal or human entry was high, then the frequency with which one looked at the road would go up. The more often the road turns, the more often must the vehicle be controlled, and the more often must the driver look in order to control. The point at issue is that a road demands attention. The attentional demand of a road is a characteristic of that road and of the traffic situation which may exist upon it as well as the velocity at which it is traversed.

A rather important notion which underlies the theoretical work is that drivers tend to drive to a limit. We suggest that the limit is determined by that point when the driver's information processing capacity, either real or imagined, is matched by the information generation rate of the road, either real or estimated. The drivers may be wrong in their estimates, but they will tend to achieve this balance of input information rate and information processing rate. A driver in unfamiliar territory sees a great deal more uncertainty in the situation than a driver familiar with the territory. With familiarity there comes reduction of uncertainty, a reduction of information flow rate, and a higher permissible velocity, granted the same territory and circumstances. This is reflected in the different ways people behave in automobiles in familiar and in unfamiliar terrains. It might be said that a curvy familiar road is "perceptually straight" since uncertainty about the road ahead is low.

Finally, drivers will accept different levels of risk and drive to a limit such that the probability of an accident is no greater than, but approaches, some upper threshold. Subjective acceptable risk level is a measurable characteristic of drivers and directly influences their behavior on the road.

We have identified a number of factors which tend to control the speed of the driver traversing a road in the presence of traffic and other dynamic obstacles. These are, in brief: the width of the road and the frequency with which it turns; the estimated probability of intrusion from other vehicles and animals; the uncertainty associated with the vehicle dynamics; the precision of the steering mechanism; the residual errors of vehicle aiming; and a risk acceptance level which is a characteristic of each driver. We are then led to the development of a theoretical model of driver behavior which describes and quantifies the cumulative uncertainty of the driver between looks at the road. The experimental program examined the actual behavior of drivers with intermittently occluded views of the road.

AN UNCERTAINTY MODEL OF THE DRIVING SITUATION

The following derivation is based on steady-state driving with intermittently occluded vision. That is, the driver is assumed to have adjusted the vehicle velocity (or the period of occlusion) to meet his criteria of performance and risk. Thus both velocity and period of occlusion may be treated as constants.

Driver Information

Let the information density of the road be H (x) bits per mile, where x is the road distance in miles. The reference point for distances (x = 0) is taken as the location of the driver at some reference time (t = 0). The amount of road information available to the driver depends on the limits of visibility and on the way in which the driver weighs the information. It is reasonable to assume that the weighing is a monotonically decreasing function of distance since the driver will attach more importance to the nearer sections of road (which require an immediate response) than to the sections further on. Let us assume, therefore, that the weighing function is $e^{-x/D}$, where D is the weighing

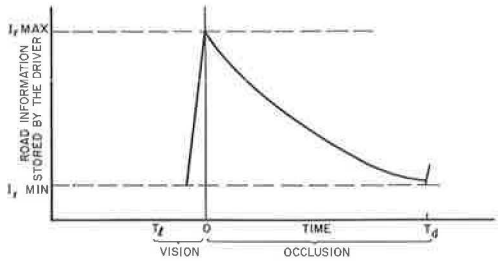

Figure 1. Timing of events.

constant in miles. This function meets the requirement of being monotonically decreasing and is mathematically convenient.

The driver, therefore, constructs a road information model that has an information density of $H(x)\, e^{-x/D}$ bits/mile. The maximum amount of information that can be stored by the driver is the integral of this density function over the range of visibility. The lower limit of useful vision, x_1, is the distance one reaction time ahead, or the distance occluded from view by the vehicle, whichever is greater. The upper limit, x_2, may be determined by external conditions or by limitations on the viewing time.

For ease of calculation, let the road information density be constant (H) over the section spanned by x_1 and x_2. If we assume further that negligible error is introduced by taking the limits of visibility between 0 and infinity, the stored information reduces to

$$I_r = H \cdot D \tag{1}$$

As the vehicle proceeds over sections of the road stored in the driver's image, information contained in these sections becomes obsolete. At the vehicle velocity of V miles/sec, information becomes obsolete at a rate of HV bits/sec. Let us consider the situation in which vision is periodically occluded. The timing of events for one cycle is illustrated in Figure 1. At $t = -T_\ell$ vision is unobstructed and the driver absorbs information. The maximum amount of information is in store at $t = 0$. Vision is obstructed for the following T_d sec, during which time the store of information continually diminishes. The minimum amount of information is in store at $t = T_d$ at which time vision is restored and the cycle repeats.

During the period of vision the driver absorbs information at a rate of R bits/sec. Let us assume that R is constant as long as there is information to be absorbed. If the driver is able to absorb all the road information available before the period of vision has terminated, the rate of information input then drops to a level that exactly balances the rate of obsolescence.

There are two sources of information loss during the period of vision: (a) the rate of information obsolescence, HV, and (b) the rate of forgetting, which we shall assume to be proportional to the amount of information stored. Let the rate of forgetting be $I_r(t)/F$ bits/sec, where F is the time constant in seconds. If the maximum amount of road information available to the driver is HD, as derived in Eq. 1, the net instantaneous rate of information absorption during the period of vision is

$$\frac{d}{dt} I_r(t) = \begin{cases} R - HV - I_r(t)/F & I_r(t) < HD \\ 0 & I_r(t) = HD \end{cases} \tag{2}$$

It will be assumed in the following discussions that the driver is able to absorb all the information available by the end of the viewing period; that is, $I_r(t) = HD$ at $t = 0$.

We shall now determine the amount of information stored by the driver at time t during the period of occlusion. The two sources of information loss remain, whereas there is no information input. The rate of forgetting is $I_r(t)/F$, as assumed above. Because of the way in which information is weighed by the driver, the rate of obsolescence varies with distance (and hence with time). Clearly, the rate at which information is "driven out" is related to the rate of forgetting. The faster the driver forgets, the less information there remains to be lost through forgetting.

The relationship between the rate of information obsolescence and the amount of information remaining in storage is

$$\frac{d}{dt} I_r(t) = -(V/D) I_r(t) \tag{3}$$

The total rate of information loss is

$$\frac{d}{dt} I_r(t) = -\frac{V}{D} I_r(t) - \frac{1}{F} I_r(t) = -[(V/D) + (1/F)] I_r(t) \tag{4}$$

Given that the information in storage is HD at t = 0, Eq. 4 yields

$$I_r(t) = H \cdot D\, e^{-[(V/D) + (1/F)]t} \text{ when } 0 \leq t \leq T_d \tag{5}$$

Before proceeding with the development of the model, let us review the assumptions and derivations that have been made so far:

1. The driving situation is in the steady state. The vehicle proceeds at a constant velocity, V miles/sec; the timing of looks is periodic such that vision is allowed for T_ℓ sec and occluded to T_d sec.
2. The road has a constant information density of H bits/mile.
3. The information density of the driver's stored image is $He^{-x/D}$ bits/mile.
4. The period of view is sufficient for the driver to absorb all the information available. The amount of information stored at t = 0 is HD bits.
5. Information is forgotten at the rate of $I_r(t)/F$ and becomes obsolete at the rate of $I_r(t)V/D$ bits/sec. The amount of information in storage t sec after the onset of occlusion is $HD\, e^{-(V/D + 1/F)t}$ bits.

Driver Uncertainty

The driver is assumed to adjust the vehicle velocity (or the occlusion time) so that his uncertainty U(t) is never greater than some criterion level U_c, measured in bits. Since the uncertainty is greatest at the end of the occlusion interval ($t = T_d$), the criterion may be stated mathematically as

$$U(T_d) \leq U_c \tag{6}$$

The driver uncertainty at time t sec after occlusion is

$$U(t) = U_r(t) + U_n(t) \tag{7}$$

where $U_r(t)$ is uncertainty about the road due to a loss of relevant information and $U_n(t)$ is uncertainty about the position of the vehicle arising from random disturbances in the orientation of the car. The latter term takes account of the vehicle dynamics, the ability of the driver, and external disturbances such as wind and variations in the road surface.

The uncertainty about the road, $U_r(t)$, is equal to the amount of information that has been lost. It is equal to the maximum amount of information originally available minus the amount of information in store at time t. Thus

$$U_r(t) = H \cdot D\left[1 - e^{-(V/D + 1/F)t}\right] \tag{8}$$

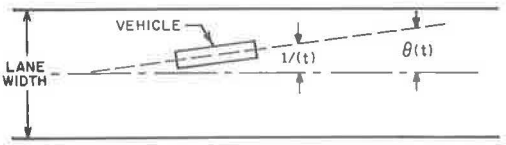

Figure 2. The driving situation.

This component of uncertainty starts from zero at t = 0 and rises asymptotically to H · D.

The other component, $U_n(t)$, also starts from zero but increases without limit as T_d is increased. To determine this component, let us analyze the situation in which uncertainty arises only from lack of knowledge about the lateral position of the vehicle. Assume that during the viewing period the driver is able to center the vehicle within the lane and orient it parallel to the (imaginary) centerline. The driver then has to worry about wandering into the next lane during the period of occlusion of vision. A reasonable rule for the driver to adopt is that σ_y/T_d—the expected value of the rms displacement of the vehicle from the centerline at time T_d—must be less than some level Y_s, or that the uncertainty of the lateral position of the vehicle must be less than U_c, where the uncertainty is proportional to σ_y/T_d.

We shall now determine σ/T in terms of velocity and occlusion time. The driving situation is diagrammed in Figure 2. Let $\theta(t)$ be the angular orientation in radians of the vehicle with respect to the centerline of the lane. Let y(t) be the lateral distance of the center of the front bumper from the centerline. The lateral component of the vehicle velocity is $dy(t)/dt = V \sin \theta(t)$. Since $\theta(t)$ is typically a small angle,

$$\frac{dy(t)}{dt} = V\theta(t) \tag{9}$$

Thus,

$$\frac{d^2}{dt^2} y(t) = V\frac{d}{dt}\theta(t) = V\frac{\partial\theta}{\partial x}(t)\frac{dx}{dt} = V^2 \frac{\partial\theta}{\partial x}(t) \tag{10}$$

where $\frac{\partial\theta}{\partial x}(t)$ is the rate of change of orientation with respect to distance along the road in radians/mile. The value of the lateral displacement at a particular time T is obtained by double integration of the right-hand expression of Eq. 10:

$$y(T) = V^2 \int_0^T \left\{ \int_0^T \frac{\partial\theta}{\partial x}(t)dt \right\} dt \tag{11}$$

In order to compute σ_{y_T}, $E(y_T^2)^{1/2}$, we must know something about $\frac{\partial\theta}{\partial x}(t)$. For mathematical ease, let us assume that this function can be described by a wide-band Gaussian random process that has a rectangular spectrum from 0 to ω_1 radians/sec. Let the spectral density be a constant S_θ randian-sec/mile^2.

The variable y(t) may be considered to be a continuous random process which is obtained by filtering the continuous random process $\frac{\theta}{x}$ (t) with a system that scales by V^2 and performs a running double integral from T-t to T.

Hence, the relation between y(t) and $\frac{\partial\theta}{\partial x}(t)$, expressed in the frequency domain, is given by the following system function:

$$H(j\omega) = V^2 \frac{(1-e^{-j\omega T})^2}{-\omega^2} \tag{12}$$

The power density spectrum of y(t), which shall be denoted as S_y, can be obtained by multiplying the power-density spectrum of $\frac{\theta}{x}(t)$ by the square of the magnitude of the system function. Thus,

$$S_y = S_\theta \, |H(\omega)|^2 = \frac{V^4 (1-e^{-j\omega T})^2 \, (1-e^{+j\omega T})^2}{\omega^2} S_\theta = 4V^4 \frac{(1-\cos \omega T)^2}{\omega^4} S_\theta \tag{13}$$

The average power of the process y(t) is the integral of S_y over the entire frequency range. Thus,

$$y^2(t) = \frac{4V^4 S_\theta}{2\pi} \int_0^{\omega_1} \frac{(1-\cos \omega T)^2}{\omega^4} d\omega \tag{14}$$

Let a new variable z be defined such that $\omega = z/T$, and assume that negligible error is introduced if the integral is carried to infinity. Then,

$$\overline{y^2(t)} = \frac{4V^4 S_\theta}{2\pi} \int_0^\infty \frac{(1-\cos z)^2}{z^4/T^4} d(z/T) = 4V^4T^3S_\theta \int_0^\infty \frac{(1-\cos z)^2}{z^4} dz \tag{15a}$$

Since the integral in the above expression is a constant, Eq. 15a can be reduced to

$$\overline{y^2(t)} = 4kS_\theta V^4 T^3 \tag{15b}$$

Assuming that the random process y(t) fulfills the condition of ergodocity (3), we may equate the time average $y^2(t)$ to the ensemble average $E[y_T^2]$* which is identical to $\left[\sigma_{y_T}\right]^2$. Thus, the expected value of the lateral displacement of the vehicle is

$$\sigma_{y_T} \propto V^2 \cdot t^{3/2} \tag{16}$$

Since the driver's uncertainty concerning the lateral position of the vehicle is assumed to be proportional to σ_y,

$$U_n(t) = K_n V^2 \, [t]^{3/2} \tag{17}$$

where the constant K_n includes the power density spectrum S_θ and other scaling factors. Substitution of Eqs. 17 and 8 into Eq. 7 shows that the total driver uncertainty is

$$U(t) = H \cdot D \left[1-e^{-(V/D + 1/F)t} \right] + K_n V^2 (T_d)^{3/2} \tag{18}$$

Thus, the driver's rule of behavior, obtained from Eq. 6, is

$$U(T_d) = H \cdot D \left[1-e^{-(V/D + 1/F)T_d} \right] + K_n V^2 (T_d)^{3/2} \leq U_c \tag{19}$$

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*The replacement of t by T as the time index is justified since both y(t) and y_T have been defined to represent deviations of the vehicle after T seconds of occlusion.

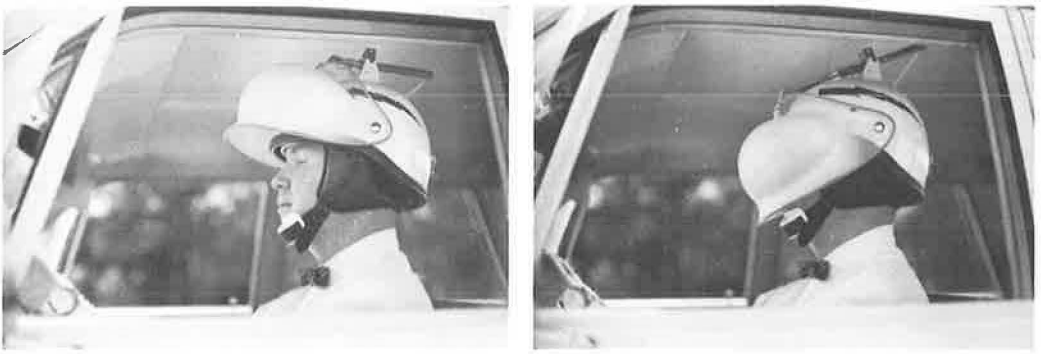

Figure 3. Device for controlling driver vision.

EXPERIMENTAL PROGRAM

An experimental program was devised with two goals. One of these was to provide data with which to test the adequacy of the theoretical notions previously expressed and to evaluate their utility. The other was to estimate the attentional demand imposed on a driver by various combinations of road, vehicle, and speed, and to explore a wide range of these variables in order to obtain data relating, for example, the radius of a curvature of a highway to attentional demand as a function of speed. Thus, the experiments stand on their own as empirical investigations into the effects of interrupted vision upon driving behavior.

In order to accomplish the goals of the program, we wished to investigate a broad spectrum of road difficulty or road attentional demand. Accordingly, two kinds of roadway were used. One of these, the "easy one," was I-495 in Massachusetts. The road is essentially straight, i.e., the radii of curvature are sufficiently large so that the viewing distance ahead is always large and the lanes are sufficiently wide so that no great precision of steering is required to stay in lane. For the difficult road we chose a closed-circuit sports-car racing course, the Bryar Motorsport Park at Loudon, New Hampshire.

Two kinds of experiments were done. One of these involved the use of a constant period of occlusion and a constant observation time, with the driver controlling speed to his maximum. The other used a constant speed and permitted the driver "to look when he wished to." The experimental apparatus was designed to permit both kinds of operation. Driver vision was controlled by a translucent screen which could be lowered over the driver's eyes and through which no road or vehicle detail could be seen. This screen was the pivoting face shield of a protective helmet and was remotely actuated by a pneumatic cylinder and linkage mounted on the helmet itself (Fig. 3).

The system provided for a variety of methods of control and safety override. The experimental vehicle was a 1965 Dodge Polara with a number of modifications. Details of roadways, recording and control apparatus, subject population and experimental procedures are given elsewhere (4).

There were four experiments using two kinds of road and two procedures:

Experiment 1—I-495, fixed occlusion and viewing time;
Experiment 2—I-495, fixed velocity and viewing time;
Experiment 3—BMP, fixed velocity and viewing time; and
Experiment 4—BMP, fixed occlusion and viewing time.

Table 1 shows the conditions which were experimentally investigated. The entries are for numbers of series each of which consists of a number of runs. A total of more then 550 runs was accumulated.

TABLE 1

NUMBERS OF SERIES COMPLETED AT THE VARIOUS CONDITIONS, OVERALL PROGRAM

Condition		Subject					Total
		D.H.K.	D.C.M.	C.W.D.	W.V.D.	J.W.S.	
				Experiment 1			
T_d	1.0		3			3	6
	1.5	1	3	6	1	3	14
	2.0	1	3	6	1	3	14
	2.5			6	1	3	10
	3.0	1	3	6	1	3	14
	3.5				1		1
	4.0	1	3	6	1	3	14
	4.5				1		1
	5.0	1			1		2
	5.5		3	3			6
	6.0	1		3	1	3	8
	7.0		3	3	1		7
	7.5	1		3	1	3	8
	9.0	1	3	6	1	3	14
Total		8	24	48	12	27	119
				Experiment 2			
V	22	2		1	1		4
	25	1		1	1		3
	30	1		1	1		3
	40	1		1	1		3
	50	1		1	1		3
	60	1			1		2
Total		7	0	5	6	0	18
				Experiment 3			
V	22	2	1	2	1		6
	25	2		2	1		5
	30	3	1	3	2		9
Total		7	2	7	4	0	20
				Experiment 4			
T_d	0.5	2		5	2		9
	1.0	2		5	2		9
	1.5	2		3	2		7
	2.0	2		1	2		5
	3.0	2		1	2		5
Total		10	0	15	10	0	35

Experiment 1—I-495: Fixed Occlusion and Viewing Times

This experiment dealt with the problem of constant viewing time, T_ℓ, and constant occlusion time, T_d. Five subjects were used: C.W.D., J.W.S., D.H.K., W.V.D., and D.C.M. Subject C.W.D. replicated the experiment completely. As a result, six sets of data are available.

Based on the preliminary experiments, three values of T_ℓ were chosen: 0.25 sec, 0.50 sec, and 1.0 sec. The T_ℓ of 0.25 sec was the shortest practical time which the driver could use. It allowed for at least a change of accommodation, even if not for more than one fixation of field of view ahead. The 0.50-sec viewing time was apparently

TABLE 2

SPEED IN MPH AS A FUNCTION OF VIEWING TIME[a] AND OCCLUSION TIME FOR SUBJECT C.W.D. (1)

Occlusion Time (sec)	Trial No.	Run No. 1	2	3	4	5	6	7	8	Obt. Mean (n)	Stand. Dev.	Calc.
1.5	2	62	59	62	60	59				60(5)	2	86
2.0	27				no limit							
2.5	9	27	44	45	51	46	50			47(5)	3	54
3.0	19	52	55	57	61	61	60			60(4)	1	45
4.0	28	35	50	45	45	48	40			46(5)	3	34
6.0	21	15	17	17	22	18	16			17(6)	2	21
7.5	22	6	9	13	13	12	13			13(4)	0.5	15
9.0	6	11	6	4	6	4	6			5(5)	1	11
										N = 42		

[a]Viewing time = 0.50 sec.

long enough to provide nearly all the information needed to drive at any speed, and only a slight increase in velocity was expected to occur with a 1.0-sec viewing time.

The number of runs made in each series was determined by the stability of the results. The earlier trials tended to be more variable than the later ones as the driver experimented with modes of perceiving, remembering, and controlling. Since each trial, by definition, was terminated only at a limit velocity, and since the limit velocity, by direction, was the "maximum possible," the task of driving was an arduous one. Subjects were relieved after fifteen minutes of driving and, in turn, acted as recorder or experimenter. Trials would take various amounts of time depending on the experience which had been accumulated and the speed involved. The criterion for performance was "adequate driving." The driver was required to stay in lane as he would if he were able to view the road continuously. On no occasion was it necessary for the safety driver to take over control.

The data for C.W.D. and J.W.S. are presented in Tables 2 and 3 and show, on successive runs, the speed reached as a limit by the subject for various T_d. The number preceding the tabular entries of mph was the position of that particular combination in the sequence of that subject for that experiment. Thus, the second run made with subject C.W.D. (1) was with a viewing time of 0.50 sec and an occlusion time of 1.5 sec. Runs were continued until, in the opinion of the experimenter, stable performance had

TABLE 3

SPEED IN MPH AS A FUNCTION OF VIEWING TIME[a] AND OCCLUSION TIME FOR SUBJECT J.W.S.

Occlusion Time (sec)	Trial No.	Run No. 1	2	3	4	5	6	Obt. Mean (n)	Stand. Dev.	Calc.
1.0	23	48	53	50	50	49	49	50(6)	2	62
1.5	17	46	48	47	45	45	40	45(6)	2	44
2.0	16	39	39	38	41	38	35	38(6)	2	34
2.5	3	25	32	33	35	32		33(4)	1	28
3.0	12	20	22	20	20	24		21(5)	2	24
4.0	22	19	20	20	19	20	19	19(6)	0.5	18
6.0	6	13	11	12	12	19		13(5)	3	11
7.5	18	11	7	5	5	7	7	6(5)	1	8
9.0	21	4	3	6	5	5	5	5(6)	1	6
								N = 51		

[a]Viewing time = 0.25 sec.

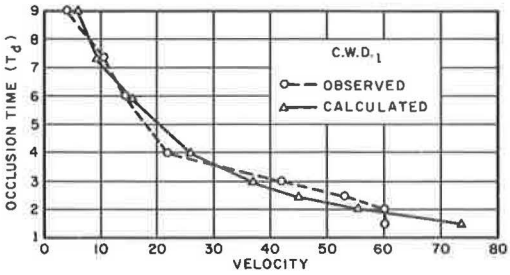

Figure 4. Relationship between occlusion time and terminal speed.

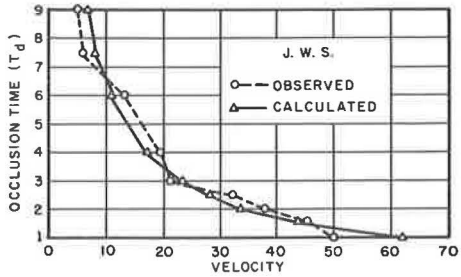

Figure 5. Relationship between occlusion time and terminal speed.

been reached. The mean was calculated on the basis of a number of points, never less than 4, which appeared to represent stable performance. The parenthetical entry after the mean is the number on which the mean is based. The standard deviation is computed on the basis of that n and is in mph. The last entry is the speed in mph calculated on the basis of the best fitting solution of the theoretical model.

Figures 4 and 5 show the obtained and the theoretical relationship between T_d and terminal speed. The calculated values are those based on a best mean square fit to the theoretical model. The fit is that which minimizes the variability of the permissible uncertainty, U_c, and allows the other parameters of the equation to vary in order to minimize the variation in U_c. Thus, for each subject, there is a table of the obtained data and of the theroetical points fitted to the curve by a minimization of the squared deviations of the permissible uncertainty, and a graph. Two such sets, for C.W.D. (1) and J.W.S., are shown. The complete data are given elsewhere (4).

The results of Experiment 1 show, as would be expected, that as occlusion time is decreased the maximum velocity which can be achieved by the subject-drivers is increased. With few exceptions, the function is a monotonic relationship and where reversals have occurred they can almost always be identified as being the result of learning.

It is possible to adjust the parameters of the model to provide a good fit to the obtained data in most cases. Table 4 shows the values of the parameters for each subject, for each condition. D, F, and U_c are individual parameters which, of course, will vary with the subject and with the conditions under which data are taken. The parameters H and K are situational and proportional parameters; K, in particular, is the same for all, having been set to adjust the general position of the model to correspond to the real numbers obtained in the experimental situation. H presents somewhat more of a problem. As we can see, H varies from as high as 34 for subject C.W.D. (2) to as low as 4 for subject J.W.S. Whether this represents a different attitude toward the roadway is not clear. Subject J.W.S. uniformly had a very small D which suggests that his performance was based largely on the information relatively close to the vehicle. Subject C.W.D. had a somewhat higher D factor and, in general, a much larger H. In this respect, it must be noted that subject J.W.S. was, in general, a more cautious subject than C.W.D. or D.C.M. In particular U_c—the amount of uncertainty which the driver will permit to be accumulated in bits—is consistent and small for subject J.W.S., and larger and more variable for the other two subjects.

An impressive feature of the data is the fact that, with the exception of subject J.W.S., an occlusion time of 1.0 sec resulted in no limit speed—at least no limit within the speed limit of the highway. The only exception to this finding occurred with a T_ℓ of 0.25 sec for subject C.W.D. (1), and on one trial with a T_ℓ of 0.5 sec. At the other extreme, subject C.W.D. (2) drove with complete control with no tendency to deviate from his path or to exceed the limits of his lane at speeds in excess of 70 mph with 1.0-sec looks at the road separate by intervals of 4.0 sec of complete occlusion of vision.

TABLE 4

MODEL PARAMETERS FOR VARIOUS T_ℓ

Subject	Parameter	T_ℓ 0.25	0.50	1.0
C.W.D. (1)	D	0.26	0.42	0.32
	H	14.0	12.0	20.0
	F	6.0	10.0	7.5
	K	0.0002	0.0002	0.0002
	U	3.13	3.76	5.22
J.W.S.	D	0.20	0.18	0.20
	H	6.0	6.0	4.0
	F	9.5	6.0	5.0
	K	0.0002	0.0002	0.0002
	U	0.99	1.07	1.13
D.H.K.	D		0.50	
	H		18.0	
	F		3.5	
	K		0.0002	
	U		4.93	
C.W.D. (2)	D	0.22	0.46	0.20
	H	12.0	34.0	26.0
	F	8.0	5.0	7.0
	K	0.0002	0.0002	0.0002
	U	2.57	13.47	8.24
D.C.M.	D	0.30	0.30	0.30
	H	20.0	20.0	12.0
	F	4.5	5.0	3.5
	K	0.0002	0.0002	0.0002
	U	7.16	5.96	4.29
W.V.D.	D		0.32	
	H		24.0	
	F		4.5	
	K		0.0002	
	U		6.99	

Experiment 2—I-495: Fixed Velocity and Viewing Time, Voluntary Control of Occlusion

This experiment dealt with the situation where speed and T_ℓ are fixed and T_d is under the voluntary control of the driver. As described earlier, the driver has available a switch (to be operated by the left foot) which initiates an observation time of fixed duration equal to T_ℓ. The purpose of the experiment was to obtain something more analogous to a point-to-point index of the attentional demand placed upon the driver by the highway. A fixed T_ℓ of 0.5 sec was used. The subject was fitted with the helmet and given preliminary familiarization with the operation of the foot switch and the viewing time.

The subject steered into the right-hand lane of the road and accelerated with the visor up until he reached the preset speed. When the driver had

TABLE 5

MEAN VOLUNTARY OCCLUSION TIME AS A FUNCTION OF SPEED, EXPERIMENT 2

D.H.K.		W.V.D.		C.W.D.	
V	$\bar{T}_d$	V	$\bar{T}_d$	V	$\bar{T}_d$
60	1.48	60	1.84		
50	1.66	50	2.50	50	2.21
40	1.75	40	2.82	40	2.42
30	2.10	30	3.19	30	3.25
25	2.26	25	3.95	25	3.57
22	3.63	22	3.98	22	3.64
22	2.60				

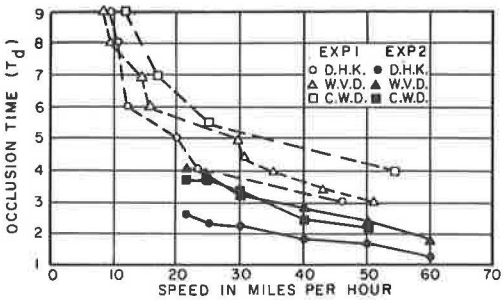

Figure 6. Viewing time 0.5 sec.

provided an adequate sample of behavior, i.e., some 60 to 120 operations with the visor in the course of 5 minutes, the experimental run was terminated with the visor's being raised, a new speed selected, and the experiment repeated.

The average T_d's chosen by the various subjects for the various speeds resulting from the process analysis are given in Table 5. It can be seen that there are no reversals of the functional relationship between V and the mean value of T_d chosen by the driver. The longer times obtained for subject D. H. K. were the result of his not adhering to the rule of error-free performance on the first 22-mph run. When the instruction was reiterated the shorter times were obtained. The results are shown in Figure 6 with the functional relationships between V and T_d for the same subjects obtained in Experiment 1 presented for comparison.

For all three subjects, it can be seen that the voluntary control T_d's are lower than would have been expected if this technique resulted in a simple replication of the results of Experiment 1. From the subjective point of view, the technique of Experiment 2 provides the driver with a more immediate control over his perceptual environment. The response time of the visor to the depression of the foot switch is virtually instantaneous. On the other hand, the vehicle, when traveling at a fairly high speed, is relatively slow to respond to minor changes of accelerator or brake pressure which might be applied in Experiment 1. The assumption of a constant limit speed in Experiment 1 is predicated on the idea of a constant H for the highway and this is almost surely not the case. The variability which is evident in the voluntarily controlled T_d's shows that the driver perceives the highway as possessing a variable H. Consequently, there is variation in the rate of uncertainty generation during occlusions. This suggests that the technique of Experiment 2 will be a more useful one for evaluating the attentional demand placed upon the driver by traffic situations or by different vehicles.

Experiment 3—Bryar Motorsport Park: Fixed Speed and Viewing Time, Voluntary Control of Occlusion

This experiment dealt with the problem of constant viewing time, T_ℓ, and constant velocity, with subject control T_d. It was thus identical with Experiment 2 but done on a very different road. Bryar Motorsport Park is 1.6 miles of well-paved and banked roadway with ten turns which vary in radius from virtually straight to "hairpin."

As was seen in Table 1, a total of 20 trials was made, with each trial consisting of a number of laps. Each lap produced a record which was analyzed separately. Our interest was in the functional relationship between the voluntary period of occlusion and the radius of curvature of the track. Since no other vehicles were permitted on the track and there was a sufficiently long period of familiarization, the only residual uncertainty would be that associated with steering around curves and maintaining the vehicle properly within the lane. Accordingly experiments were done at three constant speeds: 22, 25, and 30 mph. A speed of 35 mph is not beyond the limits of the vehicle but would present serious control problems in the event of error. For this reason, no higher speed attempts were made. (These were reserved for Experiment 4, which dealt with constant T_ℓ and T_d and allowed the driver to vary the speed at will.) A sample record (Figs. 7 and 8) shows the interval between observations as a function of position along the track. The data on a point-to-point basis are jagged, due to the discrete nature of the performance. Accordingly, running averages of 3 were made and are plotted on the same graph. The numbers of the record identify the five significant curves of the track.

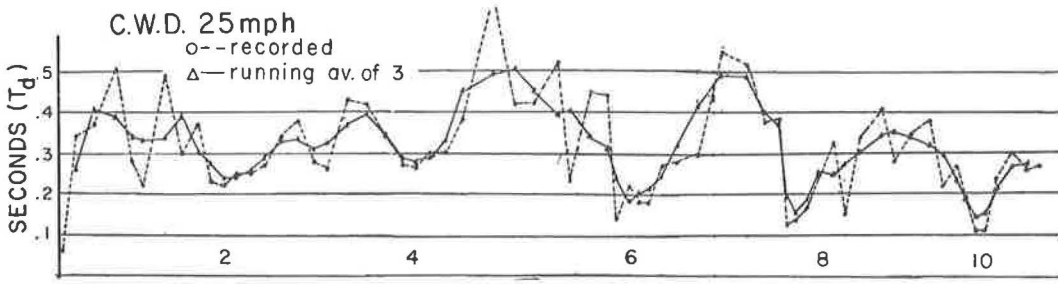

Figure 7. Interval between observations as function of position on track.

It can be seen that, in general, the higher the speed, the shorter the interval between observations. For a sufficiently low speed, we might assume that the driver will behave as he does on the superhighway. That is to say, the interval between observations would be nearly independent of the radius of curvature on the roadway. At sufficiently high speeds, on the other hand, the driver might be unable to maintain adequate steering, given a roadway that curves as it does, even with continuous viewing. At intermediate speeds, on some parts of the track the roadway will be effectively a straight road (even though in fact it may be curved), and on other parts of the track the radius of curvature might be so small as to demand more frequent viewing. We should not expect, therefore, to find a simple relationship between the speed at which the track as a whole is traversed and the total number of observations which might be made of it at any speed, since in a sense each increment of speed merely increases the part on which more frequent observations must be made rather than requiring that this be done over the whole length of the track.

If we examine the performance of W.V.D., for instance, we find that the total number of looks increases slowly with increasing speed. But there is suprisingly little difference as the speed changes from 22 to 30 mph. Thus, it would appear that the major factor which induces a new look at the road is that of distance traversed rather than either time or speed per se. Thus, at 22 mph 74 looks were taken at the track; at 25 mph 79 looks; and at 30 mph 80 looks.

We find that our estimate of the distance traveled between observations is 83.6 ft for 30 mph, 87.7 ft for 25 mph, and 100 ft for 22 mph. Since, presumably, the information content of the roadway is invariant and the U_c of the driver is likewise invariant, the variation in distance traveled must correspond to an increase in the noise power generated by the vehicle itself. In other words, at the higher speeds, the precision of the driver's steering and aiming, as well as the residual uncertainties in the steering mechanism, become more important and require more frequent observations.

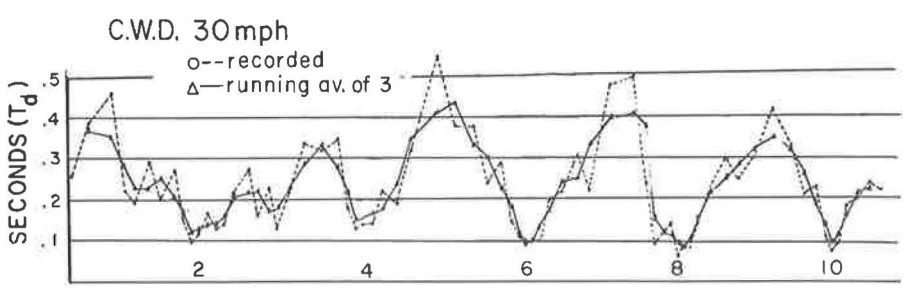

Figure 8. Interval between observations as function of position on track.

For subject C.W.D., the mean number of looks taken at the track is 69 for a speed of 30 mph, 68 for 25 mph and 67 for 22 mph. The corresponding distances traveled between observations for these same speeds are 97, 102, and 102 ft for 30, 25, and 22 mph, respectively. Thus, although there is less variation for the three speeds for this driver, the same general trend can be seen.

A factor which has not so far been considered in our discussion of Experiment 3 is the "size" of the turns or total amount of direction change. Thus, turn 2 and turn 6 involve very nearly 180 deg of direction change, turn 8 somewhat less, turn 10 still less and turn 4 less again. Turn 3 has a fairly large radius of curvature that involves a directional change of about 90 deg. Turns 5, 7, and 9 have the largest radii of curvature and involve changes of direction of only 15 deg, approximately. The more directional change there is, the more interference with vision ahead and the more demanding of attention from the driver. Thus, turn 3 has a radius of curvature approximately the same as curve 4, but involves only about half as much directional change, and it can be seen that curve 4 elicits observations from the driver in general much more often than does curve 3. Presumably, this elicitation is a result of the limitation of forward view rather than the radius of curvature per se.

Curve 10 is a special case due to the departure of the exit roadway immediately prior to its entrance. In addition, there are bridge railings which constrain, to some extent, the freedom of the driver to approach the edge of the road on the outside coming into curve 10. The remaining data for all subjects, although not presented here, have been analyzed sufficiently to show that they conform to the same general pattern.

An effort was made, on the basis of maps of the track, to determine the radius of curvature of the various curves. These were then ranked according to radius, the smallest number being the smallest radius. Similarly, the inter-observation interval utilized by the subject was also ranked, the smallest number being given to the smallest interval. In this way we were able to get an estimate of the extent to which there is agreement between the attentional demand as measured by the interval between observations and the radius of curvature of the road.

Although there is general agreement, there are factors which prevent us from arriving at a firm conclusion. First, in addition to radius of curvature and total extent of directional change which have been noted, there is also the effect of road width which controls the actual path which can be taken by a driver in negotiating a curve. A driver driving on a track attempts on each curve to negotiate the curve with a path of maximum constant radius of curvature. This path of "maximum constant radius" (MCR) minimizes the degree of control activity required and also permits the fixed speed to be most easily maintained through the curve. The line of MCR is a function both of the radius of curvature of the track itself, the width of the track, and the amount of direction change which the curve involves. Quite clearly, a circular track would have an MCR precisely equal to the radius of the outer boundary of the track. A segment of that curved road resulting in a change of perhaps 10 deg and connected by straight segments before and after will have an MCR which would be many times larger and which would be a direct function of the width of the track. Curve 10 appears to be the most demanding even though its radius of curvature shares only the second rank with curve 6. However, the constraints on the entrance to curve 10 mean that the MCR which the driver can attain is small with the consequence that the "functional radius" of this curve may in fact be smaller than the "functional radius" of any other curve. Thus, there is not a monotonic relationship between radius of curvature and attentional demand, such that the attentional demand is always less when the radius of curvature is larger, but rather the constraints on paths through the turn must also be taken into account. Of course, in dealing with highway curvature where cars are by custom or by law required to stay in lane, the curve taken by the car has a radius more nearly equal to that of the road and thus a more precise relationship could be obtained. On exit roadways from superhighways as well as on roads where visibility around curves is good due to the flatness of the terrain, there is an almost unavoidable tendency on the part of the drivers to cut curves and in this way enlarge the radius of curvature with which they negotiate the curve. This is observed, also, in open highway driving where there is little opposing traffic.

However, and this finding is more general, by comparison of the voluntary intervals between viewing on the superhighway and those obtained on the race track, it can be seen that when the average H of the road increases, the interval between observations at a given speed tends to decrease. We have, of course, only two points and we do not have any immediate estimate of where these points lie, since the fitted curves for the various drivers are best fitted by different H's. Whether H is therefore a demonstrable external physical variable or one which is a compound of psychological and physical variables is yet to be determined. The extent to which a driver is familiar with the very minor aspects of the road as well as with its statistical structure (that is, the probability of intrusion, etc.) probably modifies for him whatever basic H or uncertainty exists in the road purely because of its physical nature. Thus, the timorous, unfamiliar driver sees the same road as possessing a larger H than the man who has traversed it many times. Presumably, this would be one source of the variation in the value of the fitted parameter H of the various subjects in Experiment 1. More detailed examination of the visual stimuli present at various points along the track as well as those which exist along the highway is needed.

Experiment 4—Bryar Motorsport Park: Fixed Viewing and Occlusion Times, Voluntary Control of Vehicle Speed

The fourth experiment dealt with the problem of constant viewing time T_ℓ and with the constant occlusion time T_d while the driver retains control of the vehicle speed. The experiment is thus identical with Experiment 1 but done at Bryar Motorsport Park. The operating procedure was identical with that described in Experiment 3. After familiarization runs the experimenter in the left rear seat initiated a run by setting a particular T_d, with a fixed T_ℓ of 0.5 sec, and started the apparatus. The driver then circled the track driving as rapidly as possible and varying his speed from point-to-point along the track. Errors were not permitted; that is to say, the driver could not leave the road or cross the white line at the edge for any reason. If he did so, the run was terminated and another run begun. At the conclusion of three satisfactory runs the visor was opened by the experimenter at the finish line and the driver would rest briefly before initiating runs with a new T_d.

Thirty-five trials were made at T_d's of 0.5, 1.0, 1.5, 2.0, and 3.0 sec, by subjects D.H.K., C.W.D., and W.V.D. Each trial consisted of a number of runs as previously described. Each lap produced a record which was analyzed separately. Our interest, of course, was in finding a functional relationship between the speed adopted by the driver and the radius of curvature of the track for each given T_d. Since no other vehicles were permitted on the track and there had been a sufficiently long

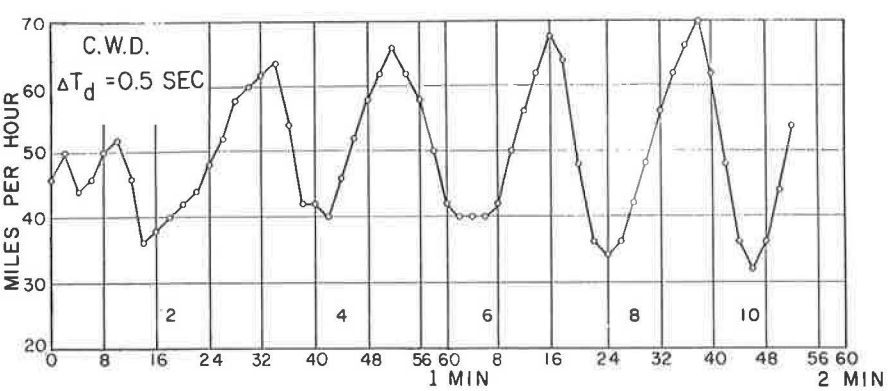

Figure 9. Speed attained as function of position on track.

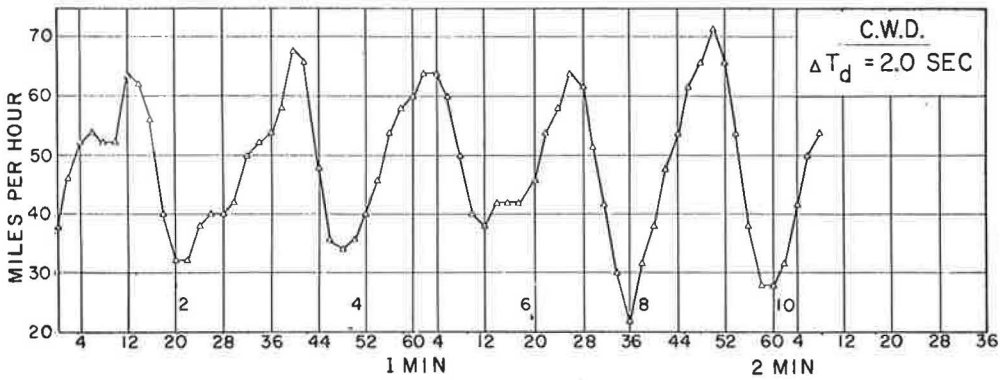

Figure 10. Speed attained as function of position on track.

period of familiarization, the only residual uncertainty would be that associated with steering on the curves and maintaining the vehicle within the lane. In addition, the available view ahead was a function of the radius and of the total directional change of each curve as indicated in the discussion of Experiment 3.

The data were obtained in the form of strip chart recordings of speed. The general form of the functions is similar to that for the constant velocity and voluntary control of visor time. In other words, if the driver is faced with a greater attentional demand at a constant speed he must look more often and similarly, if his information intake is limited, he varies his speed accordingly. The data for one subject, C.W.D., for T_d of 0.5 and 2.0, are shown in Figures 9 and 10. There is a consistent reduction of speed on the curves with increasing T_d. It must also be noted that the increased H of the track produced speed-limited runs even with occlusion times as short as 0.5 sec. It would have been possible for the vehicle to accelerate to higher speeds than those which were in fact reached, as was evidenced by the performance of the same driver with the same vehicle with no occlusion, striving for maximum circuit speed of the track.

The increased H of the track as compared with the Interstate highway resulted both from the curvature and from the limitation of the viewing distance ahead, and markedly reduced the speeds which the driver could attain with occlusion times in the region from 1 to 3 sec. It is difficult to identify on the speed records the odd numbered curves, since the reduction in speed for these was very small, if present at all. However, as is evident from Figures 9 and 10, the salient features of the record are those corresponding to the even numbered curves and it is in these turns that a reduction in speed with increasing T_d is most evident. The records for the other subjects show the same general trend. In order fully to understand the relationships which are implicit in these data it will be necessary to obtain the same information about maximum constant radius as is required to deal with the data for Experiment 3. As a result, a full analysis and interpretation of the results of this experiment must await the availability of these additional data.

GENERAL DISCUSSION AND RECOMMENDATIONS

The general purpose of the experiments was to determine empirically certain relationships between characteristics of the road upon which a car is driven, the amount of time a driver has to look at the road, the interval between such observations, and the speed at which he drives. Experiments 1, 2, 3, and 4 attempted to do so for two different classes of roads and for two different modes of operation of the experimental apparatus. The results indicate, as would be expected, that the less frequent the observations, or the shorter the period of observation, the slower will be the speed that

the driver can maintain, and, conversely, that the greater the level at which the speed is fixed the more often the driver must look at the road. In addition, the difference between the roads appears as a modifier in that the more complicated road results in a lower speed at any constant viewing and occlusion times, and results in shorter occlusion times for any constant speed and viewing time. The data with which to express the functional relationships among all of these variables have been obtained and subjected to partial analysis.

Another part of the program was aimed at testing the adequacy of a theoretical model which described the behavior of the driver in terms of information processing and uncertainty accumulation. The data for Experiments 1 and 2 provide an opportunity to verify the adequacy of the model. Figures 4 and 5 show the extent to which the model fits the observed data. Table 4 gives the parameters of the model for the various subjects for the data for Experiment 1. Because of time and cost limitations, no effort was made at this time to apply the model to the data of Experiment 2. Instead, a simple comparison of the latter data has been made with those of Experiment 1 to show that with voluntary control of occlusion by the subject the times which he generates himself are somewhat shorter for any given speed than those which permitted that same speed in Experiment 1. Experiments 2 and 3, both of which permitted voluntary control of occlusion time by the driver, suggest by their results that this technique is a useful one for measuring the attentional demand of a driving situation. Figures 7 and 8 show quite clearly that for various constant speeds, the driver must look more frequently as he enters and passes through the various curves on the track, and that this increased frequency of observation is not independent of the nature of the curve itself. Thus, we believe that this technique will allow an objective measure, based on driver behavior, of the attentional demand of any segment of a road.

Data about the view ahead must be obtained by field measurements both on I-495 and at Bryar Motorsport Park and the curve of maximum constant radius must be calculated for the various turns. When this has been done, it should be possible to establish the parameter H for the various parts of the track, and to calculate more precisely the driver uncertainties, distance constants, and forgetting time constants which will be needed to provide a crucial test of the ability of the model to predict the behavior of a driver on some new road.

If the model can make such predictions, then the identification of these parameters D, F, and U_C might permit a preliminary classification of drivers in terms of skill level. This, in turn, suggests a means of identifying those drivers who may be potentially "accident prone." The use of trained drivers as measuring instruments, using the voluntary occlusion technique, may facilitate the identification and quantification of hazardous or excessively demanding road configurations or vehicle characteristics.

ACKNOWLEDGMENT

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Discussion

J. W. McDONALD, Director, Engineering and Technical Services, Automobile Club of Southern California—The authors of this work have set for themselves a very important goal—the definition of a measure they call "attentional demand"—which has potential application to all three basic elements of highway safety, the road, the vehicle, and the driver. Various measures have been developed in efforts to determine the quality of a highway, the driveability of an automobile, and the competence of drivers. However, this is the first measure of which I am aware that has application to all three.

Applications, incidentally, are of particular interest to those of us who are in contact with drivers and with the people who design highways and automobiles. The basic notion proposed by the authors has an easily understood, logical appeal which comes through clearly because of the careful, thorough explanation presented. In addition, there are good illustrations of how the notion applies in various circumstances with which others can identify.

Two additional applications occur to me which may not be wholly distinct from those suggested by the authors but which are worth mentioning. The first of these would have to do with the efforts of traffic engineers to measure "level of service" of a highway. Time is the basic measure of service level, but perhaps "attentional demand" could provide a supplemental, qualitative measure. The second possible application would relate to more effective use of highway signs and warning devices. I am intrigued with the discussion in the report of the H factor—the "information density" of a highway. This offers a new perspective regarding warning signs and devices, and possibly a better approach to their effective use when the true H value of a highway is not apparent to the driver. As a simple illustration, a warning sign at a blind intersection should serve to alert the driver and provide the higher H value which reveals the true character of that section of highway. A dangerous situation is created, of course, when the true H value of a roadway is not apparent.

Also of interest is the discussion of curvature of a highway and its relationship to attentional demand. This has application and pertinence to discussions of scenic highway design—a popular subject at the moment. If the driver is to participate at all in the enjoyment of a scenic highway, the attentional demand cannot be all-consuming. A fine example exists today on the new interstate highway over Donner Pass in California and a comparison of this with the old road, US 40. Some argue that the old road was more scenic than the new, but certainly from the standpoint of the driver, the new road is by far superior from all standpoints, including the scenic. I know in my own experience I never felt that there was anything too scenic about the rear-end of a large truck.

Concerning limitations of the method, it would seem that in an effort to use this measure for determining proficiency or competency of drivers, there would be a varying influence of the apparatus on the normal behavior of different drivers. Some would probably take it in stride, whereas others would be badly distracted. Another limitation would occur in trying to pursue this technique in actual traffic circumstances. Such an extension of the research would seem desirable, but perhaps a little risky. Possibly dual controls could be used here, or a full-scale driver-vehicle-roadway system with controlled traffic as is contemplated at Ohio's Transportation Research Center.

Driver Characteristics at Intersections

MATHEW J. BETZ, Associate Professor, and RICHARD D. BAUMAN, Instructor, Civil Engineering Department, Arizona State University

Headways and gap acceptance characteristics of drivers at signalized intersections in the Phoenix metropolitan area were analyzed using time-lapse photographic techniques. Simultaneous operation of two cameras allowed for the recording of the particular movement involved and for the recording of license plates.

Out-of-state vehicles have headways significantly longer than in-state vehicles when the vehicles in question are at the beginning or near the end of the queue. When the out-of-state vehicles are located in the center of the queue, their headways approach those of the in-state registrants. For left turning vehicles, there is no significant difference between the gap acceptance characteristics of in-state or out-of-state vehicles. Vehicles registered in the states which do not have the "right turn on red" law make little use thereof. All categories of drivers had similar gap acceptance characteristics when they did make use of the law. A sign indicating the legality of the movement increased its usage by all categories of drivers.

•THERE is a widespread agreement among traffic engineers working in Arizona concerning the fact that out-of-state drivers display different driving characteristics from in-state drivers. If the driving characteristics of the two groups are different, then signs and signals along streets carrying high concentrations of tourist traffic should be designed to compensate for the unusual characteristics of this group. Because of the importance of tourism to the economy of Arizona and the influence of out-of-state tourist traffic on the capacity and safety of Arizona streets and highways, if was felt that this problem should be investigated.

STATEMENT OF THE PROBLEM

The number of waiting vehicles that can cross a signalized intersection in a given period of time depends basically on how soon the vehicles begin to move after the signal changes to green and how fast each individual vehicle in the queue reacts to the acceleration of the vehicle immediately ahead. This process continues until all cars in the queue are progressing or have progressed through the intersection. The dissipation of a queue of vehicles after the signal changes to green depends on the reaction time and acceleration characteristics of each individual driver and vehicle. Thus, the total time for a group of vehicles to pass through a signalized intersection can vary considerably depending on the alertness and aggressiveness of the individual drivers, their familiarity with the intersection in question, and the acceleration characteristics of the vehicles which the drivers control.

The fact is accepted that all drivers, when exposed to the same situation, have different reaction times. That different drivers when placed behind the wheel of identical cars will accelerate from a standing start at different rates is also accepted. These characteristics inject a certain expected variability into any field data collected concerning vehicle performance at intersections.

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Following similar reasoning, it could be possible that drivers unfamiliar with an area might display different reaction and acceleration characteristics from local drivers. One specific group of drivers who would be unfamiliar with an area and would probably display different driving characteristics are tourists. Also, the fact that they are on vacation may well influence their aggressiveness.

From November to April each year, Arizona experiences a major influx of tourists. Although many tourists arrive in Phoenix by plane or train, predominantly they arrive by car or have use of a car while in the area.

In addition to the problems which out-of-state drivers encounter due to their unfamiliarity with the local street and highway system, Arizona has a law concerning the right turn on a red light which is not in conformance with the standards as set forth in the "Manual on Uniform Traffic Control Devices" (1). The Manual states: "Permitting vehicle operators to make right or left turns during the showing of the red signal without a modifying arrow or sign is not recommended." The Motor Vehicle Laws of Arizona (2) state the following: "The driver of a vehicle which is stopped as close as practicable at the entrance to the crosswalk on the near side of the intersection, or, if there is no crosswalk, then at the entrance to the intersection, in obedience to a red or "stop" signal, may make a right turn, but shall yield the right-of-way to pedestrians and other traffic proceeding as directed by the signal."

The purposes of this investigation were threefold: (a) to determine and compare headway characteristics of in-state and out-of-state vehicles at signalized intersections; (b) to determine the "right turn on red" characteristics of in-state and out-of-state drivers; and (c) to determine the gap acceptance characteristics of in-state and out-of-state drivers turning left.

PREVIOUS RESEARCH

A thorough analysis of literature related to the problem was accomplished. Reports concerning vehicle headways and gaps and turning characteristics were analyzed, and pertinent information is summarized in this section.

Acceleration Characteristics

The simplest method of determining intersection characteristics involves a determination of vehicle headways. The Highway Capacity Manual (3) defines headway as "The interval of time between individual vehicles moving in the same lane measured from head to head as they pass a given point." This definition was adhered to in this report.

Considerable research has been conducted concerning the characteristics of vehicular flow at signalized intersections. Apparently Greenshields (4) in 1947 was the first to investigate comprehensively all aspects of traffic performance at urban street intersections. Since 1947, many others (5, 6, 7) have performed similar investigations.

In order to determine acceleration characteristics of vehicles at signalized intersections, Greenshields studied the following factors of individual behavior: (a) the time required for vehicles to commence motion; (b) distances reached by vehicles in given time intervals after starting, which are dependent on average accelerations between points; and (c) spacing between vehicles. The time required for a vehicle to commence motion is determined by the reaction time of the driver. Greenshields considered two types of reaction times: first, reaction time of the first vehicle related to the signal change, and second, the reaction time between the movements of successive vehicles. Starting reaction time is defined as the interval between the signal change to green and the movement of the first waiting vehicle. It was found that this time varied from 0.6 to 2.9 sec. Reaction time between successive vehicles is defined as the time elapsed between starting movements of two successive vehicles in line. This time seems to vary from 1.0 to 1.75 sec (4).

The three primary factors which affect vehicle performance in a queue are position of stop, reaction time, and time-distance performance. Reaction time, as discussed previously, depends on the characteristics of individual drivers. The exact position of

stop depends on pavement markings. The time-distance performance of each individual vehicle is not as easily analyzed. However, the distances reached in given times are of great significance to the traffic engineer because they form the basis for timing signals and for determining street capacities.

Generally, most investigators have found that headways between successive vehicles decrease at a lessening rate as one progresses through the queue. As speeds increase, time-spacing between vehicles decreases until the fifth-in-line vehicle has entered the intersection. After the fifth vehicle, headways tend to level out at approximately 2.0 sec (4, 8).

The results of a study conducted by Wildermuth (7) indicate that the length of the green phase does have a substantial effect on average headways; with a 10-sec green phase, the average headway was 2.35 sec, and with a 35- to 45-sec green phase, 2.00-sec headways were obtained. Large vehicles and turning traffic both tend to reduce the capacity of signalized intersections because they have greater headways. This conforms to the results of other investigators. As the green phase of an intersection increases, the effect of the initial starting characteristic of the queue is decreased and the vehicles far back in the queue have a greater effect on the average headway. Therefore, for long phases, average headway will be less than for shorter phases.

The preceding information formed a foundation upon which the analysis in this report is based. However, after a thorough search of the literature, no information was found which analyzed headway characteristics of different groups of drivers. Information abounds concerning all vehicles as a single group and the average headway characteristics of the individual vehicles within this group. It is unfortunate that so little has been determined concerning headway characteristics of specific groups of drivers and the relationships of these characteristics of overall headway characteristics.

Acceptable Right Turn Gaps

Because of the limited use of the "right turn on red" law, apparently no research has been accomplished concerning the gap acceptance of vehicles turning right on red. Considerable research has been conducted concerning gap acceptance at stop-signed intersections.

The term gap as used in this report is defined as the time interval between the arrival at a point by one vehicle and the arrival at the same point by the next succeeding vehicle traveling in the same direction. Gaps were measured from the rear of the first vehicle to the front of the succeeding vehicle. The vehicles' lengths were not included in the measurements.

The definition of gap as used in this report differs from the definition used by Solberg and Oppenlander (9), Bissell (10), and Greenshields (4). Their gap measurement conformed to the definition of headway as given previously in this report. Solberg found in his research that the median acceptance time for right turns was 7.30 sec. In his field investigation Bissell obtained median lag and gap acceptance times of 5.25 sec.

Greenshields defines the average minimum acceptable gap as that value which is accepted by 50 percent of the drivers. At a stop-sign intersection, the minimum acceptable time gap for right turning movements was found to be about 6.1 sec. It should be noted that Solberg did his research in Indiana, Bissell in California and Virginia, and Greenshields in Connecticut. Perhaps different areas of the country contain drivers who will take more chances (by accepting a smaller gap) than drivers from other parts of the country.

"Right Turn on Red"

Published data concerning right turn on red as related to successful use of the law were reviewed. Rankin (11) sent a questionnaire regarding the use of the right turn law to 20 cities with populations from 100,000 to 500,000. Of the 18 cities which replied, 11 allowed right turns on red with an arrow, 2 allowed right turns on red if signed, 3 allowed right turns on red with no sign, and 2 did not allow right turns on red. Both cities which did not allow right turns on red indicated that they had in the past but had eliminated the law because of numerous accidents. Of the 11 cities which allowed right turns

on red with an arrow, six indicated that they restricted the practice to special locations at outlying intersections which had low pedestrian volumes and ample lanes to allow merging movements. Unfortunately the responding cities were not grouped into geographical classification as to states allowing or not allowing the right turn on red.

A paper concerning the right turn on red problem where answering cities were segregated as to geographical location was written by Ray (12). A questionnaire regarding accidents and delays as related to right turning movements at signalized intersections was sent to 57 cities; 45 cities in 25 states replied. In responding to the question, "Have accidents resulting from right turns on red been a significant part of total accidents at intersections?" 4 cities indicated that they had experienced an accident problem. Three of these permitted such a turn only when a green-arrow indication appeared.

None of the 13 California cities contacted reported any problem. This is significant because the right turn on red law prevails in California as it does in Arizona. In connection with the California analysis, Ray attributed the apparent success of the turn law to the following factors: (a) traffic in California must stop on a red light before turning right; (b) traffic does not need to stop on a red light before turning right with a green-arrow indication; and (c) motorists in California must observe pedestrian right-of-way at all times. These factors apply equally well to Arizona traffic.

As a continuation of the analysis, Ray studied travel time and delay at specific intersections in California. The study was controlled so that the only factor affecting travel time was the manner in which right turns were made. It was determined that during off-peak periods travel time was reduced 7 percent by making use of the right turn on red law. During off-peak periods delay at each right turn signal was reduced 68 percent. During peak periods delay was reduced 38 percent.

Ray found that the right turn on red law does not add any hazard at signalized intersections. He concluded that the use of the law presents an opportunity to decrease delay and increase capacity at all signalized intersections.

Acceptable Left Turn Gaps

The subject of delay of left turning vehicles and left turn channelization has been studied at length. However, reference was found in the literature to only one study concerning left turn gap acceptability. This report by Kaiser (13) investigated opposed left turn crossings at an urban intersection. He found that delayed left turning drivers refused all gaps less than 3.75 sec and accepted all gaps of 4.75 or greater. The median value was 4.25 sec.

SURVEY ON RIGHT TURN ON RED LAW

A wide diversity of opinion exists concerning the use of a right turn on a red signal indication. Traffic engineers in many parts of the country feel that a turning movement of this type will decrease the capacity of an intersection and endanger the lives of pedestrians in the crosswalks. However, other traffic engineers feel that intersection capacity is increased and pedestrian lives are not jeopardized through the judicious use of the right turn on red law.

Classification of Drivers

In order to analyze the use of the right turn on red law in Arizona, three groups of drivers were established. Group 1 contained all drivers of vehicles registered in Arizona. Group 2 contained all drivers of vehicles registered in other states which have a similar law concerning right turn on red. Group 3 contained drivers of all vehicles registered in states which do not have a similar turn law. Presumably drivers in Group 1 would be aware of the law and act accordingly at all times. Since in the "before" section of the study none of the intersections studied were signed to explain the legality of the movement, considerable uncertainty existed concerning the turning characteristics of drivers in Group 2 and Group 3.

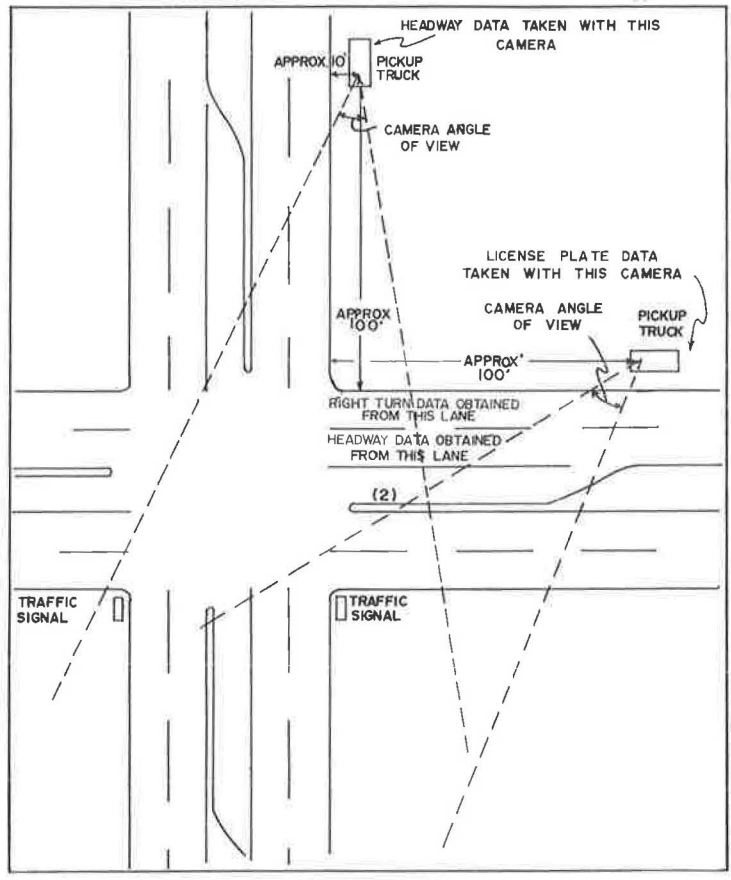

Figure 1. Typical camera location, headways and right turn gaps.

Questionnaire

To determine the legality of the right turn on red law in other states, a questionnaire was sent to the traffic engineer of each highway department in each of the 48 contiguous states. Prevailing opinions concerning the use of the law and the existing legality of the law were received from engineers in 44 states. Connecticut, New York, Tennessee, and West Virginia did not respond to the questionnaire. Of the states which answered the letter, 6 indicated that the right turn on red was allowable by state law. The states where the turn is legal are Arizona, California, Nevada, Oregon, Utah, and Washington. Alabama and South Dakota indicated that the law could be legally adopted by any municipality desiring to do so.

Figure 2. Driver's view of equipment installation.

There is general disagreement concerning the use of the right turn on red law. Basically, areas of the country where the law had never been used were strongly opposed to the concept, while states in which the turn law was legal were strongly in favor of the practice. Also, it was observed that engineers in all states where the turning movement in question was a legal

Figure 3. Location of equipment in truck.

maneuver felt that intersection capacity was improved and no specific hazards to pedestrians were caused by the use of the law. No record was found of a state which had legalized the right turn on red and then revoked the law.

Gap Acceptance

The fact that intersection capacity is either increased or decreased through the use of the law is obviously in question. One method of determining the actual effect of right turns at an intersection involves a study of gap acceptance. If the mean gap accepted is only 2 or 3 sec and through traffic is moving through the intersection at more than 25 mph, turning cars will force through traffic to slow down and thus the capacity of the intersection will be decreased and the accident potential will be increased. However, if the mean gap accepted is 6 sec or more, turning cars will not force through traffic to slow down and the capacity of the intersection will be increased with no increase in the vehicle accident potential.

EQUIPMENT AND PROCEDURES

To provide a permanent study record, and to facilitate desired exactness of measurement, time-lapse photography was selected as the most appropriate means of recording gaps and headways.

Equipment

Two 16-mm Bell & Howell movie cameras, Model 70-Dr, driven by electric motors, were used to film the traffic. The drive unit connected to the camera mounted on a tripod was geared for speeds of either 60 or 100 frames per min. For this analysis the 100-frames/min speed was used throughout. A 12-volt battery working through an inverter powered the electric motorized drive unit which operated the camera; thus the entire assembly was portable and self-contained.

The camera which was used to collect headway and gap data was equipped with a 10-mm wide-angle lens. This camera operated at a shutter speed of $^1/_{50}$ sec. The camera used to collect license-plate data was equipped with a 50-mm telephoto lens. This camera operated at a shutter speed of $^1/_{100}$ sec.

Upon receipt of all components, a test location was filmed and drive speed was checked. Variation was found to range from -1.7 to +3.0 percent. The drive speed was checked periodically during filming and was found to be consistently within this range.

Figure 4. Camera view of intersection.

Camera Location for Collection of Headway and Right Turn Data

At each intersection, the camera tripod was mounted in the bed of a pickup truck which was parked from 80 to 125 ft from the corner. The camera in the truck was positioned 10 ft above the ground and offset 8 to 12 ft from the oncoming (outside) traffic lane. The focal axis was perpendicular to the traffic lanes in which headway

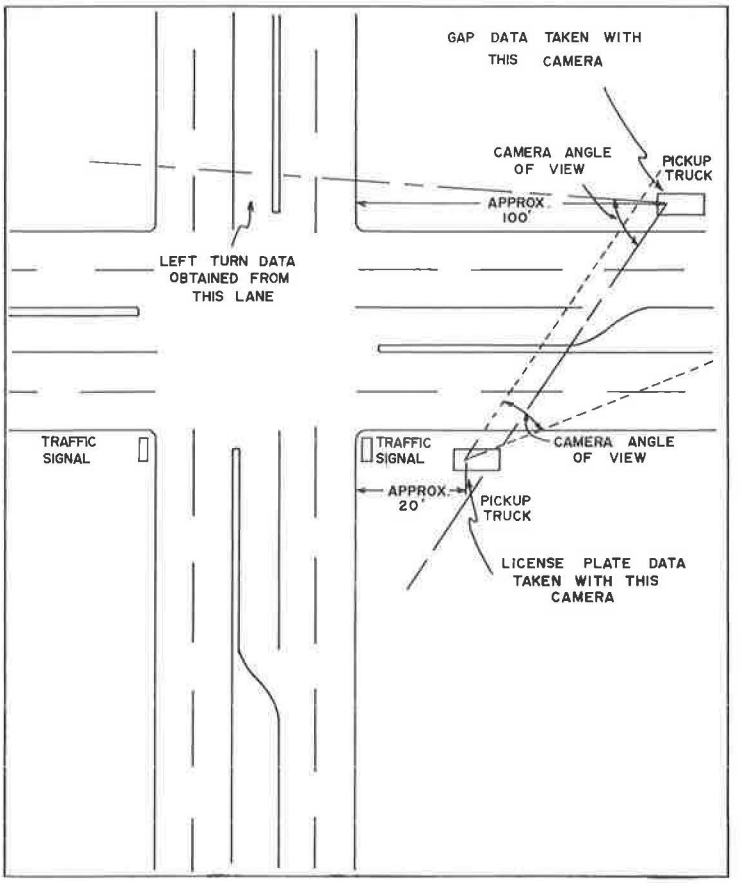

Figure 5. Typical camera location, left turn gaps.

and right turn gap data were being collected. The field of vision necessarily encompassed at least one traffic signal head to establish the initiation of the green phase. In all cases, the initiation of green on the street under analysis coincided with the initiation of red on the cross street.

The camera used to obtain license-plate data was placed approximately 100 ft in advance of the approach. The focal axis was oriented nearly parallel to the approach lanes and toward the intersection. Thus, rear license plates were photographed as vehicles entered the queue. This system was adopted after several other possibilities were tried.

Figure 1 is a sketch of an intersection and the locations of the pickup trucks containing the cameras. Camera orientation with respect to the lanes of traffic under analysis may be observed. Figure 2 shows a driver's view of part of the equipment installation. This photo was taken from the point marked (2) on the intersection sketch (Fig. 1). The unobtrusive nature of the equipment in the background of the photo should be noted. Figure 3 shows the location of the camera equipment in the bed of the truck. Use of the stepladder shown in the photo was necessary when determining the field of view prior to filming. Figure 4 shows the view of the intersection as seen through the camera with which the headway data were collected.

Camera Location for Collection of Left Turn Data

The camera used to collect the gap data was located in a manner similar to the location used to obtain headway data. However, the camera used to obtain license-plate

TABLE 1

SUMMARY OF INTERSECTION CHARACTERISTICS

City	Major Street	Posted Speed Limit (mph)	ADT	Minor Street	Posted Speed Limit (mph)	ADT
Scottsdale	Scottsdale Rd.	35	20, 280	McDowell Rd.	35	20, 560
Tempe	Apache Blvd.	35	23, 531	Rural Rd.	35	6, 670
Phoenix	Van Buren St.	35	18, 900	32nd St.	35	10, 350
Scottsdale	Scottsdale Rd.	25	19, 700	2nd St.	25	1, 830
Phoenix	McDowell Rd.	35	20, 730	Central Ave.	35	25, 750
Phoenix	Indian School Rd.	40	16, 125	44th St.	35	14, 460

Note: Major street = street on which headways were measured.
Minor street = street on which gaps were measured.
Grades at all intersections were level or nearly level.
Adequate sight distance existed at all intersections.
Commercial development at all intersections was extensive.

information was positioned so that the left turning vehicle passed through the field of view of the camera immediately after the turning maneuver was completed. This was done to obtain photographs of the rear license plate of each vehicle.

Figure 5 shows the locations of the pickup trucks containing the cameras. It is important to position the camera which photographs the rear license plates of the turning vehicles close to the intersection corner. Once the vehicles accelerate to 25 mph or more, it becomes extremely difficult to read the plate from the film.

Analysis Procedure

Data were collected on weekdays. All data were collected on color film. Two observers, upon commencement of filming, noted the color of the leading car in each queue and the length of the queue.

A daylight rear projection screen with an acetate cover was used to view the developed film containing the headway and gap information. Headways were measured with reference to an extension of the curb line which was nearest and parallel to the stop line. Gaps were measured at the merge point of turning traffic on the cross street. All reference lines and measurement points were drawn on the acetate cover.

The film containing the license-plate information was viewed on a screen adjacent to the rear projection screen. Both films were viewed concurrently. One technician read the license plate of the vehicle and thus classified the origin of the vehicle while at the same time the other technician measured the headway or gap of the same vehicle.

A frame counter on the projector was used to obtain the time increment of each measurement. Occurrences were estimated to the nearest quarter frame (0. 15 sec).

Intersections Studied

A total of seven intersections were studied. In all but one case, one approach was filmed for analysis at each site. At Scottsdale Road and McDowell Road two approaches (north and west) were analyzed. All intersections were normal at-grade designs with right-angle crossings. All locations were signal-controlled. Some used fixed time and others had actuated equipment. The general characteristics of the intersections are contained in Table 1.

Statistical Procedures

Statistical tests were utilized to determine whether there were significant differences between vehicle time headways at different intersections and also to determine relationships between headways of in-state and out-of-state vehicles. It was determined that in order to detect a headway time difference of 0. 3 sec with 95 percent confidence, a sample size of at least 37 was required.

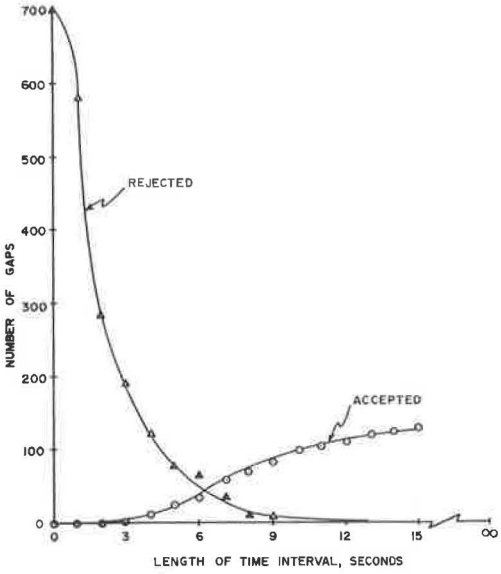

Figure 6. Distribution of accepted and rejected gaps for left turning movements, Arizona vehicles, total number.

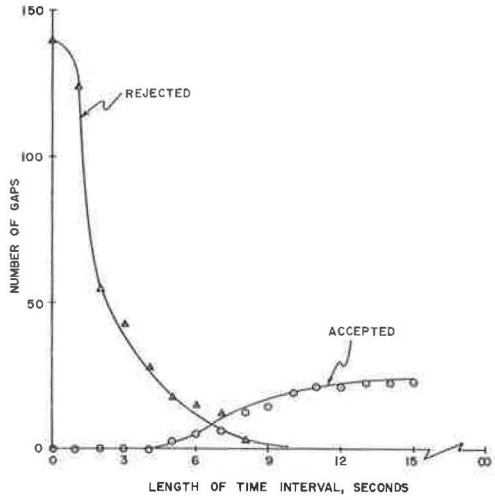

Figure 7. Distribution of accepted and rejected gaps for left turning movements, out-of-state vehicles, total number.

When testing whether there was a difference between in-state and out-of-state headways, it was assumed that the data had a normal distribution. This assumption was made only after several plots of the data were drawn and found to reasonably approximate the normal curve.

Various statistical tests were then utilized to study the difference in the headway data. The Student's "t" distribution was used to determine the existence of significant differences between in-state and out-of-state headway data at a particular intersection. Cochran's test was used to study the homogeneity of variances of data from several intersections. A test devised by Hicks (14) was used to determine if there was a significant difference in the data collected from several intersections.

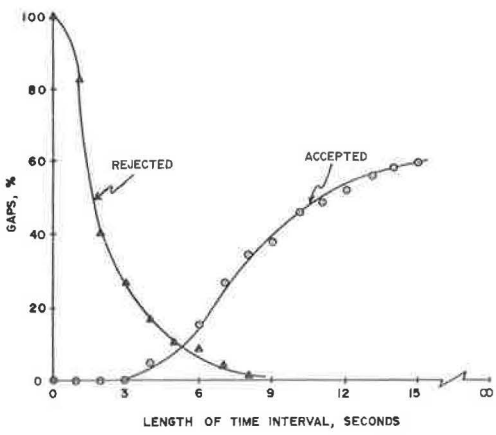

Figure 8. Distribution of accepted and rejected gaps for left turning movements, Arizona vehicles, percent.

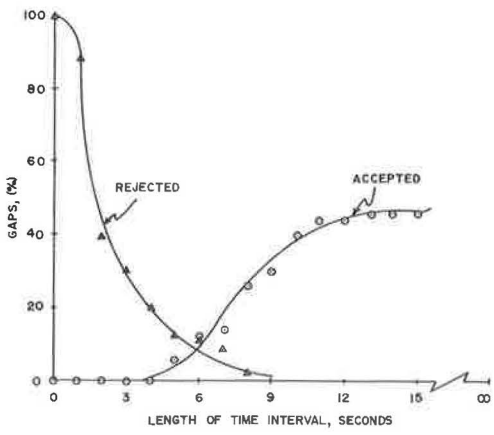

Figure 9. Distribution of accepted and rejected gaps for left turning movements, out-of-state vehicles, percent.

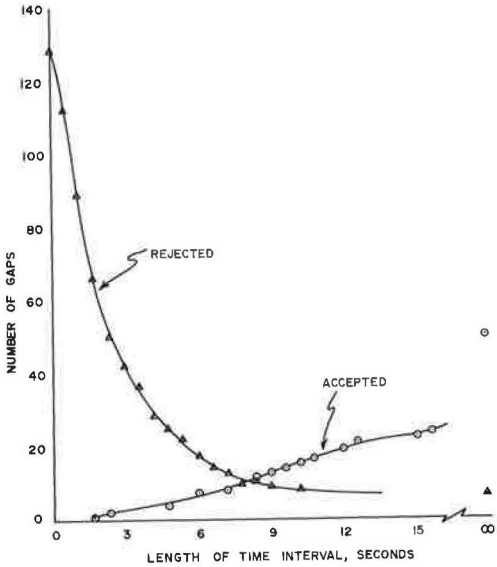

Figure 10. Distribution of accepted and rejected gaps at all intersections, total number of right turns.

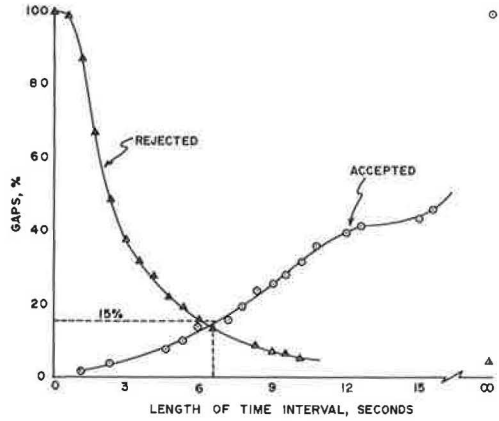

Figure 11. Distribution of accepted and rejected gaps at all intersections, percent of right turns.

TURNING CHARACTERISTIC RESULTS

The results of the field measurements concerning left and right turn gap acceptance and acceptance of the right turn on red law follow. All data pertain only to passenger vehicles and light pickup trucks.

Gap Acceptance of Vehicles Turning Left

Left turn gap data from the westbound approach on McDowell turning south on Scottsdale Road and from the southbound approach on Scottsdale Road turning east on McDowell were collected and combined. The left turning movements of 260 passenger vehicles and light trucks were obtained. Twenty-one percent of the vehicles were from out of state.

A complete description of the actual number of in-state vehicles turning left and the gap acceptance characteristics of the vehicles are shown in Figure 6. Figure 7 presents the same data for out-of-state vehicles. Figures 8 and 9 show the data with the number of vehicles expressed as a percentage.

It can be seen that the point of intersection of the acceptance and rejection curves in Figures 8 and 9 is approximately 5.5 sec. This point indicates a gap time which has an equal chance of acceptance or rejection by the average driver. Tests indicate that there is no significant difference between the gap acceptance characteristics of in-state and out-of-state drivers.

It may be possible to adopt a corollary to the 85th percentile rule as applied to speed limit determination for gap acceptance analysis. It appears that from 10 to 15 percent of the drivers will accept a gap which is so small that through traffic is impeded. Field observations indicate that for speed limits of 35 to 40 mph a 6-sec gap is the minimum gap which can be safely accepted without impeding through traffic or requiring excessive acceleration on the part of the turning vehicle. Figure 9 indicates that the gap which 15 percent of the drivers will accept is 6 sec.

Gap Acceptance of Vehicles Turning Right

It was determined that the gap data from different intersections could be combined. Consequently, all gap data presented represent a combination of data obtained from the

TABLE 2

RIGHT TURN GAP ACCEPTANCE AND REJECTION CHARACTERISTICS BY STATE REGISTRATION GROUP

Characteristic	Registration of Vehicle		
	Arizona	Other States With RTOR	Other States
(a) Number of Vehicles			
Accepted a gap	50	2	6
Rejected all gaps	24	4	10
Rejected all gaps but had at least one gap >6 sec	11	2	9
Total vehicles	74	6	16
(b) Percent of Vehicles			
Accepted a gap	67	33	37
Rejected all gaps	33	67	62
Rejected all gaps but had at least one gap >6 sec (% in terms of total rejections)	46	50	90

following intersections: Scottsdale Road and McDowell Road westbound; Apache Boulevard and Rural Road westbound; 32nd Street and Van Buren Street westbound; and Indian School Road and 44th Street eastbound.

The sample population in the film analysis contained 3,606 vehicles, 403 of which turned right. Of these 403 turning vehicles, 58 accepted a gap and turned right on red. Approximately 28 percent of the turning vehicles showed out-of-state registration. All data represent a combination of both in-state and out-of-state gap acceptance. Since it was proved in the left turn study that vehicle origin had no effect on gap acceptance, it was assumed that if a driver was aware of the law, the actual gap accepted would not depend on the driver's home state. Figure 10 shows the data in terms of total number of accepted and rejected gaps and Figure 11 shows percent of accepted and rejected gaps.

The fact that the time gap acceptable by an individual driver depends to a certain extent on the lane position of the cars in the through lanes is acknowledged. For example, when the gap occurs between a car in the right lane and a car in the left lane, a driver will accept a slightly smaller gap than when the gap occurs between a car in the left lane and a car in the right lane. However, there is no way to predict the distribution of cars in the through lanes. Therefore, determining different acceptable gaps for different positions of cars in the through lanes would introduce unnecessary complexity into the analysis.

Figure 11 shows that the point of intersection of the acceptance and rejection curves is 6.6 sec. This point of intersection indicates a time, in this case 6.6 sec, which represents a gap that would have an equal chance of acceptance or rejection by the average driver. Because of the compatibility of the left turn and right turn gap analysis, a 6-sec gap will be considered to be the minimum acceptable time gap. The results are given in Table 2 where turning characteristics in terms of total numbers observed and in terms of percent observed are listed. One section of the table notes the number and percent of vehicles that rejected all gaps but had at least one gap greater than 6 sec. Although the sample size is small, the data indicate that drivers from states without right turn on red laws react differently. This difference is obvious since 90 percent of those out-of-state drivers rejecting all gaps had a gap of greater than 6 sec, whereas only 50 percent of other drivers rejected these longer gaps. This may indicate that a significant proportion of drivers are unaware of the law. The fact that data on only 96 vehicles were obtained where the population size (vehicles in right lane) was over 3,600 indicates the data collection problem involved with obtaining this type of information.

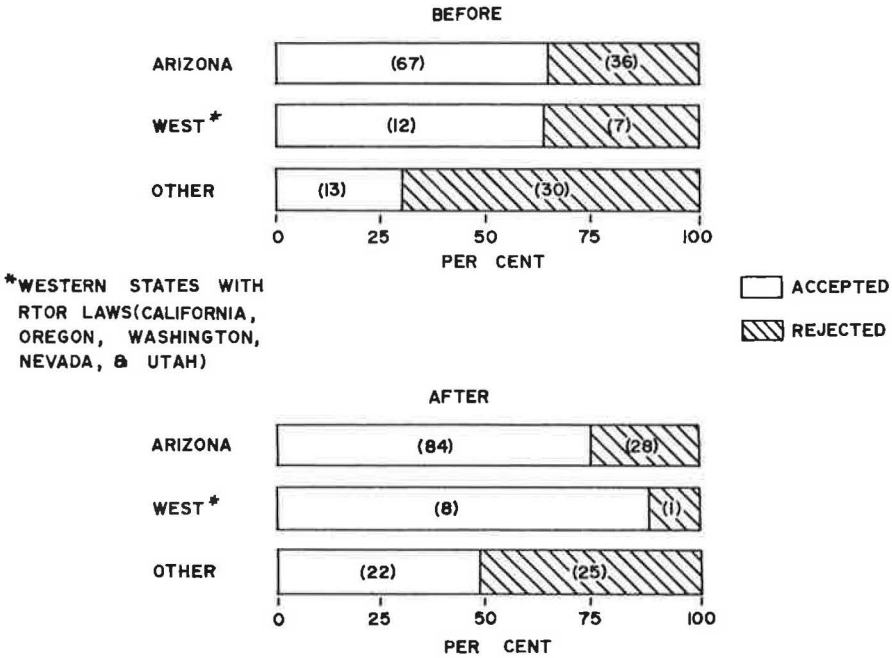

Figure 12. Right turn on red opportunities.

TABLE 3

RIGHT TURN CHARACTERISTICS AT SCOTTSDALE ROAD AND 5TH AVENUE

Characteristic	Registration of Vehicle		
	Arizona	Other States With RTOR	Other States
Before			
Total traffic			
Number	5218	1572	
Percent	76.8	23.2	
Total right turns			
Number	725	71	211
Percent	72.0	7.0	21.0
Right turns on red			
Number	67	12	13
Percent of right turns	9.2	16.9	6.2
After			
Total traffic			
Number	5011	1684	
Percent	74.9	25.1	
Total right turns			
Number	685	51	267
Percent	68.3	5.1	26.6
Right turns on red			
Number	84	8	22
Percent of right turns	12.3	15.7	8.2

TABLE 4

VEHICLE CLASSIFICATION BY REGISTRATION FOR THROUGH-LANE HEADWAY MEASUREMENTS, INITIAL PERIOD

Location	Total In-State Vehicles	Total Out-of-State Vehicles	In-State %	Out-of-State %
Scottsdale Rd. and McDowell Rd. southbound	310	90	77.5	22.5
Scottsdale Rd. and McDowell Rd. westbound	345	45	88.5	11.5
Apache Blvd. and Rural Rd. westbound	225	80	73.8	26.2
Van Buren St. and 32nd St. westbound	324	107	75.2	24.8
Scottsdale Rd. and 2nd St. northbound	321	95	77.2	22.8

Acceptance of the Right Turn on Red Law

In order to further study gap acceptance characteristics, a T intersection in Scottsdale was observed. At this intersection there was no cross traffic; therefore, motorists desiring to turn right were not faced with the choice of accepting a suitable gap in order to accomplish the right turn.

Because the right turn gap acceptance characteristics study indicated poor utilization of the right turn on red law, it was decided to perform a "before-and-after" study at this intersection. The "before" part of the study consisted of manual observation of driver acceptance of the law. The "after" part consisted of manual observation of driver acceptance of the law when the drivers were reminded that the right turn on red movement was a legal maneuver at that intersection. This was accomplished by the installation of a standard 24 by 18-in. sign on which was printed "RIGHT TURN ON RED AFTER STOP."

In the "before" study a total of 6,890 vehicles traveling in the outside lane were observed. Of these, 1,007 vehicles turned right. Twenty-eight percent of the turning vehicles were from out of state.

In the "after" study a total of 6,695 vehicles traveling in the outside lane were observed. Of these, 1,003 vehicles turned right. Thirty-two percent of the turning vehicles were from out of state.

More complete information concerning turning characteristics of vehicles at this intersection is given in Table 3 and Figure 12. Table 3 gives a numerical breakdown and Figure 12 shows a graphical comparison of the data. The "before" test indicates that 65 percent of the Arizona drivers, 63 percent of drivers from other states with the right turn law, and 30 percent of drivers from other states accepted the law. The "after" test indicates that 75 percent of the Arizona drivers, 89 percent of drivers from other states with the right turn law, and 47 percent of drivers from other states accepted the law. Use of the information sign significantly improved acceptance of the right turn on red law.

TABLE 5

VEHICLE CLASSIFICATION BY REGISTRATION FOR THROUGH-LANE HEADWAY MEASUREMENTS, FINAL PERIOD

Location	Total In-State Vehicles	Total Out-of-State Vehicles	In-State %	Out-of-State %
Scottsdale Rd. and McDowell Rd. southbound	483	95	83.5	16.5
Scottsdale Rd. and McDowell Rd. westbound	509	67	88.4	11.6

HEADWAY RESULTS

The investigation of headway characteristics can be separated into three distinct phases: the initial study, the final study, and the seasonal study. All data presented pertain only to passenger vehicles and light pickup trucks.

The Initial Study

The initial headway measurement period began in September 1964, and continued until June 1965. During this period, measurement techniques were developed and a variety of intersections were studied. Since the purpose of the investigation was to study phenomena caused by changes in driver population, it was desired to find an intersection through which large numbers of out-of-state vehicles passed. In order to determine the effect of out-of-state drivers on all positions in the queue, an intersection where large queues developed also was required.

It was soon determined that very few intersections met the out-of-state vehicle and queue requirements. It seems that because of the progressive signalization which exists on most streets in the area, the only period of the day when queue lengths greater than six cars consistently occur is during the morning and evening peak periods. Unfortunately, out-of-state vehicles, whose drivers are usually tourists, tend to stay off the streets during peak periods. Thus, analysis during peak periods proved to be generally unsuitable.

Consequently, the first problem encountered was to find an intersection which suited the project requirements. Next, it had to be determined whether or not headway data from a particular intersection would be representative of headway characteristics of the entire area.

The first step in the investigation involved data accumulation at several intersections in the area where volume counts indicated both high volumes and a large proportion of out-of-state vehicles. Table 4 summarizes the registration of vehicles whose headways were measured during the initial portion of the study. The data shown are only for vehicles in the inside lane (the through lane nearest the centerline) and all measurements were made during off-peak periods. In general, headways in the outside lane are not comparable with headways in the inside lane because of the right turning and parking movements which occur in or near the outside lane and do not occur in the inside lane. At all intersections but one (Scottsdale Road and 2nd Street), a separate left turn lane allowed traffic in the inside lane to proceed without obstruction. Thus, the headways are based on lanes with uninterrupted through movements.

In all cases concerning vehicle headways, the time required for the first vehicle in the queue to respond to the light change and advance to the reference line is not included in this section of the report. The figures show the headway between the first and second vehicles and all succeeding vehicles. The time required for the first vehicle in the queue to cross the reference line is not reported because the distance to the reference line varies from intersection to intersection.

The total population size for the headway data was 5,347 vehicles, approximately 23 percent of which were out-of-state vehicles. In spite of the sample size, some intersections produced meager data concerning the headway characteristics of vehicles within the queue.

In this initial portion of the study, data sufficient to form definite conclusions concerning headway characteristics were not obtained. However, it was determined that there was no significant difference between headway characteristics at four of the approaches tested. Because of the data collection problems, it was decided to collect headway data intensively at one specific intersection in order to obtain information in large enough quentities to form conclusions which were statistically correct. After examining the data collected during the initial study and considering the queue lengths which occurred at each intersection, the intersection of Scottsdale Road and McDowell Road was selected for more intensive study.

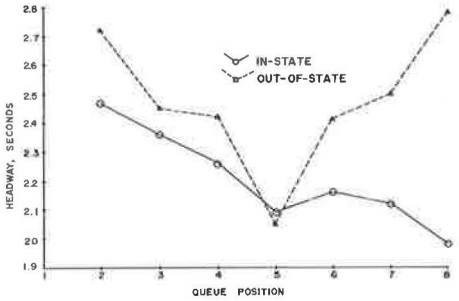

Figure 13. Headways of in-state and out-of-state vehicles.

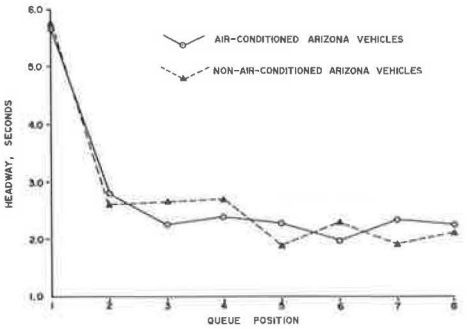

Figure 14. In-state headways for air-conditioned and non-air-conditioned vehicles.

The Final Study

The final headway measurement period began in January 1966, and continued until April 1966. This time period was selected because of its higher proportion of out-of-state traffic. Table 5 summarizes the registration of vehicles whose headways were measured during the final portion of the study. As in the initial study, the data shown are only for vehicles in the inside lane traveling during off-peak periods.

The headway relationships of in-state and out-of-state vehicles are shown in Figure 13. The points shown on the curves represent a compilation of data obtained during both the initial and final study. Analysis indicated that data for all the locations in question could be combined without impairing the significance of the results.

It can be determined by examining the curves in Figure 13 that the headway between the first and second cars for in-state vehicles is significantly different from the headway for out-of-state vehicles. The difference between in-state and out-of-state vehicle headways of the third, fourth, and fifth cars is not significant. After the fifth car, the divergence between in-state and out-of-state vehicles begins to increase until for the eighth car in a queue, the mean headway of in-state vehicles is 1.98 sec while the mean headway of out-of-state vehicles is 2.78 sec, an 0.80-sec difference. In all cases but that of the fifth car, the mean headway of out-of-state vehicles is greater than the mean headway of in-state vehicles.

The Seasonal Study

Because of the extremely high temperatures which occur in Phoenix during the summer months, a large proportion of cars in the area are air-conditioned. One objective was to determine if there is a difference in headways when comparing air-conditioned and non-air-conditioned vehicles. The second objective was to determine if there is a difference in headways when comparing in-state vehicles operating during the summer months and in-state vehicles operating during the winter months.

An intersection in downtown Phoenix (Central and McDowell) was selected for the study. Data were collected during the afternoon peak hours in March and August, 1965. During the afternoon peak hours, the lanes in question were flowing at about practical capacity.

The average maximum daily temperature in Phoenix during the month of August is 102 F. In the sample taken for this analysis, 46 percent of the vehicles were found to be air-conditioned. Because of the high temperature during the summer data collection period, if the windows of the vehicle were up, it was assumed that the vehicle was air-conditioned.

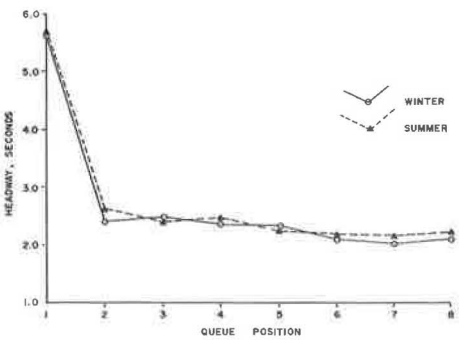

Figure 15. In-state headways for summer and winter.

No data relating to the driver characteristics of persons in air-conditioned and non-air-conditioned vehicles were found during the literature search. Consequently, at the beginning of the test, various theories were proposed concerning the driver characteristics of the two groups. For instance, it was thought that drivers in non-air-conditioned vehicles would be more erratic and aggressive than drivers in air-conditioned vehicles.

Headway measurements were taken in the two through lanes of eastbound traffic. It was determined that there was no difference between the vehicle headways of air-conditioned vehicles and non-air-conditioned vehicles. The data are shown in Figure 14.

There is approximately a 40-degree seasonal difference in the average maximum daily temperature in Phoenix. After it had been determined that there was no difference between headway characteristics of air-conditioned and non-air-conditioned vehicles, the next step in the procedure was to determine if there was a seasonal difference in headway characteristics of vehicles operating during August and March.

No data relating to seasonal variations in headway data were found during the literature search. It was thought that the out-of-state traffic, which forms a large percentage of the total traffic in winter, might influence the vehicle headways of Arizona drivers. Out-of-state traffic during the summer months was less than 1 percent on the street in question during the observation period; therefore, during the summer, headway characteristics of Arizona drivers are independent of out-of-state drivers. The sample taken during March contained 305 Arizona vehicles and the sample taken during August contained 568 Arizona vehicles. It was determined that there is no seasonal variation for in-state vehicle headways. The data are shown in Figure 15.

CONCLUSIONS

The three main purposes of this investigation were to (a) determine and compare headway characteristics of in-state and out-of-state vehicles at signalized intersections; (b) determine the right turn on red characteristics of in-state and out-of-state drivers; and (c) determine the gap acceptance characteristics of in-state and out-of-state drivers turning left. The conclusions which have been reached from this research are discussed in the following.

Headway Characteristics

In general, during off-peak periods, the headway for the first and second vehicle in a queue is longer in the case of an out-of-state vehicle than in the case of an in-state vehicle; the headway of the third, fourth, and fifth vehicles is basically the same for in-state and out-of-state vehicles; and the headway of the sixth, seventh, and eighth vehicles (and probably subsequent vehicles in the queue) is significantly longer in the case of an out-of-state vehicle than in the case of an in-state vehicle. For example, the headway of the second out-of-state vehicle in the queue is 0.3 sec longer than the headway of the second in-state vehicle, and the headway of the eighth out-of-state vehicle in the queue is 0.80 sec longer than the headway of the eighth in-state vehicle.

Probably drivers of out-of-state vehicles located in the first or second position in the queue take longer to accelerate than local drivers because of unfamiliarity with the intersections, thus causing the observed increase in headway. Drivers of vehicles in the third, fourth, and fifth position in the queue began to accelerate at similar rates regardless of driver origin because of two factors: (a) the drivers merely have to follow the car ahead of them, so familiarity or lack of familiarity with an intersection has little effect on headway; and (b) because the vehicles are situated in the midst of the queue, the drivers are under pressure from following vehicles to accelerate as quickly as possible. However, when an out-of-state vehicle is near or at the end of a queue and under little pressure from following vehicles, the driver does not accelerate as rapidly as a local driver.

The result of this phenomenon presents an interesting effect on capacity analysis. Where possible capacity is being considered (with the corresponding formation of long queues which do not clear with each signal cycle), there is little significant difference between headways of in-state and out-of-state drivers. But, if practical capacity is to be attained, then the value of the capacity would be decreased as the proportion of out-of-state traffic increases. This would be necessary since each queue should clear

within a green phase and, as indicated above, this would produce longer headways for the out-of-state vehicles near the end of the queue.

Development of specific adjustment factors to be used in capacity analysis has not been accomplished. The new Highway Capacity Manual (15) was not available until the last month of this project. This manual includes fundamental changes in definitions and concepts from the old manual (3). The preceding paragraph describes how the observed phenomena could be interpreted in terms of the older concept of practical and possible capacity.

Gap Acceptance Characteristics

Both in-state and out-of-state drivers exhibit similar gap acceptance characteristics for both left and right turning movements. It has been determined that a 6-sec gap is the minimum acceptable time gap for a section of roadway which has a maximum speed limit of 35 mph. At least 85 percent of all turning vehicles will reject all gaps of less than 6 sec. Thus, the gap accepted is nearly always large enough so that through-traffic is not forced to slow down because of turning movements. Therefore, the capacity of an intersection where 6-sec gaps are available will be increased.

Right Turn on Red Characteristics

As a result of this research, it has been shown that informing the public of the legality of the right turn on red maneuver improves the acceptance of the law. At the intersection of Scottsdale Road and 5th Avenue, installation of an information sign increased acceptance from 65 to 75 percent for Arizona drivers; from 63 to 89 percent for drivers from other states where the law exists; and from 30 to 47 percent for drivers from states where the turn is illegal. More effective communication concerning the law would probably further increase the above percentages.

In Arizona, use of the right turn on red law reduces delay and travel time and increases the capacity of signalized intersections. However, this turning movement can only be used successfully in states where pedestrian rights are observed by the driving public.

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Knowledge of Oncoming Car Speed as Determiner of Driver's Passing Behavior

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•THE purpose of the present study is to examine the effect of increased information about oncoming car speed on driver judgment in accelerative passes. An accelerative pass is one in which the overtaking driver starts the pass from a close following position with little or no speed advantage and must accelerate to complete the maneuver. In such a pass, the passing opportunity is limited by sight distance, legal passing zone boundaries or oncoming traffic. Where an oncoming car (OC) is the limiting factor, the passing driver must take into account his own speed and the speed of and distance to the OC to make a valid passing decision—that is, to pass when it is safe to do so, and not to commence a pass when it is not safe.

A number of workers (1, 2, 6) have studied driver OC-gap acceptance. These papers have been reviewed in detail elsewhere (3). However, the results indicate (a) that drivers are relatively good judges of distance in passing situations, but (b) very poor judges of either closing rate or OC speed. Support for the latter result is provided by Michaels (5), whose data suggest that at the distance at which most passes take place, the speed cue associated with the rate of change of the visual angle subtended by the OC is below the detection threshold. Further evidence for this conclusion was obtained by Franklin Institute Research Laboratories in field observational studies of passing practices in which it was noted that the passing decision appears to be completely unrelated to OC speed. However, in another study of sight distance judgment (4) it was found that drivers were able to make accurate distance judgments.

On this basis it appears that since a driver has first-hand phenomenal and metric knowledge of his own speed, and is able to discriminate distance with reasonable accuracy, much of the variability in passing judgment is associated with poor judgment of OC speed. It was thus hypothesized that if the necessity to make OC speed judgments were eliminated, a significant improvement in gap acceptance accuracy would result. The purpose of the present series of experiments is to evaluate this hypothesis and further elucidate the roles played by OC speed and distance judgment in accelerative passes.

EXPERIMENT 1: "LAST SAFE MOMENT"

The first experiment was conceived as a pilot study to provide an initial check on the proposition that judgment of OC speed is a major source of variability in passing judgments.

Method

Test Site—All of the studies described were conducted on a completed but unopened section of Interstate Highway 95 in Philadelphia. The test section provided over a mile of sight distance of which 3500 feet was straight and level. The tests were conducted on the one side of the expressway which consisted of four 12-foot lanes.

Test Vehicles—Three cars were used in the tests. A Rambler sedan and an Ambassador station wagon, loaned to the project by American Motors, were used, respectively, as the OC and lead car (LC); a 1965 Ford Galaxie sedan was used as the overtaking car (OT).

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Figure 1. Experiment 1: Experimental design.

ONCOMING CAR SPEED (MPH)	KNOWLEDGE (K) (OCS CONSTANT IN BLOCK)		NO KNOWLEDGE (NK) (OCS VARIABLE IN BLOCK)	
	LEAD CAR SPEED (MPH)			
	35	55	35	55
30				
40				
50				
60				

The OT was equipped with power steering, automatic transmission and a 352-cubic-inch V8 engine.

Instrumentation—The OC and OT were each equipped with fifth wheels for measuring speed and distance. Position calibration was provided by photocells mounted on the OC and OT which responded to the presence of strips of reflective marking tape laid across the roadway at 400-foot intervals. Together, the fifth wheel and photocells provided longitudinal accuracy of ± 4 feet. In addition to the speed and distance measuring equipment, the OT was equipped with transducers to measure lateral and longitudinal acceleration and steering wheel and throttle positions. A once-per-second time hack was generated in the OT and broadcast to the OC to provide a common time base.

Subjects—Six subjects took part in the experiment, all college students with a minimum of 4 years driving experience.

Procedure—The experimental procedure was designed to provide an estimate of the pass-no pass threshold on each trial and is similar to the technique first used by Rockwell and Snyder (6). On each trial, the subject (S) driving the OT was presented with a passing situation and was instructed to pass at the last safe moment. The time (or distance) separation between the LC and the OC at the start of the pass was considered to be an estimate of the threshold separation.

TABLE 1

EXPERIMENT 1: MEANS, VARIANCES, AND STANDARD DEVIATIONS ACROSS SUBJECTS FOR K AND NK BLOCKS AT EACH OC-LC SPEED COMBINATION

Speed (mph)		K			NK			
OC	LC	$\bar{x}$	σ^2	σ	$\bar{x}$	σ^2	σ	F
30	35	6.58	1.52	1.23	6.48	4.38	2.09	2.88[a]
30	55	6.59	1.42	1.19	6.66	2.86	1.69	2.40[a]
40	35	6.41	0.70	0.84	6.26	2.35	1.53	3.36[a]
40	55	5.70	0.78	0.82	6.27	2.87	1.69	3.68[a]
50	35	6.02	1.62	1.27	5.71	2.05	1.43	1.27
50	55	5.70	0.64	0.80	5.73	0.89	0.95	1.39
60	35	5.95	1.03	1.01	5.38	1.51	1.23	1.47
60	55	5.70	1.01	1.01	5.43	1.69	1.30	1.66[a]

[a]Significant at .01 level.

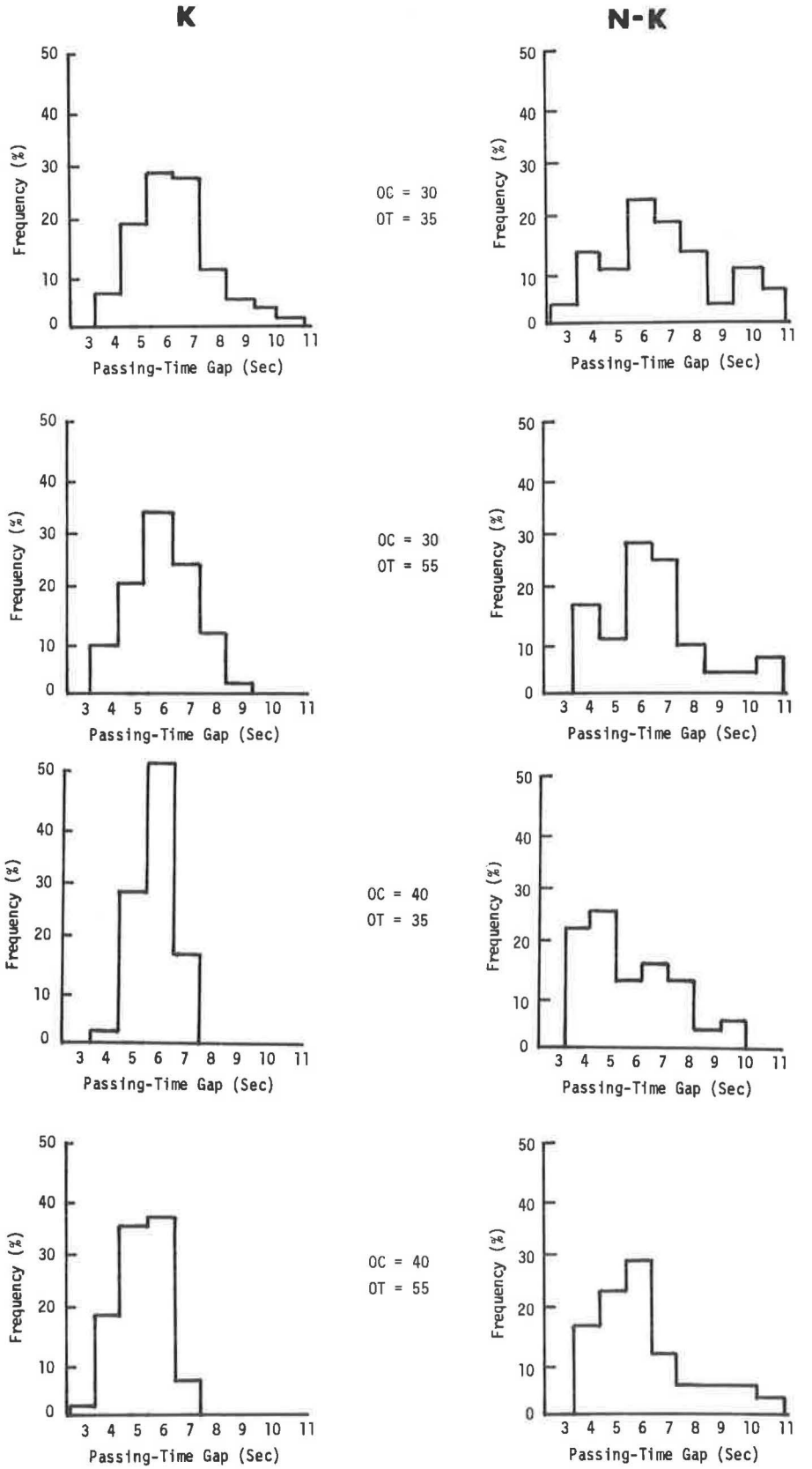

Figure 2. Experiment 1: Frequency distribution of passing time gaps for K and NK trials for different OC-OT speeds.

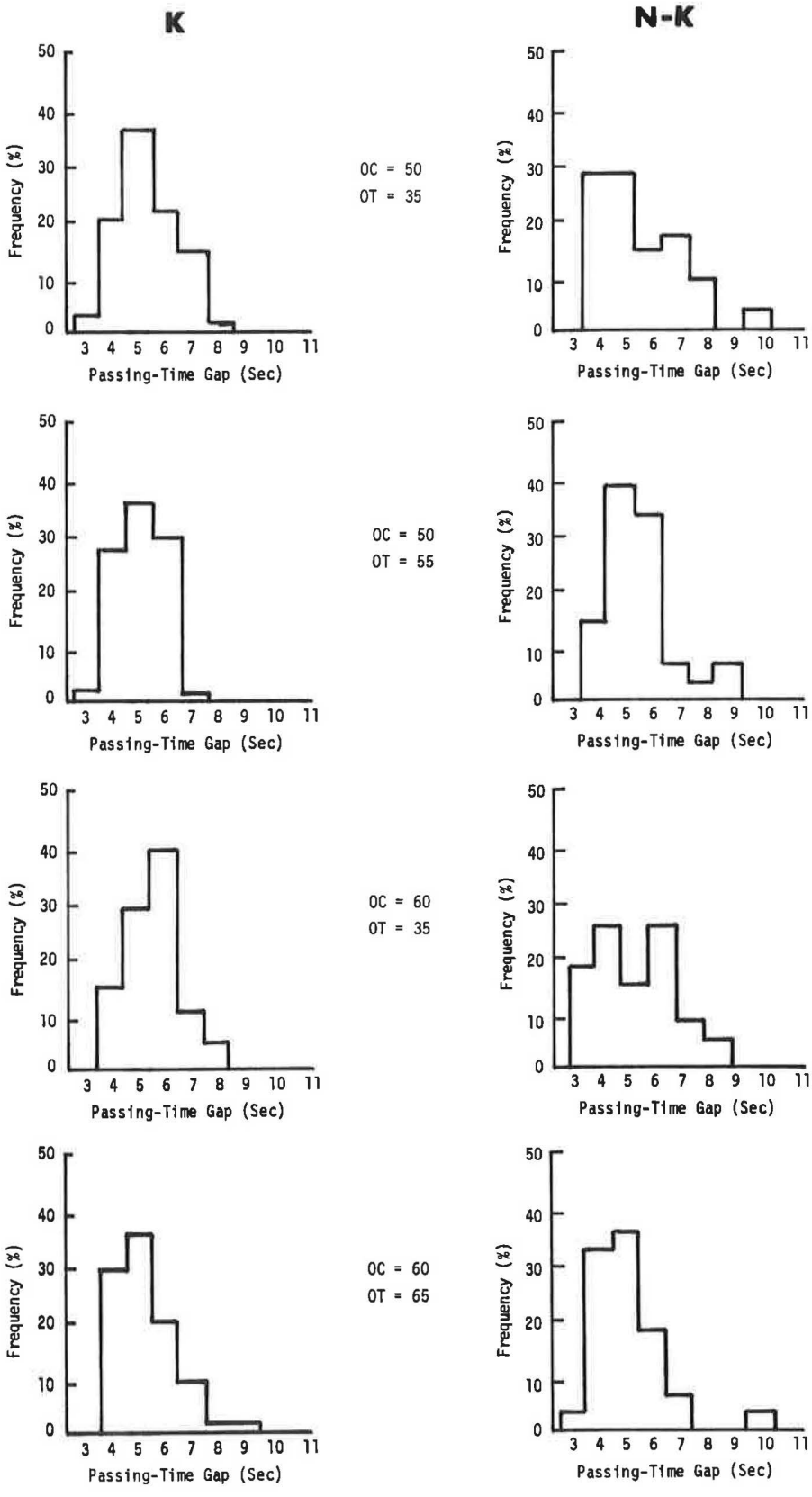

Figure 2. Experiment 1: Frequency distribution of passing time gaps for K and NK trials for different OC-OT speeds (continued).

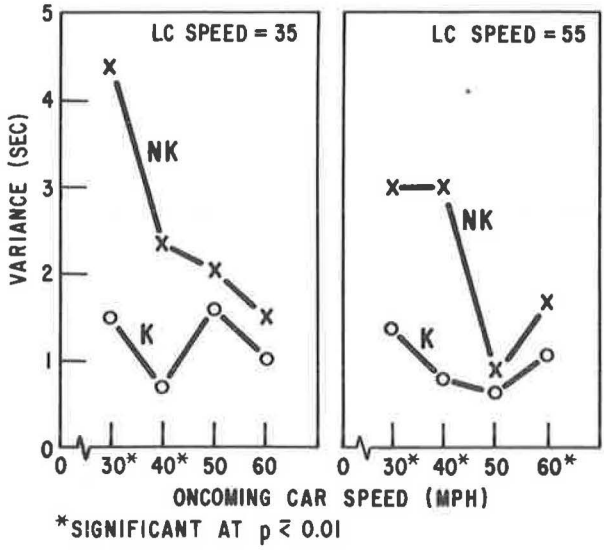

Figure 3. Experiment 1: Passing time gap variance of like speed trials for K and NK conditions as a function of oncoming car speed.

The technique employed was as follows. Before the start of a trial, the OC and LC were positioned at opposite ends of the test section with the OT immediately behind the LC. On the start signal the OC and LC (with the OT following) accelerated to their assigned speeds and drove toward each other in the two adjacent center lanes. S was instructed to follow the LC at a close distance and to pass the LC at the last safe moment. The observer (O) riding as a passenger timed the passing time gap, the OT-OC separation, measured from the start of the pass until the OT and OC were abreast, and the LC driver timed the passing time. Subjects were instructed never to enter either of the outside lanes to insure safe emergency maneuvering room for the OC and LC.

Experimental Design—Each subject had eight 16-trial blocks. Four of the blocks were knowledge (K) blocks and four were no knowledge (NK) blocks.

On NK blocks, the OC speed was varied randomly between 30, 40, 50, and 60 mph within the constraint that each OC speed was presented four times. LC speed was also varied randomly between 35 and 55 with the additional constraint that each of the two LC speeds occurred twice in combination with each OC speed. On NK trials subjects were given no information of any kind about OC speed (except, of course, what they could judge for themselves).

On K blocks OC speed was held constant at 30, 40, 50, or 60 mph for all 16 trials of a block and LC speed was randomly varied between 35 and 55. Each S had one K block at each of the four OC speeds. Prior to the start of each K block, S was told that OC speed would be constant for the next 16 trials and was also told the OC speed. Thus on K blocks, S had "perfect" phenomenal or experiential knowledge of OC speed after the first few trials, i. e., after the first few trials there was no need for S to make judgments of or compensations for speed. All S had to consider was the distance to the OC and his own (OT) speed. The experimental design is shown schematically in Figure 1.

According to the hypothesis, it was predicted that the variance of the passing time gaps would be significantly less across a K block than across NK trials of the same OC speed.

Results

The results of the experiment are summarized in Figure 2, which shows eight pairs of histograms. Each histrogram is a frequency distribution, combined across subjects, of the passing time gaps. The histograms on the left show the distribution of time gaps

ONCOMING CAR SPEED (MPH)	KNOWLEDGE (K) (OCS CONSTANT IN BLOCK)	VERBAL KNOWLEDGE (VK) (OCS VARIABLE IN BLOCK)	NO KNOWLEDGE (NK) (OCS VARIABLE IN BLOCK)
30			
40			
50			
60			

Figure 4. Experiment 2: Experimental design, verbal knowledge of oncoming car speed.

recorded under K conditions; the NK histograms show the time gap distributions observed across like OC speed NK trials. There is a pair of histograms for each of the eight OC-LC speed combinations.

Note that the K histograms tend to show less variability and more clustering about the center than the NK histograms. This observation is summarized in Table 1, which shows the means and variances for each distribution and the F ratio between like K-NK pairs. In each comparison the K condition produced less variance from trial to trial than the corresponding NK condition. However, the difference in variances was significant in only five of the eight comparisons. Somewhat surprisingly, the variability of the NK trials was consistently higher at the lower OC speeds. These data are summarized graphically in Figure 3, which shows passing gap variances as a function of OC speed for K and NK conditions.

The inconsistency in the results is attributed to the fact that the experimental technique tended to produce spuriously low variances. Since all subjects passed on each trial, and the passing gaps were quite small generally, the range of variation of accepted time gaps on the low side of the average was obviously restricted. This effect can be seen in the NK histograms which tend to be skewed to the right. Note also that since the time gaps tend to decrease as OC speed increased, the variance restriction effect is greater at high OC speeds than at low OC speeds. Further, since the correlation between OC speed and average time gap is greater for the NK trials, the variance reduction effect is also greater for NK trials—a possible explanation of the lack of significant differences at the higher OC speeds.

Perhaps the most important factor which could account for the low variability of the NK data is the fact that the average passing distances were small enough for the rate of change of the apparent size of the OC to be well within threshold. In support of this contention is the fact that the variation in average NK passing gap with OC speed is somewhat less than would be expected if subjects were completely insensitive to OC speed.

In spite of the inconsistencies in the data, the weight of the observation tends to support the contention that a significant proportion of the variability in passing judgment is associated with oncoming car speed.

EXPERIMENT 2: VERBAL KNOWLEDGE OF OC SPEED

The objectives of Experiment 2 were (a) to obtain a more precise estimate of the contribution of OC speed to the variability of passing judgments; (b) to determine the accuracy with which drivers can judge distance to the OC; and (c) to determine the effect of presenting verbal information about OC speed to drivers.

Method

Subjects—Four subjects were used, all public school teachers with a minimum of 6 years driving experience.

TABLE 2

EXPERIMENT 2: MEANS, VARIANCES, AND STANDARD DEVIATIONS OF TIME GAP JUDGMENTS ACROSS SUBJECTS BY BLOCKS

Knowledge Condition	Block Number	Speed (mph)	$\bar{x}$	σ^2	σ
K	1	30	12.07	1.69	1.30
	2	40	11.40	1.50	1.22
	3	50	12.14	2.58	1.60
	4	60	11.79	1.60	1.26
VK	1	Varied	12.11	2.23	1.49
	2		11.63	1.54	1.24
	3		11.30	1.48	1.21
	4		11.62	2.02	1.42
	5		11.62	2.00	1.41
	6		11.73	1.42	1.19
NK	1	Varied	12.16	5.72	2.39
	2		11.98	6.18	2.49
	3		11.23	5.07	2.25
	4		11.32	3.45	1.86
	5		11.71	5.22	2.29
	6		12.30	5.75	2.40

Test Site, Vehicles and Instrumentation—As described for Experiment 1.

Procedure—The general procedure was similar to that employed in Experiment 1. However, to avoid the hazards and spuriously low variances inherent in the "last-safe-moment" technique, a new measure of passing judgment accuracy was developed. Subjects were instructed to estimate the time gap between the OT and the OC and to pass when the time gap closed to 12 seconds. After each trial, subject was told what the time gap actually was at the start of the pass. Subjects were further instructed to estimate the time gap by judging distance and to adjust their response according to their performance on the previous trial, taking OC speed into account. Thus, if on the preceding trial a subject passed at a time separation with a given deviation from 12 seconds, he would adjust for the error by passing a little sooner or later, depending on the direction of the error and, to the best of his ability, the change in OC speed. This

TABLE 3

EXPERIMENT 2: DISTANCE JUDGMENT 95 PERCENT CONFIDENCE LIMITS

Speed (mph)	Mean Judged Distance (ft)	95-Percent Confidence Limits	
		Feet	Percent
30	1328.0	286.1	21.5
40	1421.5	304.3	21.4
50	1691.9	446.0	26.4
60	1816.0	388.2	21.4

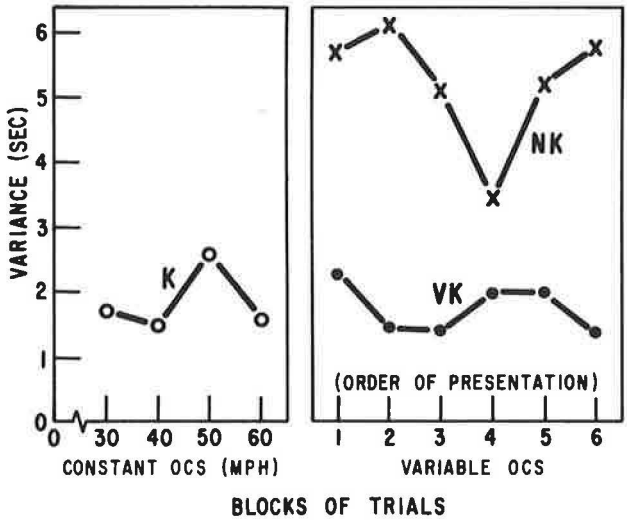

Figure 5. Experiment 2: Variance of passing time gaps as a function of blocks of trials.

technique is clearly quite sensitive to a subject's ability to judge distance and OC speed, and to take OC speed into account. If subjects were able to judge and take into account OC speed and distance perfectly, they would pass at 12 seconds on every trial. Hence the consistency of the time gaps about 12 seconds observed from trial to trial is taken as a measure of passing judgment accuracy. Also, by having subjects pass at or close to distances equivalent to 12-second separations, all of the artifacts and most of the hazards associated with the previous technique were eliminated.

Experimental Design

Each subject had 16 blocks of 12 trials each. The first four trials for each subject were constant OC speed, knowledge (K) blocks with OC speeds of 30, 40, 50, and 60 mph. Thereafter, each subject had six no knowledge (NK) blocks and six verbal knowledge (VK) blocks in alternating sequence. Each NK and VK block consisted of 12 trials in which OC speed was varied randomly between 30, 40, 50, and 60 mph within the constraint that each speed had to appear three times. LC speed was held constant at 45 mph throughout the experiment. On NK blocks, subjects had no OC speed information at all except what they could judge for themselves. The experimental design is shown in Figure 4.

The purpose of the four K blocks was to provide subjects with training and phenomenal experience with each of the OC speeds, and to meet the objective of providing an estimate of the ability of drivers to judge distance to an OC. Note that with LC and OC speeds held constant, the only variable determining the time gap is distance. Hence the variability of passing time gaps across a block of trials would be directly related to variability of distance judgments.

Results

Table 2 shows the means and variances, across subjects, of the observed passing time gaps for K, VK and NK blocks. The variances under the K condition indicate the consistency or accuracy with which the subjects were able to judge distance to the OC. Because distributions of the estimates were quite normal, it is legitimate to state the distance judgment accuracies in terms of confidence limits. These data are shown in Table 3, which gives the distance-judgment error limits in feet and percent within which 95 percent of the judgments fell. The high variance in the 50-mph condition may have resulted from several halts in testing in the middle of a 50-mph K block due to

TABLE 4

EXPERIMENT 2: MEANS, VARIANCES, AND STANDARD DEVIATIONS OF TIME GAP JUDGMENTS ACROSS SUBJECTS BY OC SPEED

Knowledge Condition	Speed (mph)	$\overline{x}$	σ^2	σ	Equivalent Mean Distance
K	30	12.07	1.69	1.30	1328.0
	40	11.40	1.50	1.22	1421.5
	50	12.14	2.58	1.60	1691.9
	60	11.79	1.60	1.26	1816.0
VK	30	12.03	2.49	1.58	1323.6
	40	12.16	2.00	1.41	1516.3
	50	11.72	1.64	1.28	1633.4
	60	11.12	1.56	1.25	1712.9
NK	30	14.40	3.83	1.96	1584.3
	40	12.36	3.19	1.78	1541.2
	50	11.13	2.58	1.60	1551.1
	60	9.67	1.76	1.32	1489.5

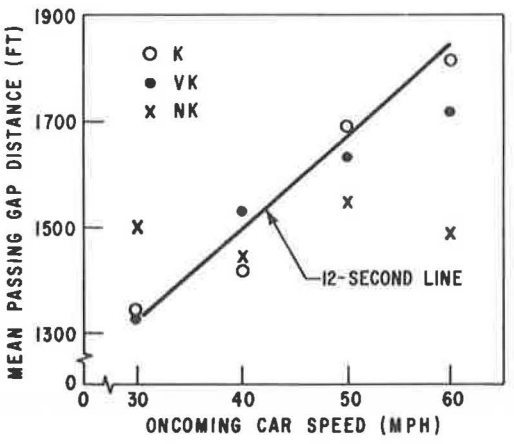

Figure 6. Experiment 2: Mean passing distances for K, VK, and NK trials as a function of oncoming car speeds.

ONCOMING CAR SPEED (MPH)	KNOWLEDGE (K) (OCS CONSTANT IN BLOCK)		VERBAL KNOWLEDGE (VK) (OCS VARIABLE IN BLOCK)		NO KNOWLEDGE (NK) (OCS VARIABLE IN BLOCK)	
	LEAD CAR SPEED (MPH)					
	35	55	35	55	35	55
30						
40						
50						
60						

Figure 7. Experiment 3: Experimental design.

TABLE 5

EXPERIMENT 3: MEANS, VARIANCES, AND STANDARD DEVIATIONS FOR SIX SUBJECTS OF PASSING TIME GAPS FOR K, VK, AND NK CONDITIONS BY OC AND LC SPEEDS

Condition	Speed (mph)		$\bar{x}$	σ^2	σ
	OC	LC			
K	30	35	13.00	4.24	2.06
	30	55	12.45	4.02	2.00
	40	35	12.40	5.48	2.34
	40	55	10.86	1.92	1.39
	50	35	12.10	3.23	1.80
	50	55	11.76	1.68	1.30
	60	35	11.95	4.20	2.05
	60	55	11.37	2.48	1.57
VK	30	35	14.87	6.82	2.61
	30	55	12.47	2.37	1.54
	40	35	12.71	2.95	1.72
	40	55	11.97	3.92	1.98
	50	35	13.23	6.26	2.50
	50	55	11.08	7.52	2.74
	60	35	11.59	2.22	1.49
	60	55	11.16	3.15	1.77
NK	30	35	15.56	4.19	2.05
	30	55	13.50	4.54	2.13
	40	35	13.40	2.49	1.58
	40	55	11.51	2.12	1.46
	50	35	11.91	1.76	1.33
	50	55	10.76	2.57	1.60
	60	35	10.30	2.33	1.53
	60	55	9.57	2.38	1.54

mechanical difficulties with the test vehicles. If the 50-mph data are ignored, the evidence is that the subjects were able to make distance estimates with an error of 20 percent or less 95 percent of the time.

Table 2 also shows the variance of the passing time gaps for the six VK and NK blocks. These variances are summarized in Figure 5. All of the VK variances are significantly lower than the NK variances, indicating that subjects were able to take verbal OC speed information into account in judging the time separations. There is a suggestion of learning in the variable downward trend of the VK variances while the NK variances are uniformly high. The means of the judgments show no systematic trend. Note that the K and VK variances are quite comparable, even when the high variance associated with the 50-mph K condition is not considered. The implication is that providing the subjects with OC speed information is equivalent to holding OC speed constant.

Table 4 shows the means, variances and standard deviations for K, VK and NK conditions for each OC speed. The K data are repeated from Table 2 to facilitate comparison.

TABLE 6

EXPERIMENT 3: MEANS, VARIANCES, AND STANDARD DEVIATIONS FOR SIX SUBJECTS OF PASSING TIME GAPS FOR VK AND NK CONDITIONS BY OC AND LC SPEEDS

Condition	Block	LC Speed (mph)	$\bar{x}$	σ^2	σ
VK	1	35	13.28	4.11	2.03
	1	55	11.87	3.10	1.76
	2	35	12.61	7.72	2.78
	2	55	11.11	1.76[a]	1.33
	3	35	12.65	4.18[a]	2.04
	3	55	12.54	3.51[a]	1.87
NK	1	35	12.46	5.23	2.28
	1	55	11.11	3.26	1.81
	2	35	12.42	8.32	2.88
	2	55	11.16	4.91	2.22
	3	35	12.56	9.08	3.01
	3	55	11.91	5.74	2.40

[a] Significantly larger than the corresponding NK value.

Note that for both knowledge conditions the mean passing time gaps tend to remain constant, while under the NK conditions subjects increasingly overestimated the time gap as the speed of the OC increased. These data are shown graphically in Figure 6, in which mean passing distances for K, VK and NK conditions are plotted against OC speed. The straight line indicates the 12-second equivalent distance for each speed and is obviously a very good fit for the K means. The NK means show no such trend, indicating

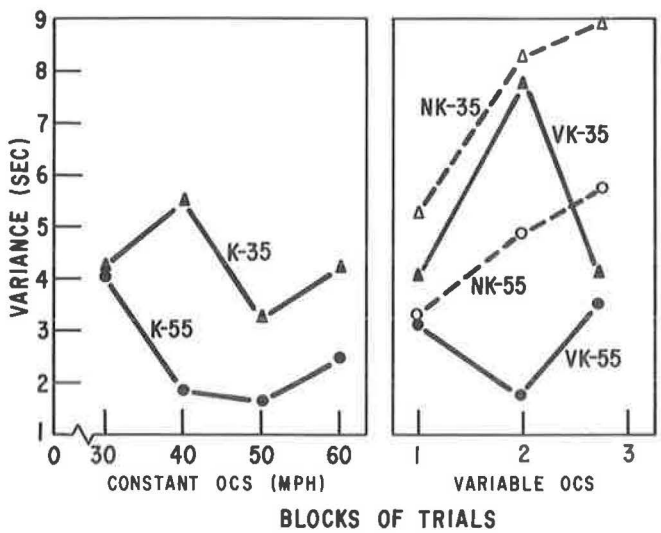

Figure 8. Experiment 3: Variance of passing time gaps as a function of blocks of trials.

little if any speed judgment. The fact that the mean NK passing distance at 60 mph was actually less than at 30 mph indicates that the subjects were not able to discriminate between these extreme speeds. This is in contrast to the results of the previous experiment in which there was some suggestion of speed discrimination at the very short distances which obtained in that study. The VK means show a consistent increase with OC speed, with relatively low variability. However, the trend does not follow the theoretical line and appears to be curvilinear. The indication is that subjects did not completely compensate for OC speed. The difference between the VK and NK means in Figure 6 reflects the difference between knowing and having to judge OC speed while the difference between the VK and K (or theoretical) means is associated with having to apply knowledge of OC speed.

Note that the variances associated with the time gap means shown in Table 4 diminish consistently with increasing OC speed under all three conditions. The variances about the 60-mph mean are quite low and very close while at 30 mph they are much higher, with the NK variance significantly larger than the K or VK variances. These data are similar to those obtained in the first experiment, but none of the explanations developed to explain similar results in the previous study apply here. One possible explanation is that at the higher speeds the amount of tangent roadway was somewhat limited placing an artificial upper limit on the time gaps.

To summarize the above results it was found that (a) subjects were able to make relatively good judgments of the distance between the OT and OC—a 20 percent error or less 95 percent of the time; (b) subjects showed virtually no ability to judge OC speeds at distances equivalent to a 12-second OT-OC gap; and (c) subjects were able to use information about OC speed in adjusting their time gap estimates.

EXPERIMENT 3: VARIABLE LC SPEED

Experiment 2 established that with constant LC speed most of the variability in passing gap judgments was associated with OC speed; that distance judgment was relatively good; and that subjects were able to make effective use of verbal OC speed information. The purpose of the third experiment was to determine the effect of LC (and hence OT) speed on passing gap judgment.

Method

Six subjects were used, all public school teachers with a minimum of four years driving experience. The experimental setup and procedure was identical to that employed in the previous experiment except that subjects had 16 trial blocks and LC speed was varied randomly between 35 and 55 mph throughout the experiment. The design is shown in Figure 7.

Results

The results of Experiment 3 are summarized in Tables 5 and 6. Table 5 shows the means, variances, and standard deviations of the passing time gaps for K, VK, and NK trials broken down for OC and LC speeds. As in Experiments 1 and 2, higher variances are consistently associated with the lower speeds. This is shown graphically in Figure 8. Note that the K and NK variances are generally higher than those obtained in Experiment 2, and the difference between the knowledge and no knowledge conditions less. These effects can be attributed to variability associated with having to correct for LC speed.

Table 6 shows the passing time gap statistics for VK and NK blocks, broken down for LC speed but computed across OC speed. In each comparison the NK variances are larger than the VK variances but the differences are not as striking as in the previous study and only three of the differences are significant. Apparently the variable LC speed produces a general increase in variability which tends to mask the effect of giving OC speed information.

Figure 9 is a plot of the mean passing distances against OC speed for K, VK and NK conditions and with LC speed as a parameter. As in Figure 2, the straight line shows

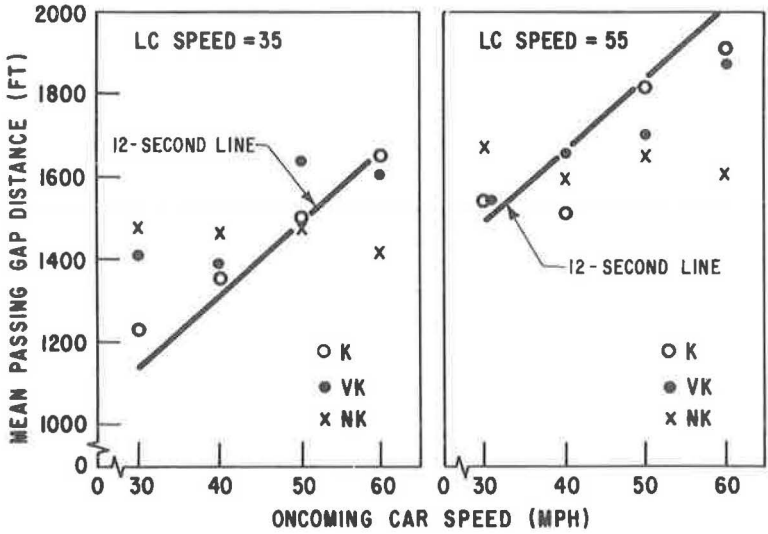

Figure 9. Experiment 3: Mean passing gap distance vs oncoming car speed and lead car speed for K, VK, and NK conditions.

the 12-second equivalent passing distances. Under the 55-mph LC speed condition the K means fit quite well. The VK fit is also good although there is a pronounced drop-of at the higher OC speeds. This tendency also appears to a lesser extent in the K means and is attributable in part to the relatively large effect of subject and experimenter (stopwatch) reaction time at high closing rates. Under the 35-mph LC speed condition the K fit is good although there is a tendency to overcompensate at low OC speeds. The VK means show a trend in the right direction but there are reversals and a pronounced tendency to overcompensate, i. e., to underestimate the time gap. The poor fit is

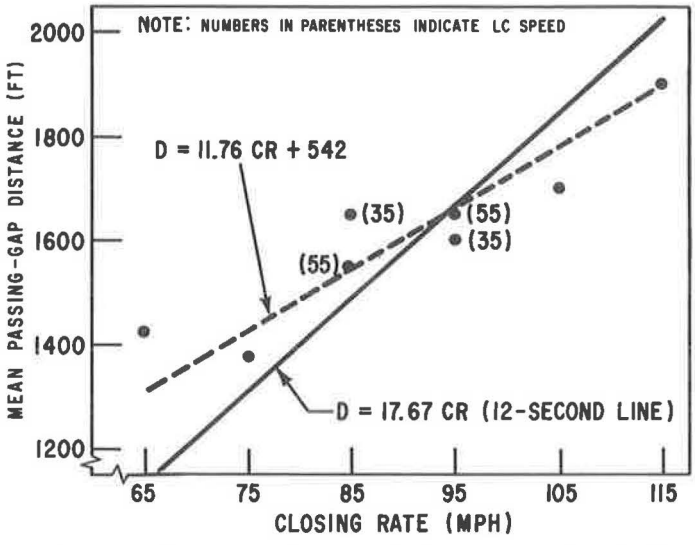

Figure 10. Mean passing gap distance as a function of closing rate with verbal knowledge of closing rate.

reflected in the relatively high VK block variances. As in the previous experiment the NK means indicate no OC speed discrimination at all and a tendency to pass at a constant distance equivalent to 12 seconds at a closing rate of 80-90 mph.

In Figure 10, the VK mean distance data have been combined for both LC speed conditions to show mean passing gap distance as a function of closing rate. A straight line provides a good fit and the line shown in the figure is a least-squares approximation. The slope of the line is somewhat less than the ideal, or 12-second, line indicating that the drivers tended to pass a little too soon at low closing rates and a little late at high closing rates. Nevertheless, the performance represented by the slope of the VK means is a considerable improvement over the time gap judgments obtained under the no-knowledge condition. Drivers apparently were able to compensate effectively for their own speed and OC speed, when the OC speed was known.

CONCLUSIONS

This series of experiments produced a number of clear-cut results. It may be concluded (a) that drivers are able to make good judgments of the distance to an oncoming car; (b) that at normal passing distances drivers do not respond appreciably to oncoming car speed; and (c) that drivers are able to make good use of verbal knowledge of oncoming car speed in making passing judgments. The finding that drivers were unable to judge oncoming car speed is consistent with that of Michaels (5), who showed that the relevant cues are below threshold at normal passing distances, and with Bjorkman's (1) data.

It would appear then that one way to improve passing performance is to provide some information about oncoming car speed. The present data show that a marked reduction in passing time gap variance (and hence, safety margin variance) can thus be achieved. It should be noted that the mean passing time gap and resultant mean safety margin adopted by a group of drivers may not be affected by the provision of oncoming car speed information. Nevertheless, a reduction in variability in passing gap acceptance and safety margin can have important consequences for both safety and throughput. Lower variance means that more drivers will pass when they should and fewer will pass when they should not. Therefore, it is felt that alternative techniques for presenting oncoming car speed information to drivers should be explored from a cost-effectiveness standpoint.

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Estimation of Vehicular Velocity Under Time Limitation and Restricted Conditions of Observation

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This study reports an investigation of the ability of subjects to estimate the velocity of the vehicle in which they are traveling. Equipment was developed to control the locus of visual stimulation and the time that the stimulation was available for observation. The acceleration of the vehicle was a parameter of the experiment. Stimulation time was held constant.

Results show that, with time limitation, the locus of visual stimulation is significant in determining the accuracy of the estimates. Peripheral visual stimulation results in more accurate estimates of the absolute velocity of the vehicle than stimulation of the frontal visual field. The higher acceleration rate used to attain velocities alters the function such that all velocities are underestimated.

It is hypothesized that fixation of the frontal field in "normal" driving may be a factor in highway hypnosis, i.e., gross underestimation of absolute velocity. The significance of absolute velocity appreciation for steering behavior and multiple-car maneuvers is pointed out.

•FIELD studies concerned with the estimation of the absolute velocity of the vehicle in which one is traveling have been few. In 1916, Richardson (1), in a paper devoid of numerical values, emphasized the irregularity and variability of the estimates obtained in his particular experimental situation.

After a lapse of forty years, two studies of direct interest appeared. Suhr (2) in 1957 compared speed estimation for laboratory and field conditions. A range effect was found. Low speeds were underestimated and high speeds overestimated. Also, overestimation at the high speeds was more pronounced with the laboratory device. Barch (3) in 1958 attempted to reproduce the effects of speed adaptation or highway hypnosis, which has been suggested as a contributing factor in certain types of traffic accidents. An adaptation speed of 50 mph maintained for as long as 8 minutes did not produce the effect according to the criterion used. A slight underestimation of the two terminal velocities, 30 and 40 mph, was attributed to the 50-mph anchor point and the fact that only deceleration was used to arrive at the estimate. The speed judgments were found to be "quite reliable."

Of particular interest are the studies of Hakkinen (4) who compared estimates made by subjects responding to films in which the camera was in the position of the driver with estimates made by passengers in an actual traffic situation. It was found that though the split-half reliability for each technique was high the correlation between the two techniques was not significantly different from zero.

The most recent work in speed estimation has been done at Ohio State University. Chubb and Ernst (5) explored the velocity subjects attained in response to a velocity commanded by the experimenter across two traffic densities. They report an inversio

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of the range effect—lower velocities overestimated and higher velocities underestimated. Also, heavy traffic increases the estimate uniformly. Snider (6) examined the factors of (a) order of presentation of the estimation or production procedure, (b) presence or absence of feedback, (c) time under feedback condition, and (d) velocity, using the technique of the analysis of variance. Of these factors only velocity was statistically significant; however, many significant interactions were reported.

The literature concerning the perception of motion in the laboratory, though instructive, will not be reviewed here. The laboratory studies generally display small moving targets usually within the confines of the parafovea, whereas for the situation of interest—the vehicle moving through the environment—it has been shown (7) that angular velocity is minimal in the fovea and maximum in the periphery.

In the real world, the rapidity with which an estimate is obtained is of importance. Especially in those emergent traffic conditions which call for a reappraisal, the estimate which takes longer is worth less if the two estimates are of a given accuracy and reliability. It is one purpose of the research to test the hypothesis that with time limitation, stimulation of the peripheral visual field[1] results in more accurate assessment of absolute velocity than stimulation of the frontal visual field. A second subsidiary hypothesis states that the estimates obtained with peripheral stimulation are of greater magnitude than those estimates obtained with frontal stimulation.

The question of whether the velocity of moving objects is perceived directly or by a cognitive operation relating perceived spatial displacement to perceived duration is pertinent. In the periphery, angular velocity is high and movement obvious so that movement of the vehicle through the environment can be apprehended directly, whereas

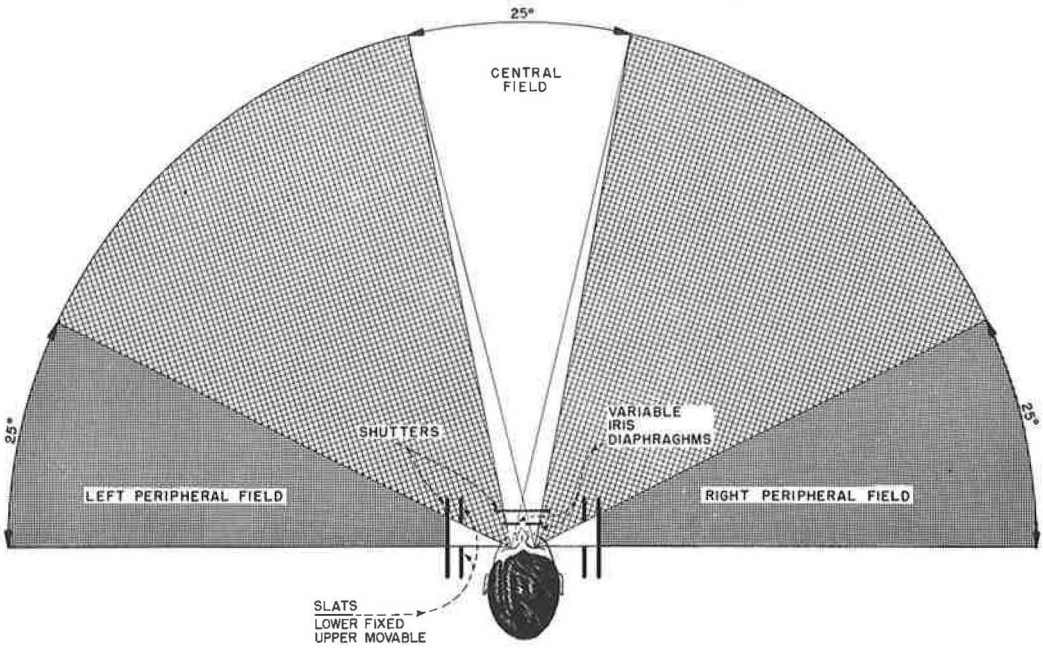

Figure 1. Equipment and visual field, top view.

[1]Frontal field refers to the 25 deg centered on the optical axis or line of sight and in the direction of motion; peripheral field refers to the field subtended between 65 and 90 deg (see Figs. 1, 2 and 3).

in the fovea movement is slower so that velocity may have to be computed from an estimation of distance traversed and a separate estimate of elapsed time. The latter is, of course, more time-consuming and in the extreme, corresponds to the solving of the equation, velocity equals distance divided by time, after the proper measurements have been made in the appropriate units.

METHOD

Apparatus

The equipment constructed to control the segment of the visual field available and its duration for observation is shown in Figure 1. All observations were made binocularly. The frontal field was controlled by two camera iris diaphragms. The distance between iris centers, corresponding to interocular distance, was made adjustable to accommodate individual variation.

The peripheral field was controlled by two slats in a groove running parallel to the optical axis at a distance of 5 in. on either side of the observer's eye. The rear slat subtended an angle of 90 deg and the forward slat 65 deg at the observer's eye. Baffles blocked out all but the visual field of experimental concern (Figs. 2 and 3). The apparatus was positioned in the front passenger seat of the experimental vehicle, a 1963 Ford sedan, by means of a boom. The subject's head was kept in position by means of a chin rest.

The duration that the visual field was available for observation was controlled by three 4½-in. diameter shutters. An electronic timer controlled the voltage to the solenoids that operated the opening and closing of the shutters.

Test Site and Subjects

Experimental runs were conducted on a 5-mile stretch of unopened Interstate 64, a 4-lane divided freeway in Virginia. The utilized westbound road consisted of two con-

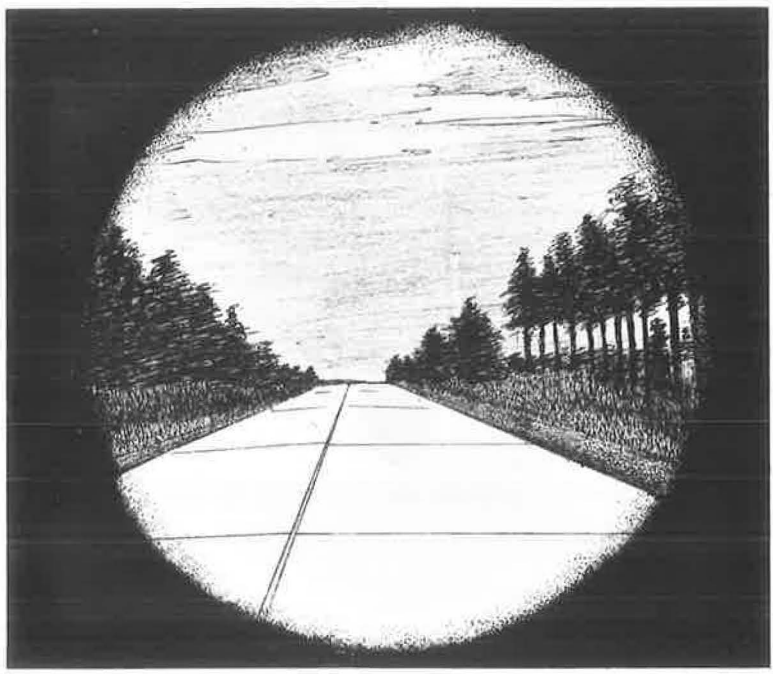

Figure 2. The frontal field.

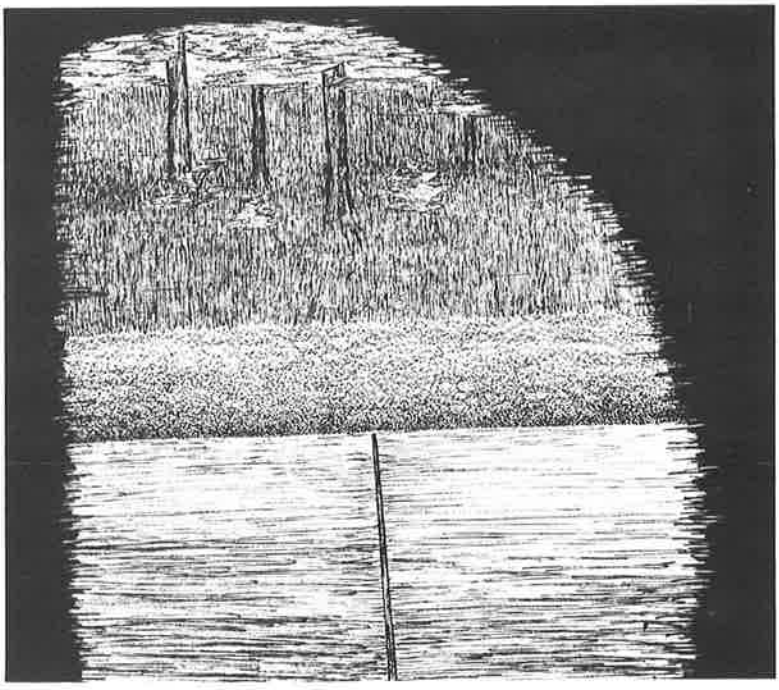

Figure 3. The peripheral field.

crete lanes 12 ft wide, free of road striping and of traffic. During the experiments, the vehicle was centered in the right-hand lane.

Four subjects were chosen at random from a list compiled from responses to call for volunteers. The three females and one male in the sample ranged in age from 18 to 37 years with a mean age of 25 years. All drove an automobile without glasses. Ortho-rater tests indicated visual acuity of 20/29 or better and peripheral field of 80 deg or more on both sides. Driving experience ranged from 2 to 20 years with a mean of 8 years.

Experimental Design

The research was carried out as a two-factorial design. The factor of experimental interest was called "mode of observation." It consisted of the segment of the visual field that provided the stimulus and was varied in two ways—25 deg frontally and 25 deg peripherally. The second factor, vehicle speed, was varied three ways—20, 40 and 60 mph. The four subjects ran through the six experimental conditions five times each for a total of 120 observations. Since acceleration is necessarily implicated in the attainment of velocity, the basic design given above was replicated. Experiment I attained velocities at a change of 1 mph/second and Experiment II at a change of 5 mph/second.

In both experiments, the visual exposure time was constant at one second. In both experiments, a masking noise eliminated auditory cues and the windows of the vehicle were kept closed to eliminate the cues from wind velocity. In Experiment I, the time between visual exposures of the field was constant at 45 sec to mitigate the influence of time on estimates. In Experiment II, visual exposure was made on achievement of the experimental velocity. The order of the experimental conditions was semi-random.

Instructions

The subjects were instructed to give verbal estimates of the velocity of the vehicle to the nearest 5 mph. It was impressed that head or eye movements were not to be made.

"Your view of the road will be blocked by the apparatus for most of the time that you are in the experiment. Every 45 seconds either the front or side shutters will open for a short time. You will not know if your view is forward or to the side so be ready to observe in either direction. The way to accomplish this is to stare straight ahead in what we call the stare mode. Try it. Staring straight ahead, you will be able to observe the sides without moving your eyes. As you did on the eye test.

"The sequence of events will be:

1. Dark phase for 45 seconds.
2. Tap on shoulder: prepare to observe.
3. Opening of side or front shutters: observe.
4. Closing of shutters: report estimated speed to nearest five miles.
5. Repetition of the above."

RESULTS

The analyses of variance (Table 1) show that the factor of experimental interest, mode of observation, is significant. The rate of change partially destroys the effect as is evidenced in the decreased level of significance in Experiment II.

Individual variation is at the chance level in Experiment I, but is significant in Experiment II. Therefore, the higher acceleration increases the variance associated with this source. Velocity is, of course, highly significant—the three levels chosen for this factor are easily distinguishable across acceleration level and mode of observation. The only significant interaction, Velocity × Subjects, occurs in Experiment II. Since the difference between the two experiments is acceleration, this interaction implies that the higher acceleration level which spreads the variance associated with the subject source affects the velocity levels differentially.

The meaning of the analyses of variance is clarified in Table 2, which shows the means and standard deviations for all experimental conditions. In both experiments, the mean estimates of velocity for the peripheral condition are higher than the mean estimates of the frontal conditions. The peripheral estimates of velocity are also close to the actual velocities. Thus, both hypotheses are corroborated by the experimental data.

The mean estimates of Experiment II are consistently lower than the mean estimates of Experiment I. Not only does the higher acceleration partially destroy the effect of observation mode, as reflected in the smaller mean difference of Experiment II, but it generally affects accuracy. All mean estimates with 5-mph acceleration are underestimates. Further, this negative absolute error increases with velocity.

There are two points of interest that concern the standard deviations of Table 2. Condition for condition, the standard deviations of Experiment II are smaller than those of Experiment I. Thus, though the higher acceleration produces the greater absolute error, i.e., produces greater deviation of the mean velocity estimates from the true velocity, it does so in a consistent manner. Secondly, the standard deviations associated with the peripheral means are generally smaller than those of the frontal means. And this variable error becomes

TABLE 1

ANALYSES OF VARIANCE

Source	df	Experiment I (1 mph/sec)		Experiment II (5 mph/sec)	
		MS	F	MS	F
Velocity	2	14,690.83	229.62***	11,290.00	386.51***
Mode	1	991.88	15.50***	130.21	4.46*
Subjects	3	42.98	NS	204.75	7.01**
V × S	6	125.28	NS	148.56	5.08***
V × M	2	47.50	NS	10.33	NS
S × M	3	140.48	NS	65.28	NS
V × S × M	6	59.03	NS	49.33	NS
ERROR	96	63.96		29.21	
Total	119				

*P <0.05
**P <0.01
***P <0.001

TABLE 2

MEANS AND STANDARD DEVIATIONS FOR THE EXPERIMENTAL CONDITIONS

Velocity		Experiment I		Experiment II	
		P	F	P	F
20	M	19.25	15.00	16.25	14.50
	SD	8.41	6.00	4.97	4.72
40	M	42.75	34.25	36.00	31.25
	SD	7.33	8.05	6.05	8.06
60	M	57.75	53.25	49.50	48.25
	SD	7.33	10.54	5.68	8.82

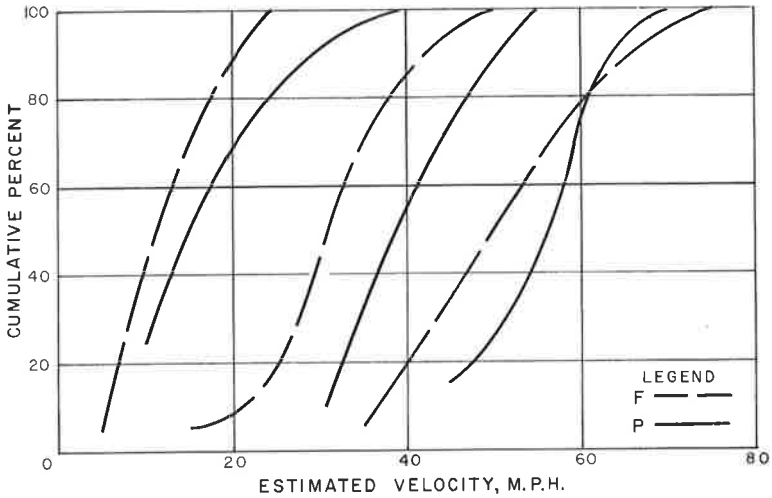

Figure 4. Cumulative percent, 1 mph/sec.

greater as velocity increases at the frontal condition, whereas it appears to be uninfluenced or getting smaller with increasing velocity at the peripheral condition.

The total range may be inspected in the cumulative frequency curves of Figures 4 and 5. The points on the curves which are crossed by the vertical lines would divide the curves in half if 50 percent of the estimates fell on each side of the true velocity. Most of the curves lie below the dividing line indicating a general tendency to underestimate in the experiment. Thus underestimation is here shown to be more strongly associated with the frontal stimulation and the higher acceleration. The higher acceleration results in more symmetrical, esthetically pleasing curves but displaces the whole distribution away from the true velocity.

The data are shown as bar graphs in Figure 6. The percentage of responses within 5 mph of the true velocity are rather stable in Experiment I with underestimates occurring more frequently at the frontal condition. In Experiment II the percent of re-

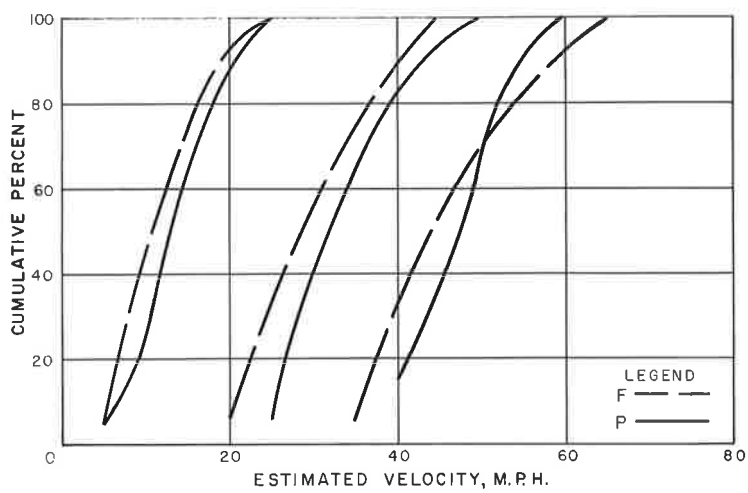

Figure 5. Cumulative percent, 5 mph/sec.

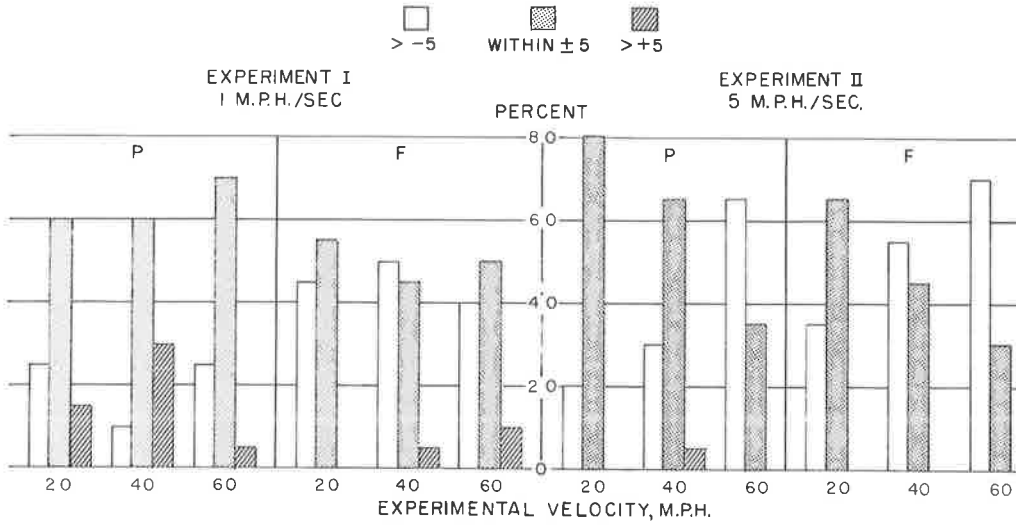

Figure 6. Percent of estimates within or greater than 5 mph.

sponses within 5 mph of the true velocity declines steadily with increasing velocity and underestimates become more frequent. Overestimates are almost absent.

DISCUSSION

The experiment strongly indicates that peripheral visual stimulation is more conducive to accurate speed estimation than stimulation of the frontal field. The immediate explanation for this result appears to be that angular velocity is much greater in the peripheral than in the frontal field. For example, under conditions of the experiment, at a vehicular velocity of 60 mph and 25 deg of field available, the maximum angular velocity is 81 deg per sec frontally and 1080 deg per sec peripherally. With a constant 1-sec period for observation, the peripheral stimulation is easier to differentiate because it is much greater. Angular velocity in both fields is directly proportional to vehicular velocity but since it is greater in the periphery by more than one order of magnitude, it is more accessible to scaling.

In addition, an attention mechanism was reasoned to play a factor in the formulation of the hypothesis tested. Since the perception of motion in the frontal field is detrimental to steering or tracking performance, the possibility exists that in "normal" driving the attention tends to focus on the fovea, that aspect of the frontal field which has the smallest magnitude of angular velocity. Thus, the secondary prediction, that frontal estimates would be of lower magnitude, is based on the same factors. The contrasting magnitudes of angular velocity and the habitual tendency to preserve clarity in the frontal field would not be sufficiently countermanded by the compensatory set established by the instruction to estimate the velocity of the vehicle.

It must be noted that the range effect—the underestimation of low speeds and overestimation of high speeds—did not obtain in this experiment. Rather, a general underestimation of velocity was seen which increased directly with velocity and acceleration. The most veridical perception of velocity occurred under the condition of minimal acceleration effects and peripheral visual stimulation. Quite possibly the range effect depends on the conditions of stimulation.

Previous investigations have left uncontrolled, i.e., under the control of the subjects, the observation time, nature of the sensory stimulation and acceleration of the vehicle. These three facts are a priori significant for the judgment of velocity. It is apparent that in the usual situation, in addition to the movement of the field on the retina, auditory cues of engine and road noise, kinesthetic and tactual cues of acceleration,

wind velocity and gas pedal displacement plus the instrumental aid of the speedometer are available. However, these cues are likely to be inappropriate in the more demanding situations. Our experiment was designed to partially simulate the condition where critical decisions must be made from the safety point of view. This condition, involving emergent traffic situations, calls for a reappraisal of the situation and updating of the information store on which decisions are made in a minimum of time.

In this experiment underestimation of absolute velocity was related to the frontal visual stimulation and the higher acceleration. Since underestimation or absolute error increases with speed, it is quite possible that the range effect results from a complex interaction of these two factors, velocity and acceleration, with others that are excluded from the experiment, i.e., engine noise, etc. From the point of view of veridical perception, it is unfortunate that velocity judgments rely heavily on acceleration. The estimates made under the higher acceleration, though more reliable, are less accurate. In this experiment, therefore, deceleration was more effectively sensed than acceleration and a net effect of acceleration, positive and negative, was to decrease dependence on the visual field. Since the effect of acceleration is not constant over individuals, the idea of a complex interaction is supported. The situation elicited in our experiment provides an example of the information being available in the environment but improperly processed.

The absence of a range effect is consistent with the findings of Hakkinen, who also found underestimation at all velocities for the conditions where the camera was in the position of the driver and the subject not in control of the vehicle. Thus the lack of significant correlation between techniques strongly suggests that the processes underlying judgment are altered by substituting frontal for peripheral stimulation.

It is now possible to suggest that the adaptation hypothesis as an explanation of highway hypnosis is insufficient. Time or exposure to a particular velocity per se does not necessarily result in gross underestimation of high speeds. However, the attention, after prolonged driving, may become restricted to the frontal field, the normal fixation area, and thereby produce the effect. Further research should be directed toward this area.

The study is important in isolation for several reasons. Wohl (8) indicates that the proper steering input is a complex function of vehicle dynamics and is inversely proportional to the speed or square of the speed of the vehicle depending on the primacy of the visual cue used as reference on the roadway. Poulton (9), in analyzing tracking as an analogue of the driving task, emphasizes that speed anticipation, the decision aspect based on the perception of or inference about the stimulus movement, is of importance in steering. Similarly, Cumming (10) states that the ability to program ahead with speed control is the mark of a developed skill.

Thus, for the single-car situation, the appreciation of velocity plays a role in the prediction of future states of the system which involves coordination or response programming and the elimination of reaction time limitations. Therefore, steering control is intimately connected to appreciation of velocity. Additionally, multiple car maneuvers such as car-following and passing always involve the projection of one's vehicle into the future.

In addition to absolute velocity, the driver has to process information concerning heading, headway and lateral placement. However, none of these topics can be studied in total isolation and the understanding of any one process leads to a better definition of the integrated driving task.

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Controls for Automotive Brakes

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•IT is well known that the automotive death rate per year is over 40,000; this can be dramatized as "In 1965, 35 times more deaths than Viet Nam" or 500,000 deaths since 1953. For every death, there are many injuries; in 1965 there were 49,000 deaths and 1,850,000 injuries. In addition to the suffering and sorrow from death or injury, there is the dollar; $8.9 billion of them in 1965 (1). The problem is serious.

The problem also is complex. Just as the accidents occur from Key West to Seattle, during summer and winter, on expressways and dirt roads, in compact and competition cars, with sober teenagers and tight senior citizens, the solutions must be many-faceted. This paper describes some exploratory research on the controls for automotive brakes. The hope is to increase the operator's permissible margin of error (avoid accidents) or, alternatively, to decrease the consequences of an error (less serious accidents).

THE EXISTING SYSTEM

The presently used control system for automotive brakes is foot-actuated. Although it is possible to actuate the control with the left foot, existing designs make this awkward and fatiguing so, in effect, the control usually is actuated by the right foot. According to Morgan et al (2), "It requires about 20 percent longer to respond with the foot than the hands; response with the preferred limb is about 3 percent faster than the nonpreferred limb. Thus, for right-handed operators, when the controls must be selected entirely on the basis of speed of activation, the order of selection should be right hand, left hand, right foot and left foot."

However, in the typical driving task, the left foot is idle while the other three limbs are occupied. The right foot is assigned the task of activating both the acceleration control and the deceleration control. The left foot is utilized only in the 20 percent of automobiles that have standard transmissions and then only when the gears must be shifted.

EXPERIMENT ONE

Task

Sixty-watt light bulbs were positioned 15 ft ahead of the front bumper and in line with the headlights of a stationary 1964 model American auto. Upon the onset of either light, the subject honked the horn or depressed the brake pedal. The conditions were:

1. Honk horn. Starting position of hand on horn ring.
2. Honk horn. Starting position of hands on steering wheel.
3. Depress brake. Starting position of left foot on brake.
4. Depress brake. Starting position of right foot on depressed accelerator.

The time from the light onset until the horn or brake light received an electrical pulse was timed electronically.

Subjects

Twelve university faculty and students, with an average age of 38, volunteered. Each subject had four times recorded for each of the four conditions. The sequence of conditions was randomized.

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Results

The average time for Condition 1 was 0.38 sec, for 2 was 0.56 sec, for 3 was 0.39 sec and for 4 was 0.59 sec. The times seem consistent with the results of other investigations of reaction times. Warrick, Kibler and Topmiller (3) reported a median time of 0.60 sec for alerted secretaries to reach 11 in. to a button from a typewriter keyboard; this is roughly analogous to Condition 2 which had an average time of 0.56 sec. A Wilcoxon Matched-Pairs Signed-Ranks test (4) established that Conditions 1 and 3 were not significantly different, 2 and 4 were not significantly different but 1 and 3 were significantly shorter than 2 and 4.

Discussion

Perhaps the most interesting fact is that, for drivers experienced in the existing right-foot system, both braking with the hands resting on the brake control and braking with the left foot resting on the braking control were significantly faster than the existing system. The improvement of approximately 0.2 sec is equivalent to 9 ft at 30 mph and 18 ft at 60 mph.

The advantage seems to reside in the elimination of the movement of the body member to the control rather than foot vs hand differences. When Condition 1 is compared with 3 and 2 with 4, the hand is faster than the foot by 0.01 and 0.03 sec. These differences are an order of magnitude less than the differences between the body member moving to the control vs the body member starting at the control. Since the elimination of the body limb movement not only had the largest saving but also eliminated the possibility of moving and missing, it was decided to concentrate on elimination of movement between controls.

One possible concept is to design the brake control so that the left foot (the only body limb not normally occupied during driving) rests on the control. Another concept is to give one of the three remaining limbs the brake control task in addition to its primary task but to combine the controls of the primary task and the braking task. If the control is to be combined, probably it is simpler mechanically to combine the brake control with the accelerator than with steering since the position of the foot is relatively constant while the position of the hands varies not only from driver to driver but also while turning. Of course, a brake control which simply required moving the entire wheel rather than a portion of the wheel might be quite satisfactory.

Because a combined brake and accelerator pedal was available (5), it was the focus of the next experiment.

TABLE 1

REACTION TIMES FOR BRAKING WITH COMBINED CONTROL, EXPERIMENT TWO

Subject Characteristics	No. of Subjects	Avg Reaction Time (sec)
Subjects also in Exp. One	11	0.41
Other subjects	110	0.42
Total subjects in Exp. Two	121	0.42
Female with heels	11	0.44
Female without heels	29	0.44
Total female	40	0.44
Total male	81	0.41
Age of subject:		
14-25	55	0.40
26-35	15	0.40
36-45	9	0.42
46-65	39	0.45
Unknown	3	0.44

EXPERIMENT TWO

Winkleman's combined control (5) activates the accelerator when the toe is pressed down and activates the brake when the heel is depressed. An interlock prevents simultaneous operation.

Task

A single 60-watt light was placed approximately 5 ft straight ahead of the subject who was seated in an ordinary wooden chair in a laboratory. He depressed the "accelerator" until the needle on a dial before him pointed to 40; at the light onset, he lifted his toe and depressed his heel 1 in. to actuate the "brake." Each subject was given four trials after 10 to 20 sec instruction and practice.

Subjects

One hundred twenty-one visitors to an Engineering Open House volunteered their services; of the 121, 11 had also participated in Experiment One. The subject characteristics and the results are given in Table 1.

Results

The subjects from Experiment One had times representative of the 121. The average time for these 11 subjects when using the right foot in Experiment One was 0.62 sec; the 0.41 sec when using the combined control was significantly ($p < .01$) lower when it was tested with a Wilcoxon Matched-Pairs test (4).

Therefore, although a direct comparison between controls could not be made for all 121 subjects, it seems likely that the average savings of 0.21 sec enjoyed by the 11 would also be enjoyed by the other 110.

Some other characteristics also are interesting. There seemed to be no difference in reaction times between women with high heels and those without high heels. The lower time for men than women is not statistically significant, but men normally have faster times than women (6). The correlation between age and reaction time was significant ($p < .001$) when the Spearman Rank Correlation Coefficient was calculated.

Since these data, as are most performance data, were positively skewed, it is of interest that the minimum reaction time was 0.27 sec, the maximum time was 0.94 and 95 percent of the average times were less than 0.60.

The data, although suggestive, are not conclusive since the experimental conditions were not exactly identical. In addition, it was noticed that the subject's times decreased with practice. Therefore, the third experiment was tried.

EXPERIMENT THREE

Task

Two brake control devices were used:

1. An American Automobile Association reaction timer; this "black box" of the conventional system had a "clutch" pedal, a "brake" pedal, an "accelerator," signal lights and a timing mechanism.
2. The Winkleman combined control.

Microswitches on the combined control were connected with the AAA timer and with two 60-watt light bulbs mounted at eye level in front of the subject's chair. Light 1 was activated by the accelerator of either control; light 2 could be activated by the experimenter provided light 1 was on. When light 2 was activated, a relay produced a "snap of the fingers" sound; thus the subject had both a visual and an auditory cue. The timer automatically recorded the time between the onset of light 2 and the 1-in. depression of the brake.

Subjects

Twenty-five university faculty and students, with an average age of 28, volunteered.

Procedure

Three conditions were tested:

1. Depress conventional brake. Starting position of left foot on brake.
2. Depress conventional brake. Starting position of right foot on depressed accelerator.
3. Depress experimental brake. Starting position of right foot on depressed accelerator portion of the combined control.

Each subject had ten times recorded for each of the three conditions. The sequence of conditions was randomized. Each subject took from three to six practice trials.

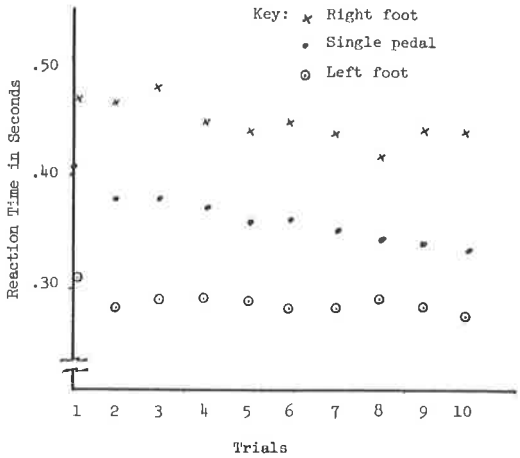

Figure 1. Effect of learning on reaction time for the three controls.

TABLE 2

ANALYSIS OF VARIANCE, EXPERIMENT THREE

Source	df	SS	F
Subjects	24	2,546	—
Controls	2	86,993	129.45*
Trials	1	4,793	38.04*
Sub × Controls	48	672	7.72*
Sub × Trials	24	126	1.45
Controls × Trials	2	486	5.59*
Residual	48	87	
Total	149		

*$p < .01$.

Results

A subjects × treatments (trials) × treatments (conditions) analysis of variance was calculated (Table 2 and Fig. 1). For computational simplicity the total of the first five trials was considered as trial one and the second five as trial two in the analysis of variance.

Both trials and conditions were significant ($p < .01$). The significant effect of trials means that the subjects improved with practice and the significant effect of conditions means that the reaction time was affected by the type of control. A Wilcoxon Matched-Pair Signed-Rank test established that the times for all three controls are different from each other; that is, the 0.29 sec when using the left foot was significantly ($p < .05$) less than the 0.36 sec of the combined control and the 0.36 sec was significantly less than the 0.45 sec when using the right foot.

The significant subject × control interaction indicates that certain subjects did better on certain controls; the significant trials × controls interaction indicates that the rate of learning was not the same for all three controls.

Discussion

The experiments to date have been more interesting than informative. A laboratory is certainly not the same as the highway. The controls which minimize movement may be even better when operated in an actual automobile, or far worse. The relatively small decrement with age for the combined control indicates it might be especially advantageous for older drivers.

Training may or may not be a problem. None of the users to date have had any problem even with as little as 10 sec instruction. Of course, none were in danger of losing their life either. A system in which the existing brake pedal remained in place and a combined accelerator-brake pedal was connected in parallel might be advantageous. It would eliminate any possible regression problem in emergencies, would permit simultaneous use of the brake and accelerator and, perhaps most important, would minimize automotive industry opposition to something new since it could be sold as an extra-cost option.

In any case it seems that additional research is desirable to give drivers that "most important quarter-second."

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Discussion

E. S. KRENDEL, Professor of Statistics and Operations Research, University of Pennsylvania—It is always commendable when new techniques or devices are suggested to improve the performance of motor vehicles. Tradition and the harsh demands of economic competition have dominated design and innovation decisions for far too long. In the present climate of interest in improving the safety with which man-automobile systems operate, long overdue suggestions may finally get a fair hearing.

Konz and Daccarett have examined human acceleration and braking behavior in an effort to use the output actuators—hands and feet—of the human operator more effectively. A measure of the importance of this problem is indicated by the present confusion which exists among driver training schools as well as among licensing jurisdictions on the advisability of braking with the left foot; in fact, about 25 percent of these jurisdictions fail candidates for braking with the left foot.

Belzer and Huffman (7) examined brake response with left and right feet in various starting positions and thus clearly demonstrated that "right foot braking in the usual manner is superior to left foot braking unless the left foot is already poised on the brake pedal when a demand for quick braking occurs." The question of what dangers exist because of the possibility that the left-foot braker has allowed his right foot to linger on the accelerator has not been explored. Belzer and Huffman obtained time delays somewhat lower than did Konz and Daccarett. For example, the quivalent condition to Experiment One, Condition 4, for which the paper under discussion determined the delay to be 0.59 sec, resulted in 0.46 sec in the referenced study. The reason may be that the subjects were younger—all of them being 15 years old in the earlier study.

A general agreement exists, however, between the findings, where comparable, of the paper under discussion and the paper by Belzer and Huffman, and this serves to reinforce the general findings.

That a parallel braking system—i.e., a conventional and a combined accelerator and brake system—will be a feasible interim device to overcome habit prejudices is rather doubtful at present because of the additional costs. As the authors rightly point out, more data, particularly on highway and stress-producing circumstances, will be needed for a more complete evaluation. Certainly, the combined brake and accelerator pedal is an attractive and promising concept.

However, I have personal reservations of a more general sort. Drivers may fall into a car-following behavior which is consistent with the delays which they know exist in the system. As an example of introspective data, I know that I behave differently when I drive a car with power brakes than when I am using a conventional hydraulic braking system. I adapt in such a way as to, in effect, maintain more or less equal margins of error. I suspect that this is a common characteristic of drivers. It is certainly the characteristic form of behavior exhibited by humans in coupling with a control system characterized by lags. If this view be true, then the major problems in traffic safety may be more successfully attacked in the perceptional and judgmental aspects of driving than by effecting possible improvements in braking times. Despite this caveat, however, I do feel that the possible improvements suggested by Konz and Daccarett are desirable and that their suggested method of implementation merits further test and study.

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J. E. UHLANER, U.S. Army Personnel Research Office—The extremely interesting study on automotive braking devices interests me not only because it is a carefully planned and executed research project, but also because it is representative of the caliber of human engineering required as input to the overall systems approach to automotive safety. This approach studies the characteristics of the total organized system, rather than the separate parts. In the area of automotive safety this involves the interaction of the driver, his machine and the total surrounding environment, and encompasses the design of equipment, both machines and roads, and the selection and training of drivers.

This systems approach is relatively new, but the need for it has been recognized for several years. In 1964, Drucker and I reported the results of a study of driver selection tests (8). At that time we stated that while licensing in terms of the personal limitations of the driver is a legitimate basic approach to reducing accidents, it was, and still is, our belief that a broader approach is obviously needed. This need arises from the fact that the traffic accident usually occurs not as a result of a single variable—such as inattentiveness because of fatigue or preoccupation, slippery roads, or insufficient light—but as a result of a complex of variables. Indeed, one of the most encouraging signs of progress in recent years is the success of driving safety researcher personnel in reducing the total problem to manageable proportions. Just as the military man and the weapon or machine with which he interacts and the environment in which he performs his assigned duties are viewed as a man-machine or man-weapon system, so the driving process gradually has begun to be considered as a system. From this point of view, malfunction of the driver system can occur because of (a) poorly designed and mantained vehicles, (b) poor roads and poorly controlled traffic patterns, and (c) poor driving.

In line with this, I believe that ultimate reduction of accidents is likely to come about through more effective human engineering of the automobile, the road, and the traffic system, as well as through greater effort in understanding the driver process. Particularly needed is a better understanding of the relationships involved in various situational behaviors—that is, the psychological functioning in driving both at night and in daylight on turnpikes, in rural areas, and in the city.

This research approach dictates highly sophisticated simulation facilities and should be directed toward the alternate outcomes of educating the potential driver (and retraining the old driver) to difficulties inherent in a variety of conditions, or limiting the situations in which he may be permitted to drive.

Since public officials are inclined to shrink away from any action which would eliminate millions of drivers from the road in order to reduce the national accident rate, it seems necessary to embark on this systems approach to driving research. This is essentially a reexamination of the total problem to consider the interaction involved in the man-vehicle-road-traffic complex and to derive principles of engineering traffic, vehicles, roads, and identifiable driver limitations.

In line with this, it would seem that the next step in the program initiated by Konz and Daccarett would be to validate their findings on a large population sample. This sample would have to include not only the range of average drivers, but also those at either end of the spectrum—the very good and the very bad, in terms of whatever criterion is adopted. Then, the results could be fed into a simulation study which would examine the task within the overall driving setting rather than in isolation in the laboratory. These results could be fed, in turn, into vehicle design studies and into driver training research. In this manner, the findings reported here could be developed into an operational improvement of the modern automobile—an improvement based on a combination of carefully controlled laboratory research, simulation research and the latest advances in equipment design and training techniques. It is only through such an integrated approach to the entire problem of the man-vehicle-environment complex that progress in automotive safety research will be accomplished.

Reference

8. Uhlaner, J. E., and Drucker, A. J. Selection Tests—Dubious Aid in Driver Licensing. Highway Research Record 84, pp. 41-53, 1965.

ROBERT C. O'CONNELL, U.S. Bureau of Public Roads—I first want to compliment the authors for undertaking research which I believe does have a direct application to operating a motor vehicle more safely. Nearly everyone has heard of the existing differences between the several state driving examinations. In some states, driver examiners are refusing licenses to applicants who use the left foot for braking during the driving test. In other states, examiners criticize drivers for not using left-foot braking for more sensitive control of the vehicle in heavy traffic. Each method of braking has several good and bad points. For example, critics believe that drivers having the left foot poised on the brake tend to "ride" the pedal, with the result that the brake lights are excessively illuminated thus lowering their value in intervehicular communication. There probably is more control of the vehicle with the left foot poised on the brake, but what then happens to this driver when he must drive a car equipped with a clutch and change his braking habits entirely? This is the main reason that some driver examiners feel the left foot should be on the floorboard when the vehicle has an automatic transmission and that all accelerating and braking should be done with the right foot.

Early automobile design required a driver to use both feet in controlling a car. Both feet were in regular use between the clutch, brake, accelerator pedal, and light switch, thus requiring heavy use of the slowest acting parts of the body, the limbs. I agree with the authors that our current method of vehicular control has historically grown "like Topsy."

This particular study and others that have measured brake reaction time point out that generally three-tenths of a second can be saved in braking time by using the left or right foot poised over the brake. Three-tenths of a second difference in response time amounts to 4.4 ft at 10 mph, 13.2 ft at 30 mph, and 30.8 ft at 70 mph. Therefore, we are talking in terms of improving stopping distances by approximately 4 ft to about 10 yd in emergency braking situations. At first glance, this might seem insignificant; however, in an emergency situation such distances can make a difference between a near miss and a collision. In my opinion, the advantages offered by making a small adjustment in the design in the vehicle braking system are well worthwhile.

Although the position of the operating controls on vehicles has frequently been changed, I believe we must agree that we are generally bound by the criteria of steering through the use of hands and arms with the control of acceleration and deceleration to be provided by the feet and legs. It would seem almost incongruous to require the hands, fingers, or arms to provide the braking function while at the same time attempting to steer the vehicle. Therefore, what limitations in vehicle design must we consider in the application of criteria designed to improve braking time?

Before attempting to answer this question, I believe a review of past and present practices would be helpful. The problem of left-foot braking became prevalent with the advent of the automatic transmission, and about a decade ago it appeared that the standard-shift vehicle would be a relic of the past. However, a current fascination for the "jet set" is to discuss "four on the floor"; whether we like it or not some younger drivers are prone to "dig out" at the turn of the traffic signal light and these drivers do prefer a manual clutch. Similarly, some drivers in mountainous regions prefer to have the clutch operation for use in downhill deceleration. Therefore, it appears that there will always be some need in vehicle design for manual clutch operation. By the same token, the acceleration function probably must be limited to the right foot even though many of us probably remember the throttle and spark control on the steering post of the old "Model T."

This problem involves driver limitations as well as vehicle design limitations. Our modern driver must be an ambidextrous individual because of the many different types of vehicles that he may be required to drive. A personal car generally differs from the fleet car or the commercial truck that an average driver must regularly use in his day-to-day business and pleasure. It therefore seems to me that, with the physical handicaps of the human and the mechanical limitations of the vehicle, we can adopt the results of this paper to effect an improvement in the design of the vehicle.

Possibly the only difference I might express with the authors' recommendations would be to suggest that the acceleration pedal be designed separately from the braking pedal. I would argue against the proposed system of utilizing a combined brake and accelerator

with an over-the-center action. In my opinion, there is an advantage gained in some lateral transfer of the foot or at least the toe part of the foot from the accelerator to the brake pedal with no movement of the leg. I am also of the opinion that there is more sensitivity in the toe of the foot than in the heel. The advantage gained would be in requiring similar toe actions for both accelerating and decelerating. In other words, we are asking for a similar response to accelerate the vehicle and to brake it which depend upon a similar pressure by the toe. Thus, the harder you push the accelerator the faste the vehicle will go and similarly for braking the harder you push the brake the more quickly you will decelerate. However, no research exists to support this opinion. Many commercial buses do utilize two separate pedals for toe action, leaving the heel in approximately the same position on the floorboard.

I believe the results of this study can be utilized for design improvements that would provide an accelerator pedal and a brake pedal on a continuous plane, approximately level with each other so that the heel of the right foot can remain in one position, with no need to raise the entire leg for the proper braking action. Perhaps the brake will have to be a power brake, which would minimize the downward movement of the toe. I further believe that the length required to depress the brake, that is, the downward motion, should not be greater than the totally depressed position of the accelerator.

This research paper does advance our knowledge of human factors as they affect driving capabilities, and I would like to see the laboratory results applied to a real situation to further evaluate the effectiveness of improved vehicle design. In particular, I think the design changes that would keep the heel of the right foot in a permanant position on the floor, utilizing the toe of this foot to effect the process of acceleration and deceleration through the use of two separate pedals, offers excellent possibilities for safer motor vehicle operation.

STEPHAN KONZ and JOSE DACCARETT, Closure—We thank the reviewers for their constructive comments. We feel it is unfortunate that the impetus for a systems study of automotive brakes must come from a university and that none of the reviewers is from the automotive industry, but perhaps it is unrealistic to expect the industry to be more concerned with safety than sex.

Normative Model for Control of Vehicle Trajectory In an Emergency Maneuver

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This paper proposes a mathematical norm against which driving simulation results (one driver and one vehicle interacting with an environment of fixed and moving obstacles) can be directly compared. The norm is, in effect, an optimal control strategy (in terms of steering, braking and accelerating) given specific constraints on driver's visual span, dynamic equations of the vehicle, and the cost function or trading relation between penalty for colliding with an obstacle and the penalty function of increased control effort or time. The mathematical model, embodied in a digital computer, is being used by the authors in conjunction with both a closed-circuit TV laboratory simulator and actual road tests. To illustrate the idea, some empirical trajectories obtained on the driving simulator are presented together with various computed trajectories which are optimal for particular cost functions and a simplified dynamic model of the automobile. Three appendixes describe the simulator, give comparable data from both simulator runs and road tests with a standard automobile, and provide a simple numerical example of dynamic programming.

•A major hurdle to the satisfactory engineering of private vehicles and highways is the lack of quantitative criteria for driver performance. How far can we trust the driver? Under what conditions do we permit autonomous control of the vehicle by the driver with a modicum of help by signs and traffic laws and policemen, and under what conditions should we by-pass the driver and impose active control on the vehicle from outside, on the basis that the expected behavior of the driver does not fall within satisfactory tolerances?

Two theoretical approaches have borne some relevance to this problem. The theory of traffic flow, deriving from classical fluid mechanics plus developments in applied probability such as theory of queues, predicts flow phenomena based on average behavior of large numbers of vehicles and drivers in relatively steady streams (1). The micro-behavior of one vehicle relative to its environment is not tractable by this approach.

The second approach, the theory of automatic control, has been applied to the individual driver, but in a somewhat misguided way. While quasi-linear differential equations are now available which predict the human controller's response surprisingly well in the context of flying aircraft and spacecraft along smooth, well-charted paths (2), no such success has been achieved in the automobile driving context. The explanation is simple. In the former case the human controller's inputs are well defined, continuous, single-valued functions of time, and "tracking" or "error nulling" in the closed-loop servomechanism sense is not too bad an explanation of what the human is actually doing (though there is some room for argument here, and the aircraft takeoff and landing operations do not fit the servomechanism paradigm). If automobile driving were a matter of following a white line across the California salt flats, the servomechanism model would fit.

Paper sponsored by Committee on Driving Simulation and presented at the 45th Annual Meeting.

THE PROBLEM

Unfortunately, keeping the vehicle on the road is not the crux of the driver's problem, and the driver's more difficult tasks are to:

1. Visually identify the obstacles in his immediate environment as to the penalty for hitting them, relative to costs of effort and time expenditure;
2. Predict the future course of those obstacles which are in motion, i.e., other vehicles and pedestrians;
3. Chart a course through all the obstacles which will minimize the expected penalty over some "interval of predicament"; and
4. Control his vehicle to effect the programmed trajectory.

It is these requirements for preview of the input and preplanning of control which make driving a car a more sophisticated control task than keeping an aircraft or spacecraft on a command course by error nulling.

The problem, it would appear, can be formulated in terms of the currently developing theory of optimal control. Given an initial state (set of initial conditions), a terminal state or range of allowable terminal states, and a cost function which specifies the incremental costs and constraints in moving from any one particular state to another in the space between initial and terminal states, the minimum cost trajectory (and the optimal control strategy) can be straightforwardly and uniquely specified. Included in the cost function are (a) the costs of colliding with each of the fixed or moving obstacles; (b) the cost of time in getting between initial and terminal states; (c) the constraints on maximum forward accelerating and decelerating forces and sideward accelerating force; (d) the manual control dynamics (steering wheel or pedal displacement to vehicle position). The suggested means for computing the optimal trajectory, because of its generality, is the dynamic programming algorithm of Bellman (3), and the means for implementing this algorithm is a digital computer. These techniques will be described by example.

Having once determined an optimal trajectory, one can observe in a simulated or controlled vehicle experiment with a human subject, how much and in what way the human driver deviates from the optimal control strategy (or the vehicle deviates from the optimal trajectory). Alternatively one can assume the human is an optimal controller (we know in the simple servomechanism case he is not far off) but that he is subject to internal constraints additional to those posed by the vehicle and environment. In this case one can try to find under what additional constraints the human driver is optimal. (This so-called "indirect problem" of optimal control is less straightforward than the "direct problem.") With either orientation, the aim is to discover the human's cost trade-offs in a particular context of vehicle control. This cost or criterion problem is not a consideration of available models of the human operator. In the preview situation it would seem to be the governing factor.

The theoretical problem will be formulated under one set of assumptions, then the computation technique will be described. Several alternative formulations will then be given, and finally some associated problems of experimentation will be discussed.

CASE 1: COMPLETE PREVIEW, DETERMINISTIC PREDICTION

Physically, the problem is to start from the origin of an xy Cartesian space at some initial time t_o (Fig. 1) and chart a best course down the road. It will be convenient to let x, y and t have values only at discrete points at regular intervals Δx, Δy, Δt. There are k obstacles, some fixed (beer cans, parked cars, etc.) and some moving (vehicles, pedestrians, bicycles, etc.). We will assume in this first case that all obstacles are within the driver's preview and that all obstacles maintain constant derivatives so that the positions of all obstacles at each time t are determined (can be predicted) by the driver at t_o:

$$\begin{aligned} x_k(t) &= x_k(o) + \dot{x}_k(o)t + \ddot{x}(o)\,\frac{t^2}{2} + \ldots \\ y_k(t) &= y_k(o) + \dot{y}_k(o)t + \ddot{y}_k(o)\,\frac{t^2}{2} + \ldots \end{aligned} \tag{1}$$

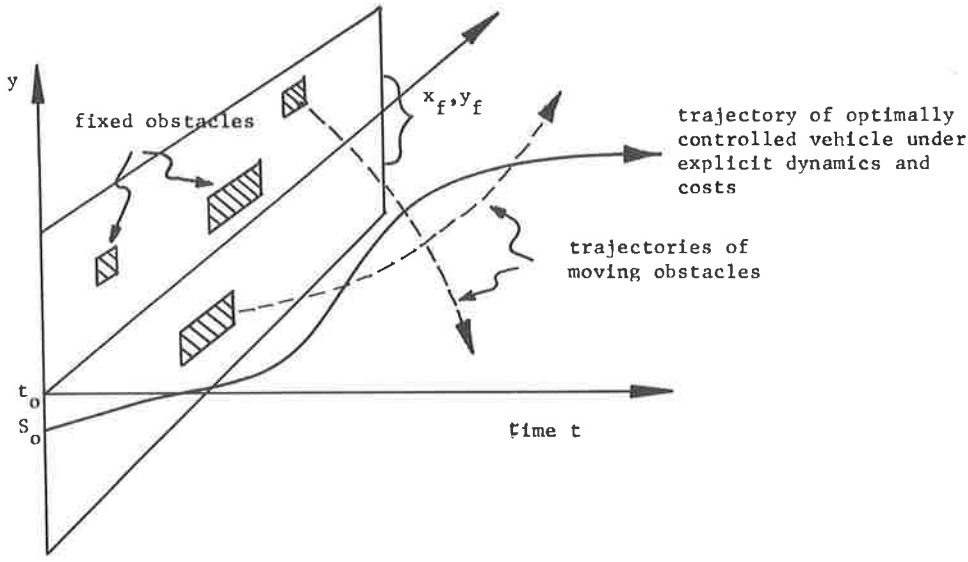

Figure 1. Physical space of desired trajectory and obstacles.

where x_k and y_k are the forward and lateral positions of the kth obstacles. For each obstacle in any given increment of time Δt we assume the driver perceives a cost C_k, which may have a value only for a collision, i.e.,

$$C_k = c_k, \quad | x-x_k | < w_k \text{ and } | y-y_k | < \ell_k; \; C_k = 0 \text{ otherwise} \tag{2a}$$

or C_k may be a function of the miss distance from some obstacles or targets, i.e.,

$$C_k = K_{kx} | x-x_k |^{\alpha} + K_{ky} | y-y_k |^{\beta} \tag{2b}$$

where x and y specify position of the controlled vehicle and w_k and ℓ_k represent effective length and width of the kth obstacle.

We assume some equations of motion for the vehicle, such as

$$\begin{aligned} A\ddot{x} + B\dot{x} &= f_x \\ C\ddot{y} + D\dot{y} &= f_y \end{aligned} \tag{3}$$

where f_x and f_y are tire forces. A simplest assumption for the sake of our example is that steering dynamics are sufficiently "tight" and accelerating or braking sufficiently fast that the driver can command f_x and f_y directly, i.e., the dynamic lags of the human neuromuscular response and steering, tracking and accelerating mechanisms are not appreciable. (The elemental human reaction time of, say, 0.25 sec is compensated by the driver's preview and anticipation.)

Since the driver is constrained by fuel expenditure, tire wear and social criticism from too violent use of the steering wheel, brake and accelerator pedals, we must assume an "effort" cost over a unit time increment, such as

$$C_e = K_{ex} | f_x^3 | + K_{ey} | f_y^3 | \tag{4}$$

The values f_x and f_y may be constrained to be less than certain limiting values, $f_{x\,max}$ and $f_{y\,max}$, which represent skidding.

There is one more cost to consider, a cost C_T per unit of time to reach a terminal state $x(t_f)$, $y(t_f)$, $\dot{x}(t_f)$, $\dot{y}(t_f)$ or one of a set of such states. This represents how big a hurry the driver is in.

It is convenient to consider the total cost function as the cumulative cost up to last time increment plus the incremental costs for collision, for effort and for time

$$C(t) = \underbrace{C(t-1)}_{\substack{\text{cumulative}\\ \text{cost to}\\ \text{last time}\\ \text{stage}}} + \underbrace{\Sigma_k\, C_k(t)}_{\substack{\text{incremental}\\ \text{collision}\\ \text{cost}}} + \underbrace{C_e(t)}_{\substack{\text{incremental}\\ \text{effort cost}}} + \underbrace{C_T(t)}_{\substack{\text{incremental}\\ \text{time cost to}\\ \text{reach required}\\ \text{terminal stage}}} \qquad (5)$$

It is the ratio of the weightings on these costs which we seek to determine for the human driver in various situations. For example, we know that the weighting C_k he attaches to collisions is very high. Letting $C_k \to \infty$, there is still presumably a variety of control strategies which will trade off between how much of a hurry he is in, C_T, and his reluctance to be a wild driver, C_e.

DETERMINING OPTIMAL TRAJECTORIES BY DYNAMIC PROGRAMMING FOR GIVEN OBSTACLES, GIVEN VEHICLE DYNAMICS, AND GIVEN COST WEIGHTINGS

For purposes of computing a minimum cost trajectory it is convenient to think in terms of a state space, a space of sufficient variables (and derivatives) of the system at each stage in time that transition from given state $S(t)$ at time t to another given state $S(t+1)$ at $t+1$ completely specifies the cost incurred over that time interval Δt.

C_T is dependent only upon whether the present state satisfies the terminal conditions, S_f. C_k for a collision with an obstacle positioned at x_i and y_j depends only on $S_{ij}(t) = x_i(t)$, $y_j(t)$. C_e for a jump (Fig. 2) from a state $S_{ijuv}(t-1)$ to a different state $S_{IJUV}(t)$ depends upon $S_{ijuv}(t) = x_i(t)$, $y_i(t)$, $\dot{x}_u(t)$, $\dot{y}_v(t)$ since the effective $\dot{x}_{iI}$ across the intervals is $x_I(t) - x_i(t-1)$ and the effective $\ddot{x}_{uU}$ across the interval is $\dot{x}_U(t) - \dot{x}_u(t-1)$, and similarly for $\dot{y}$ and $\ddot{y}$ in Eq. 3. Thus at each time stage t we need a four-dimensional space in S_{ijuv} with sufficient range of the variables chosen artfully at the outset to include those states through which the optimal trajectory has reasonable probability of passing (Fig. 2).

The basic idea of the dynamic programming algorithm is best explained by example. For the reader not at all familiar with this optimization procedure a numerical example is provided in Appendix C.

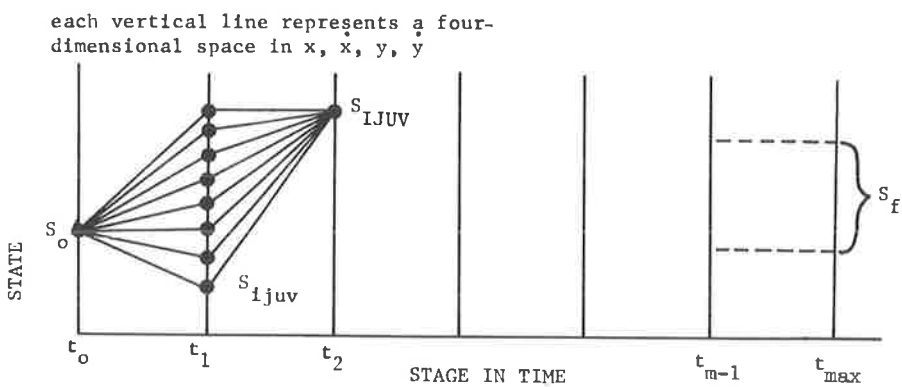

Figure 2. State space of desired trajectory and obstacles, showing trial paths to determine least cost path to $S_{IJUV}(t_2)$: IJUV is a particular state to which all ijuv states at the previous stage are considered paths.

In the present problem the dynamic programming algorithm proceeds as follows. We start at either end of the time range of interest, i.e., at $S_o(t_o)$ or at $S_f(t_{max})$; it does not matter unless there is no prespecified terminal condition. Assuming we start at t_o, the cost of jumping to each next start $S_{ijuv}(t_1)$ is determined from Eqs. 1, 2, 3, 4, and 5, and each resulting value $C_{ijuv}(t_1)$ is stored. Next we consider in turn each of the states S_{ijuv} at t_2, to determine the path by which the least cost trajectory arrives at that particular $S_{IJUV}(t_2)$. In other words we choose the one of all $S_{ijuv}(t_1)$ from which to set out for the particular $S_{IJUV}(t_2)$ under consideration in order that the cumulative cost C_{IJUV} at t_2 be least. This involves a brute force application of Eqs. 1, 2, 3, 4, and 5 to each and every S_{ijuv} at the last stage paired with the single S_{IJUV} at the present stage. Since every C_{ijuv} for the last stage is already in memory, the least cost is easily obtained following Eq. 5 as

$$C_{IJUV}(t) = \underset{ijuv}{\text{minimum}} \left[C_{ijuv}(t-1) + \underset{\substack{\text{from ijuv at } (t-1) \\ \text{to IJUV at } (t)}}{(\Sigma_k C_k + C_e)} + \underset{S \text{ not an } S_f}{C_T} \right] \tag{6}$$

where now $t = t_2$. This equation is essentially a statement of Bellman's principal of optimality. The optimal path is then simply the previous state by which to obtain least cost for the present state. This value is stored:

$$P_{IJUV}(t) = \underset{\text{minimum}}{[ijuv]} \tag{7}$$

These cost and path values are stored in memory and the process is repeated for every S_{ijuv} in the state space at t_2. We then have in memory a least cost to get to each S_{ijuv} at t_2 and the corresponding best path to get there. The cost information at stage t_1 may then be thrown away.

The whole process is repeated at each successive stage forward in time, until t_{max} is reached. At this last computation stage, either only a unique state S_f is allowed, or the least cost state within a set of states S_f is chosen. Since any stored path P(t) specifies the best state at the adjacent time stage, and P at that time specifies the best state at the next time, and so on, the optimum path is easily traced through the stored table of best paths. A computational flow chart is shown in Figure 3.

The great saving of the dynamic programming algorithm is that the amount of computation is a linear progression with T and not a geometric progression. For N states at T times only N^2T comparisons need be made, not N^T, the number of different trajectories, and, more importantly, only NT values of path P need be stored, not N^T values. The dynamic programming algorithm can handle with ease various essential nonlinearities in the vehicle equations and cost functions which some other optimization techniques cannot.

EXEMPLARY FITS OF THE MODEL TO DRIVING SIMULATOR DATA

Using a driving simulator (described in Appendix A), an experienced subject was instructed to drive a straight course down the center of an open track, and that upon reaching a certain point along the track two "targets" (negative obstacles or obstacle "holes") would suddenly appear before him at fixed positions down the road. He was to overrun the targets with equal penalty for lateral errors on both targets. He controlled only steering. His forward velocity was held constant. The subject had been trained in the same experiment and knew that the location of the targets was a random distance from the center of the track and was equally probable to the left or to the right. He also knew that in some cases both targets appeared at once (type A) and in other cases the second appeared just as he started responding to the first (type B), which was actually ½ sec after the first appeared.

Figure 4 is a plot of an ensemble average of ten runs of type A for one particular location of the targets (heavy crosses) and an average of ten runs of type B for the same

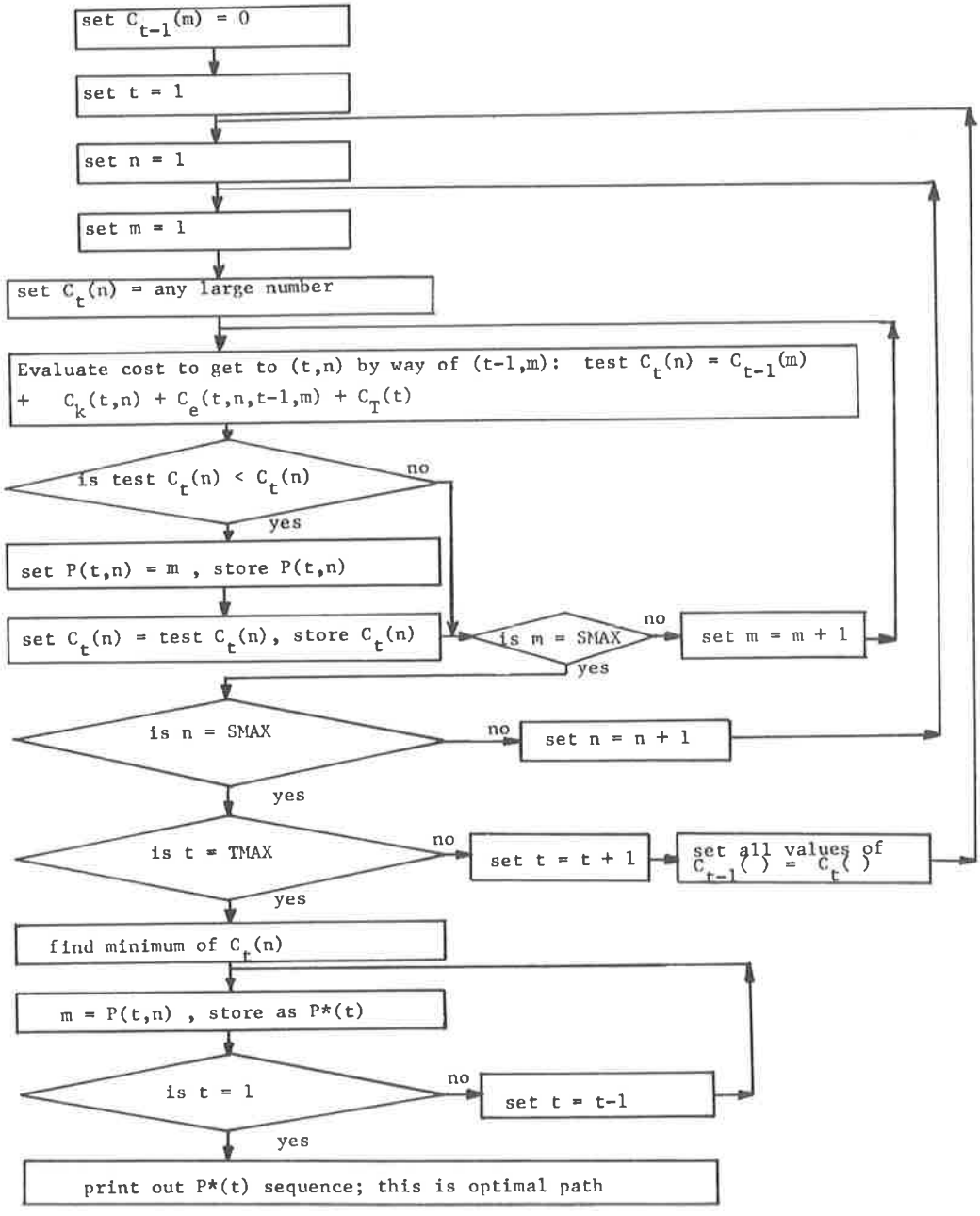

Figure 3. Computational flow chart for dynamic programming example: m is a running index for every ijuv state at stage t-1, n is a running index for every IJUV state at stage t.

target locations. Note that the ordinate and abscissa are not the same scale. As indicated, these runs had been interspersed with runs for other target locations.

On the same plot are exemplary optimal trajectories for various performance cost functions. The latter are based on the extremely simple model in which the lateral position of the vehicle (the ordinate of the graph) is the second integral of the vehicle's front wheel (or steering wheel) position. The vehicle's forward velocity (rate of motion along

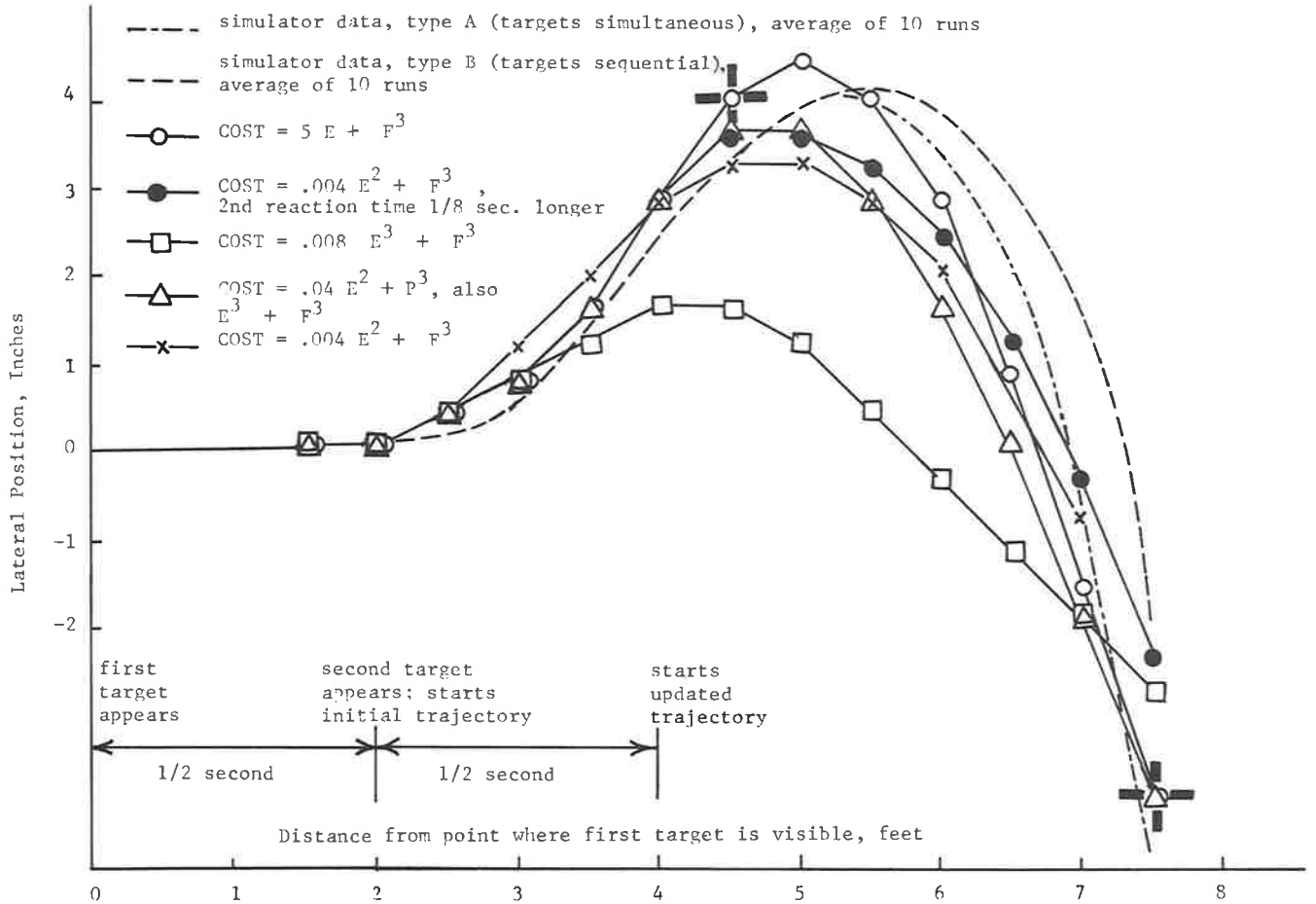

Figure 4. Examples of optimal trajectories for various cost functions of error (E) and effort (F) compared with driving simulator data.

abscissa) is constant. All of the computed optimal trajectories shown presume a type B stimulus situation where the second target appeared ½ sec after the first appeared. Our model assumes that the driver planned an optimal trajectory with respect to the first target which is to begin after his own ½ sec reaction time (after 2 ft). The finite position change is therefore at the 2½-ft point. At the same time he started his initial optimal trajectory the second target appeared, but he could not initiate an updated trajectory until after his ½ sec reaction time.

The empirical data seem to suggest that for all cost functions the trajectory updating occurred after a longer delay with respect to the appearance of the second target than with respect to the first target. However, it is not the authors' purpose to draw quantitative conclusions from these data but only to note qualitatively how different cost functions result in different forms of approximation to the empirical data.

An experiment similar to that described above was performed with a standard automobile in a large parking lot. This experiment is described in Appendix B, and some results are given which compare vehicle trajectories of the actual car with those of the driving simulator in the same type of task.

ARTFUL USE OF COMPUTER MEMORY

The dynamic programming algorithm poses severe demands on computer memory, and it is important to understand these if practical solutions are to be implemented. For example, suppose in the present problem x and y were reticulated into 40 increments, $\dot{x}$ and $\dot{y}$ into 10 increments, and t into 100 increments. Then we must keep in memory at any one time the least costs of every state at two adjacent time stages, requiring $2 \cdot 40 \cdot 40 \cdot 10 \cdot 10 = 320{,}000$ locations. In addition we must store paths for every state at all 100 time stages, or 16,000,000 locations. Clearly we cannot put all of this in the core memory. (Of course this is still better than separately evaluating the $160{,}000^{100}$ separate trajectories which are possible.)

Fortunately there are ways out. These will not be detailed here, for they would comprise at least another paper this size. Briefly, however:

1. One can store in core memory the cost information, i.e., the C_{ijuv} values of only a small part of the state space at only the two stages where least costs are being computed, retaining the rest on tape or disk files and playing it back into core when needed. Suppose one could allocate 1000 core locations to cost values at each of two adjacent stages and do tape-to-core and core-to-tape transfer in blocks of 1000. The number of block transfer cycles to make all possible comparisons of states at adjacent stages is the square of the ratio of the state space size to the size of the memory block, which is 160^2 in our present example. More block transfers would be necessary for storing paths.

2. To save storing on tape the required 16,000 blocks of best paths, the 160,000 path specifications at each stage can be printed out on paper. A human clerk should be able to trace from one stage to the next in less than a minute since he is told by the present P(t) specification precisely where to go for the next P(t). But if only a one-character printer is available at 10 numbers per sec, printing the required 160,000 best paths would require close to 5 hours of printing per stage plus the paper, clearly not a practical approach for problems of this size, but certainly feasible for smaller problems when long-term computer memory is not convenient (or when a high-speed printer is!).

3. The state space can be broken into blocks (hyperspace rectangles) and optimal trajectories determined for a number of Δt intervals within these blocks by interpolation techniques, storing in each case the costs and paths to get to the surfaces of these blocks. This technique presumes a preferred direction of motion through the state space and still requires storage of optimal costs and paths in a large number of states at different time stages, but it greatly reduces the high-speed storage requirement (4).

4. Nominal trajectories can be drawn through the state space and improved trajectories only in the neighborhood of the nominal trajectory can be considered. Thus, if we consider 100 time-units in a state space of 5 increments in both x and y and 3 increments in both x and y, centered on the nominal trajectory, we have a state space of only 225 numbers. The dynamic programming solution is now easily within reach of the smallest computer (far better than brute force comparison of 225^{100} possible trajectories).

This small state space even makes practical the print-out technique of method 2 above if it is necessary. Successive iterations can be made to keep improving the current "optimal" trajectory (though one must be careful in order to avoid converging on sub-optimal paths, a built-in limitation of all steepest ascent techniques in which the best path is not within the range of original consideration). Much experimentation remains to be done using people in roles of artfully posing nominal trajectories and working with the machine in real time to improve them.

CASE 2: COMPLETE PREVIEW, PROBABILISTIC PREDICTION

Having looked at some computational aspects of the original formulation, let us return to a slightly different formulation. In case 1 we assumed that at t_o the future positions of all moving objects are known by direct extrapolation on present states and a perfect optimal control strategy is computable from the outset. However, we may alternatively assume the human driver does not plan his control on precise extrapolations, that he knows he could not make accurate prediction anyway. Therefore, let us assume that the locations (of the centers) of various moving obstacles are known only on a probabilistic basis. In particular let us assume a two dimensional unimodal probability distribution with its mean at $x_k(t)$, $y_k(t)$ and with a variance which increases with time. Thus, in evaluating the penalty for a potential collision with obstacle k,

$$C_k = c_k' \exp \frac{-[(x - x_k)^2 + (y - y_k)^2] \; (t + K_k)}{R_k} \tag{7}$$

This adds a growing uncertainty or smudge to the prediction of obstacle positions with parameters R_k (a "rate of smudge") and K_k (initial "smudge") in lieu of the length and width parameters ℓ_k and w_k in Eq. 2a. This formulation presumes the human driver is unable to take in new information and update the optimal control strategy during the course of any one predicament time interval, t_m.

CASE 3: COMPLETE PREVIEW, UPDATING OF TRAJECTORIES TO COMPENSATE FOR EXTERNAL INFLUENCE ON OTHER OBSTACLES

When the potential collision predicament lasts more than several seconds there is time for the driver to update his optimal control strategy based on new estimates of the positions and velocities of moving obstacles. If the kth obstacle takes some arbitrary path (subject to about the same dynamic constraints as the vehicle whose control we are interested in), after some time t_u the driver would make a new extrapolation, analogous to Eqs. 1:

$$\begin{aligned} x_k(t - t_u) &= x_k(t_u) + x_k(t_u) \; (t - t_u) + \ldots \\ y_k(t - t_u) &= y_k(t_u) + y_k(t_u) \; (t - t_u) + \ldots \end{aligned} \tag{8}$$

Then he would take $S_u(t_u)$ as an initial state and recompute an optimal trajectory based on the newly predicted obstacle positions at future time stages, with or without "smudge" considerations on his predictions. This might be repeated several times during the course of a total predicament interval t_{max}. The optimal trajectory in each case would be based upon the range of x remaining.

CASE 4: CONSTRAINED PREVIEW, UPDATING OF TRAJECTORY

Suppose that either because of poor visibility or limited perceptive capability the driver can attend only to obstacles less than x_{lim} ahead. If x_{lim} were short relative to the total range of x involved in the present collision predicament, we would certainly expect the driver to update his optimal trajectory as often as he could, each time basing his optimal strategy on all the obstacles in his present preview—some of those he saw on the early computation plus the new obstacles which the "moving window" of his preview

might now reveal to him. All of the exemplary trajectories given earlier included one updated computation based on new evidence when the second target (obstacle "hole") appeared.

CASE 5: SIMULTANEOUS OPTIMAL CONTROL OF TWO VEHICLES WITH UPDATING OF TRAJECTORIES

Suppose, in case 3, that one of the k obstacles, instead of taking an arbitrary path, is a vehicle being controlled optimally with respect to its driver's preview. And suppose, further, that the drivers of both vehicles update their optimal control strategies periodically during a collision predicament. The study of certain cooperation/competition, or "social" aspects, of driving would seem to be tractable in terms of the costs netted each of the drivers as a function of the various parameters of the control situation previously described plus the updating interval t_u.

AN ORIENTATION FOR EXPERIMENTS

The aim, to restate, is to determine how much and in what way the human driver deviates from an optimal controller (the direct problem), or under what additional constraints to those posed by the vehicle and environment the human driver is optimal (the indirect problem), and by either means discover the nature of the driver's control cost criteria. It has been shown that the greatest difficulty in implementing computation of optimal control strategies or trajectories by dynamic programming is the computer memory requirement, and that the use of nominal trajectories artfully posed by a human experimenter can reduce the memory requirement to a very workable level. Suppose a driving simulation is set up under careful control such that the dynamic parameters of Eqs. 3 are few and known, the states of the k obstacles are known, the constraints on $f_{x\,max}$ and $f_{y\,max}$ are represented, and the relative costs assumed at the start of the experiment for C_e ("wild driving"), C_k (collision) and C_T (elapsed time) are at least realistic and are made explicit to the driver. Then empirical trajectories recorded from the simulation can be used directly as nominal trajectories for an optimal control computation in a digital computer using the same parameters.

Having available such relative cost weightings for the human operator under a reasonable range of circumstances, one can speculate on their use for design purposes. A group of transportation designers in conference around a scale model simulation of a highway intersection (or the futuristic equivalent) could pose different configurations to the highway, the vehicles, the traffic signals, etc., by physically changing objects in the simulation, or typing into a computer conditions of speed, weather, etc., for sample vehicles. The answer to their "what would happen if" questions would be produced in short order by the computer and displayed by a mechanical plot of probable trajectories of the various vehicles.

ACKNOWLEDGMENT

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Appendix A

A BRIEF DESCRIPTION OF THE LABORATORY DRIVING SIMULATOR

The driving simulator consists of a 16-inch long vehicle (Fig. 5a) which carries a television camera. Its front wheels are steered remotely by means of a servomechanism, and it is accelerated and braked remotely by means of an electric motor and an electric clutch. The vehicle is designed to have steering dynamics similar to those of a conventional automobile. The vehicle is driven along a 40-ft long model roadway (Fig. 5b) and into a "test section" where a variety of fixed and moving objects can be made to suddenly appear; e.g., cardboard "obstacles" (or, alternatively, "targets") are driven up through slits in the test track at random positions by means of electronically timed solenoids. The electrical umbilical is suspended from an overhead rail in such a way that it does not cause a significant drag force.

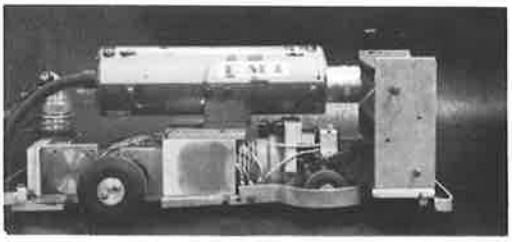

Figure 5a. Servo-controlled model vehicle with vidicon and periscope.

The experimental subject sits in a darkened cab controlling the vehicle with actual steering wheel, brake and accelerator (Fig. 5c) and has a 30-degree view in the TV monitor equivalent to what he would see if seated in the model vehicle.

Timing is accomplished by means of photocells strategically placed along the model roadway. Records of the vehicle's trajectory are generated by a device on the vehicle which makes a continuous mark on a piece of black paper laid along the test section of the model roadway.

Figure 5b. Model vehicle approaching targets in test section.

Figure 5c. Experimental subject in darkened booth viewing targets on TV.

Appendix B

COMPARISON OF TRAJECTORIES FROM SIMULATOR AND FULL-SCALE VEHICLE TESTS

A standard automobile (late model Ford Mustang) was accelerated along a straight course (in a large parking lot) to about 40 miles per hour. The driver's forward vision was blocked; he maintained lateral alignment by vision through the side window. At a predesignated point along the course the driver's forward view was restored by a passenger and the driver attempted to overrun two successive targets (rubber lane marking cones), centering them on the front bumper, with equal importance attached to lateral position errors for both targets.

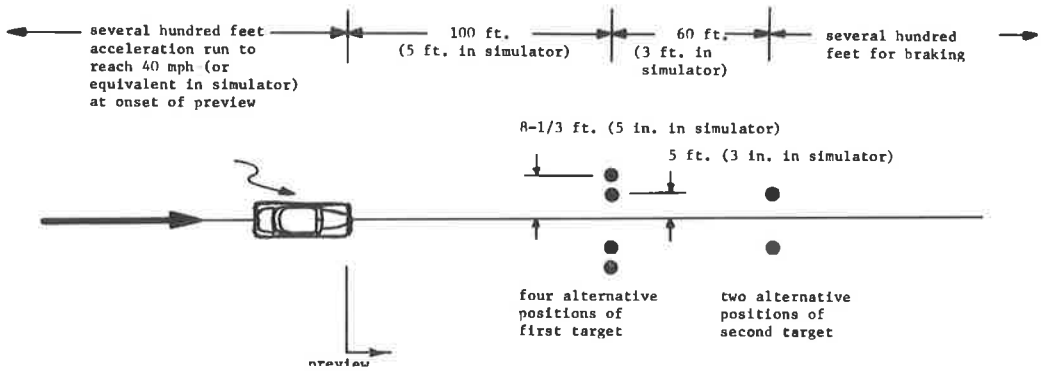

Figure 6. Plan view of experimental course.

A plan view of the experimental course is shown in Figure 6. As indicated, the analogous course and task were set up on the driving simulator described in Appendix A. (This was a different group of subjects and slightly different task from that described earlier in the body of the paper.) The first target was randomly placed in one of the four alternative positions shown and the second target in one of the two alternative positions shown.

On each run with the standard automobile a record was obtained (using stripes of toothpaste spread on the parking lot) of the position and the angle at which the vehicle crossed each of the target lines. Comparable measurements were made using an ink marking device built into the driving simulator.

Experimental results from four of the eight alternative target configurations are show in Figure 7. This set of four all started to the left; the target configuration in the four not given was the mirror image, and the resulting trajectories were roughly comparable

Comparison of results from the full-scale tests and from the driving simulator revealed one striking difference: there was a marked tendency to oversteer the driving simulator by the relatively inexperienced subjects used. (It will be noted in reference to the simulator results given earlier for a comparable task with an experienced subject that there was no such tendency to oversteer.) This is believed to have been due primarily to the lack of kinesthetic and vestibular cues (velocity and acceleration senses) available to the driver of the simulator, for these senses are known to play the same role that artifical rate feedback does in automatic control of otherwise undamped system

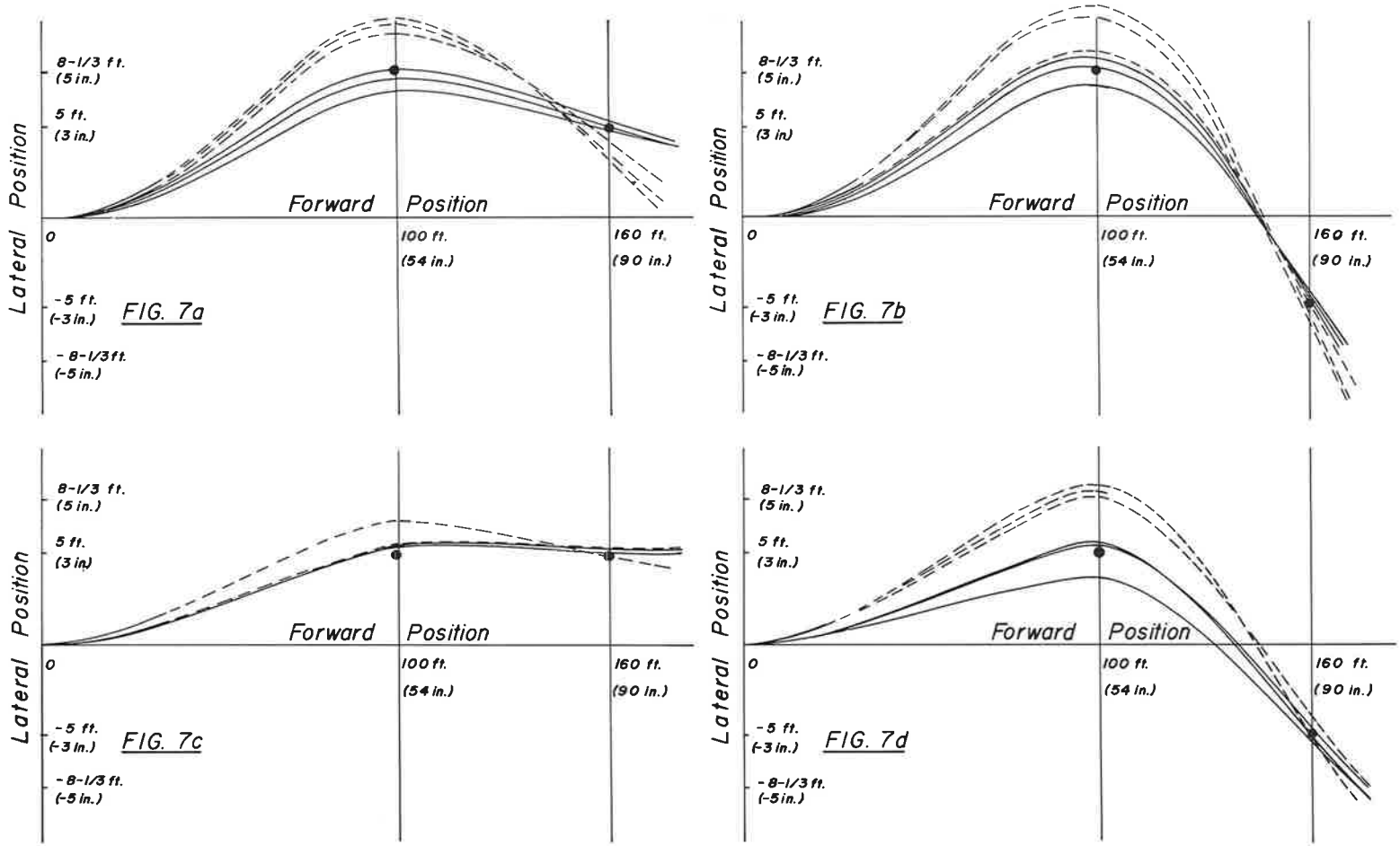

Figure 7. Trajectories from simulator and full-scale vehicle. Key: dashed line and numbers in parentheses = simulator; solid line = full-scale vehicle.

Appendix C

A SIMPLE NUMERICAL EXAMPLE OF DYNAMIC PROGRAMMING

Assume at each of four stages in time after the initial stage there are three possible states of a system, represented by circles in Figure 8, and that from each state at a given stage, the cost to get to any state at the next stage is directly a function of the two states. These costs are represented by the numbers along the lines connecting the states

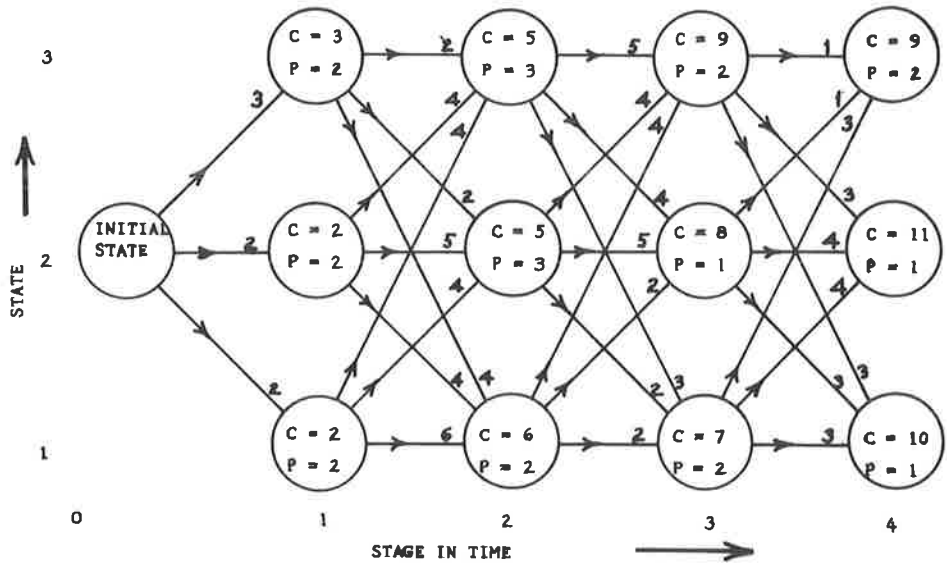

Figure 8. A simple numerical example of dynamic programming: numbers above lines represent state transition costs; numbers in circles represent cumulative least cost values C and best path values P.

Starting with stage 1, the cost, C, indicated within each circle at stage 1 is simply given by the number along the line from the initial state; the least-costs path, P, is 2 in every case since this is the only previous state available.

At stage 2, the cost to state 1 is the least of path 1 (cost = 2 + 6 = 8), path 2 (cost = 2 + 4 = 6), and path 3 (cost = 3 + 4 = 7). The state 1 circle is thus marked with the least cost and best path. Similarly the cost to state 2 is the least of path 1 (2 + 4), path 2 (2 + 5) and path 3 (3 + 2) and is thus marked as cost 5 and path 3, and similarly for stat 3 at stage 2.

Having completed the least cost and best path determination for stage 2 we can throw away all cost information about stage 1, since in determining costs at stage 3 we need know only the costs to the states at the previous stage. But the best path information must be retained.

At stage 3 we similarly obtain the least cost and corresponding path to reach each of the three states, and so with stage 4.

Now, assuming stage 4 is the terminal stage we could require that state 2 be the terminal state. We observed from our stored path information that we should have come there via state 1 at stage 3, and at state 1 at stage 3 we observe we should have come via state 2 at stage 2, thence via state 3 at stage 1, and finally back to the initial state. This is the optimal trajectory, the least-cost way of reaching state 2 at stage 4.

On the other hand we could have looked for the least-cost state at stage 4, which is found to be state 3. The optimal trajectory to reach this state is found to be entirely different: state 2 at stage 3, state 1 at stage 2, state 2 at stage 1, and back to the initia state.

All trajectories need not be different. The optimal trajectory to state 1 at stage 4 is seen to be the same as to state 2 except for the last step.

The reader should note that in determining the least-cost paths from any one stage to the next the number of trial comparisons was 9, the square of the number of states, and only the three best path values were stored. Both the total number of comparisons and the total number of stored path values was linear with the number of time stages traversed.