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CONTENTS

FOREWORD

Recognizing the significant safety contribution possible from improved driver performance capabilities, the researchers whose papers appear in this RECORD have attempted to learn more about the human aspects of driving. The material will be of interest to safety and human factors professionals, driver education specialists, and others concerned with the driver's ability to gather, understand, and act on pertinent information.

Zwahlen set out to develop a method of classifying drivers according to their risk-acceptance decisions, their visual-perception capabilities, and their driving skills. Seeking a driver safety index, he experimented in the laboratory with 4 subjects in a drive-through gap situation and concluded that the method seems sensitive and successful in detecting differences among the drivers.

The perceptual threshold of drivers in following cars was studied in a series of experiments designed by Evans and Rothery to circumvent difficulties that had led to potentially erroneous results in earlier work. Their results indicate that the dominant cue used to judge the sign of relative motion between cars is the average value of the relative speed divided by spacing, that there is response bias in favor of indicating negative rather than positive relative motion, and that there is a high level of sensitivity to relative motion. Stimulating and challenging discussions of this work are presented by Mortimer and Snider, both of whom have done work in the same field.

In the final paper, Olsen describes a skid simulator developed to provide a laboratory model of a skidding automobile for use in driver training and research. The model allows the driver to experience the yaw motions of a skidding vehicle and affords him the opportunity to control the skid through application of the brake pedal, the accelerator, and the steering wheel. It is planned to use the simulator to study the human-factors aspects of acceleration effects on perception.

DRIVER RISK-TAKING: THE DEVELOPMENT OF A DRIVER SAFETY INDEX

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A methodology to classify automobile drivers according to their risk-acceptance decisions, their visual-perception capabilities, and their driving skills is presented. A drive-through gap situation was used to develop and experimentally investigate the concept of the driver safety index. The concept is based on the assumption that a driver's "safety distance" between the mean of his psychometric risk-acceptance function and the mean of his psychometric visual-perception function for a gap, expressed in multiples of the standard deviation of his driving-skill distribution for centerline path deviations in the gap, is a representative measure of his risk-taking behavior. Four subjects were used in the experimental investigation. A sequential estimation procedure was used to obtain points on the psychometric visual-perception and risk-acceptance functions. The experimentally obtained values indicate that the methodology seems sensitive and successful in detecting differences among the drivers. In addition, the drivers who exhibited either rather large or small values under a given set of experimental conditions exhibited similar large or small values under a different set of experimental conditions. Considerable differences with respect to how the subjects perceived gaps of a given size were found.

•ACCEPTING risks is probably one of the most basic characteristics of mankind. Wherever people engage in some sort of activity, we may expect risk-taking situations. Entering a busy freeway, overtaking a slower moving vehicle, selecting a particular driving speed range, and driving through obstacles are just a few examples of the many risk-taking situations an individual may encounter when driving a car.

Risk acceptance is a basic area of concern in safety. For many years it has been evident to those working in the safety field that individual risk-taking behavior appears to be a major factor in accident causation (23, 25). Studies with respect to risk-taking have been conducted in various fields and disciplines. A series of studies dealing with risk acceptance in man-machine systems and driving (3, 4, 5, 6, 19, 24, 25, 26) represents the background for this research. Much pioneer research has been conducted in related areas such as accident proneness (30), personality correlates (1, 9, 21, 22, 28), decision theory and information-seeking (7, 11, 12, 13, 20, 29), and passing behavior and gap acceptance (2, 8, 9, 14, 16, 17, 18). The research presented here is thought to be one of the first attempts to measure a driver's risk-acceptance behavior in a real driving situation within the framework of his visual perceptual capability and his driving skill.

THE RISK-ACCEPTANCE PROCESS

A drive-through gap situation was used to develop and experimentally investigate the concept of the driver safety index (DSI). Experiments using a similar gap situation

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have been conducted (3, 4, 6, 19). A stationary gap situation is simple when compared with other risk-taking situations such as overtaking or gap-acceptance at intersections. Although little is known about the risk-acceptance process in a gap situation, a risk-acceptance schema can be theorized that incorporates the gap situation, the driver factors, the vehicle factors, the driver decisions, and the outcome. A risk-acceptance schema representing the drive-through gap situation is shown in Figure 1. It is assumed that biographical factors, psychological factors, sociological factors, and previous life experiences, as well as the subjective value of the vehicle, provide the underlying basis for a driver's inherent value judgment. It should be noted that the subjective value of the vehicle is not necessarily limited to a utility value for a dollar and cents amount but may be based on other features of a bio-robot relationship between a driver and his vehicle, as suggested by Cohen and Preston (6). It is assumed that at the time a driver is perceiving a gap, the value judgment with respect to the utility of driving and the utility of not driving is immediately available. It is assumed that a driver has a rather good subjective knowledge about his ability to drive the vehicle as closely as possible through the center of the gap. A driver's driving skill is represented by the standard deviation of vehicle path error from the gap centerline, which includes an element of chance resulting from errors generated by a vehicle's steering mechanism. It should be noted that these random errors beyond a driver's control may represent a considerable proportion of the total standard deviation. It is assumed that the visual perceptual capability of a driver with respect to judging the exact size of a gap, or the task requirements, represents the major uncertainty element in the sensory judgment process of matching personal steering skills with the task requirements. During the approach toward the gap this sensory process of matching personal driving skill ability with the visually perceived task requirements, or gap size, may be repeated for a number of times. It is assumed that this sensory judgment cycle represents the nucleus of the gap risk-taking situation.

THE DRIVER SAFETY INDEX CONCEPT

Based on the risk-acceptance schema in Figure 1, it seems almost mandatory that a driver's risk-acceptance decisions should be viewed within the framework of his visual perceptual capability and his driving skill ability. The DSI concept is based on the assumption that a driver's "safety distance" between the mean of his psychometric risk-acceptance function and the mean of his psychometric visual-perception function for a gap, expressed in multiples of the standard deviation of his driving skill distribution for centerline path deviations in the gap, is a representative measure of his risk-taking behavior.

The DSI for a given set of experimental conditions is defined as follows:

$$\mathrm{DSI} = \frac{\mu_{RA} - \mu_P}{\sigma'_S}$$

where

μ_{RA} is the mean of the psychometric risk-acceptance function for a given set of experimental viewing conditions;

μ_P is the mean of the psychometric visual-perception function for the same set of experimental viewing conditions as were used in the risk-acceptance experiment; and

σ'_S is the adjusted standard deviation of the driving-skill distribution for a given set of experimental driving skill conditions.

The following steps outline how a driver's DSI is obtained from experimentally collected data:

1. The mean μ_P and the standard deviation σ_P with respect to judged gaps of equal car width are obtained from the experimental data. These two parameters are used to represent the driver's visual perceptual capability. The standard deviation is not directly used in the DSI. However, σ_P is used by the experimenter to obtain some idea about the consistency of a driver's perceptual judgments. Both estimates are expressed in inches.

2. The mean μ_{RA} and the standard deviation σ_{RA} with respect to the risk-acceptance decisions are obtained from the experimental data. These 2 parameters are used to represent the driver's risk-acceptance behavior. Again, the standard deviation is not directly used in the DSI but is used to give the experimenter some idea about the consistency of a driver's risk-acceptance decisions. Both estimates are expressed in inches.

3. The mean μ_S and the standard deviation σ_S with respect to vehicle deviations from the gap center are obtained from the experimental data. If it is assumed that the vehicle deviations from the gap center are normally distributed (experimentally confirmed) with a mean μ_S, any absolute deviation of the mean μ_S from the gap centerline will result in some increase with respect to the probability of failure, or making contact with the obstacles, for a given positive gap clearance. The skill measure used in the DSI concept should therefore be based on an adjusted standard deviation σ'_S, which will account properly for the increase in the probability of contact due to a given absolute deviation of the mean μ_S from the gap centerline. The adjusted standard deviation σ'_S is defined as the standard deviation of a normal distribution with a mean of zero that yields the same probability of contact for a given positive gap clearance as the normal distribution with mean μ_S and standard deviation σ_S. Thus, to determine σ'_S for a given positive gap clearance, the probabilities of contact have to be determined for the left-hand tail and the right-hand tail of the normal distribution with mean μ_S and standard deviation σ_S. The sum of these 2 obtained tail probabilities is then divided by 2 and the appropriate Z-value from a standard normal table is assigned to this tail probability. This Z-value represents the number of adjusted standard deviations that make up half of the positive gap clearance. Dividing half of the positive gap clearance by the Z-value will provide the adjusted standard deviation σ'_S in inches. (Note that $\sigma'_S \geq \sigma_S$.)

4. The mean gap estimate of judged equal car width is subtracted from the mean gap estimate of the risk-acceptance decisions. This difference represents a driver's appreciation for safety. A large positive difference would generally suggest a rather high appreciation for safety, whereas a small positive difference would generally suggest a rather low appreciation for safety. A negative difference would suggest that a driver is making irrational decisions most of the time.

5. The obtained difference between the gap mean of the risk-acceptance decisions and the gap mean of the visual perceptual judgments will be divided by the adjusted standard deviation σ'_S. The DSI is thus a dimensionless number that represents the positive difference attributed to a driver's appreciation for safety in multiples of his actual driving skill.

The following example will illustrate how a single DSI is determined from a given set of experimental data. In this example the visual perception mean μ_P has been assumed to be 73 in. and the standard deviation σ_P 3 in. The risk acceptance mean μ_{RA} has been assumed to be 91 in. and the standard deviation σ_{RA} 3.8 in. These values are rather typical for a 46-ft static viewing distance and an 80-in. wide car at the gap. The two psychometric functions are plotted as a function of the gap size in the top half of Figure 2. Based on a 90-in. wide gap, a 79-in. wide car and a 20-mph driving speed, the mean μ_S of the driving skill distribution has been assumed to be located 1.2 in. to the left of the theoretical gap center. The standard deviation of the driving skill distribution σ_S has been assumed to be 2.75 in. Using the previously outlined steps, the adjusted standard deviation σ'_S was determined as 3.0 in. The driving skill distribution is shown in the lower half of Figure 2.

Based on the foregoing data, a DSI of $(91.0 - 73.0)/3.0 = 6.0$ is obtained. A DSI of 6.0 would suggest that this particular driver would probably be classified as neither a "truly" high risker (DSI range 0-3) nor a highly cautious individual (DSI range > 15) but would straddle these 2 extremes.

According to the DSI concept the "truly" high risker (low DSI, range 0-3) would be an individual who seems to have assigned rather low utilities to the range of possible bad outcomes. His risk-acceptance decisions appear to be based on a set of value judgments that seem rather conducive to engaging in risk-taking situations characterized by high subjective probabilities of failure. It should be noted that if a "truly" high risker

Figure 1. Risk-acceptance schema for the drive-through gap situation.

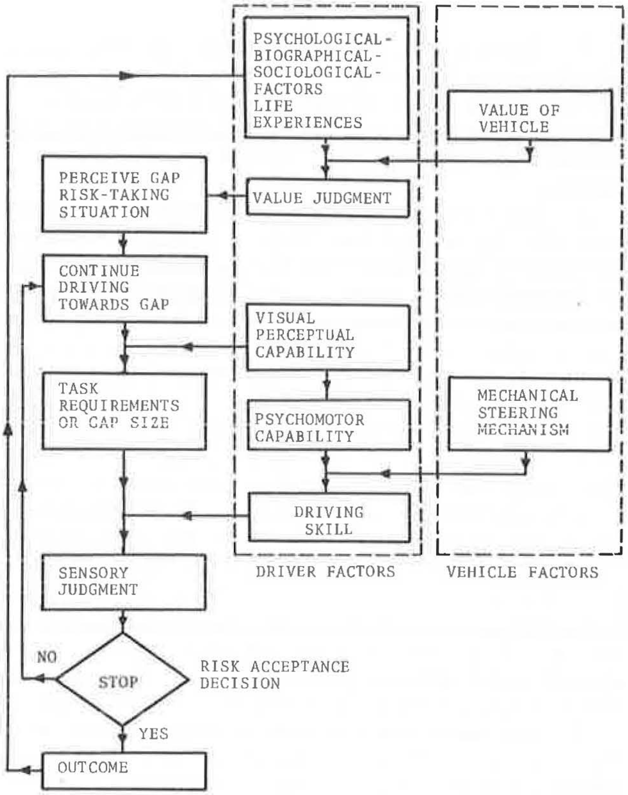
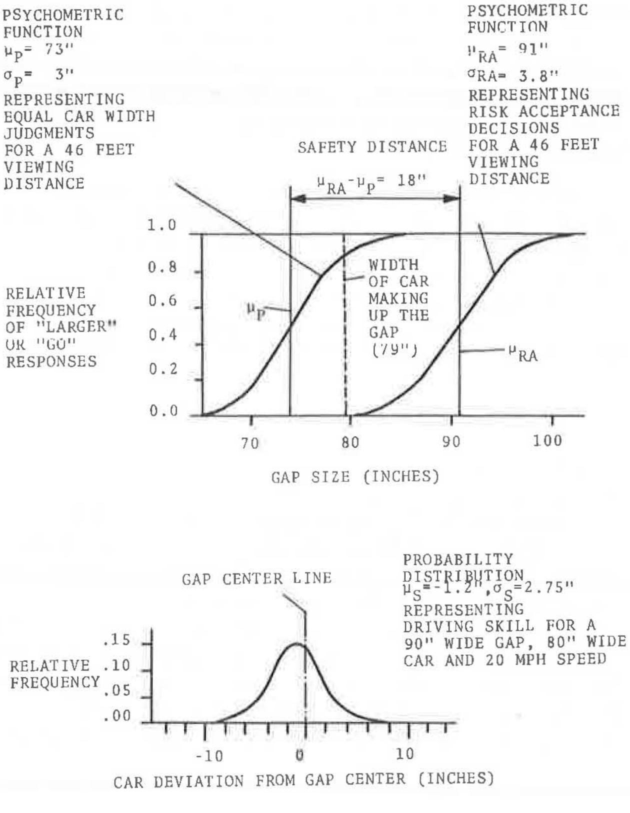


Figure 2. Examples of a visual-perception and a risk-acceptance psychometric function and a driving-skill distribution.



perceives gaps consistently much smaller than they actually are, then he might not incur any hazard, hazard being defined as the actual or objective probability of failure. However, such a driver would still be classified as a "truly" high risker according to the DSI concept. A "perceptual" high risker would be an individual who could have a rather high DSI (6-10). However, considerable hazard is incurred because he perceives gaps consistently as much larger than they actually are (dangerous perceiver). The driver in the foregoing example could be considered as a slightly dangerous perceiver since he indicated a too-small gap (approximately 9 percent) as being equal in width to the car.

It should be noted that the measurements of human characteristics such as risk-acceptance behavior, visual-perception capability, and driving skill are not as accurate as the measurements of height and weight, for example. Thus, the DSI, which is based on all three characteristics, will itself be a measure of limited accuracy. There are not enough experimental data available at the present time to make any reliable statements about the degree of accuracy of a single DSI measurement. Further, traumatic experiences might alter temporarily or permanently a driver's previously obtained DSI. If other psychological or physiological human characteristics and their changes over time are considered, it seems very likely that shifts in a driver's DSI will occur over his lifetime.

THE DRIVER SAFETY INDEX EXPERIMENTS

Subjects

Four subjects were used in the DSI experiments. Three of the subjects (E.T., B.B., M.P.) were 16-year-old female high school students. All of the 3 subjects were enrolled in a school driver education program and had very little driving experience at the beginning of these experiments. The other subject (R.F.) was a 25-year-old experienced male driver. All subjects drove without glasses and had a visual acuity equal to or better than 20/20. Peripheral vision as well as other aspects of vision were all within normal ranges. None of the subjects had any physical handicaps. The subjects were paid and participated in these and other experiments over a period of 3 months.

Test Site

The test site is shown in Figures 3 and 4. A straight, dead-end service road approximately 1,000 ft long and 15 ft wide was used to conduct all of the DSI experiments. The road was paved and had no lane markings. A wire fence with wooden posts, 10 ft away from the pavement edge, extended along both sides of the road. The road traversed an open field and no buildings were located along the road. All experiments were conducted during daylight and with no other traffic on the road.

Arrangement for Visual-Perception and Risk-Acceptance Experiments

The experimental arrangement for the perception and risk-acceptance experiments was the same. The selected experimental arrangement consisted of a gap placed approximately at the midway point of the road as shown in Figure 3. The gap was made up by a dark blue 1970 Buick Electra (79 in. wide) parked on the left side of the road with the front toward the front of the experimental car and a 4-ft high, 4-in. square black and white wooden post placed on the road perpendicular to the B-pillar position of the Buick. A 1-in. wide strip of beige adhesive masking tape was placed across the road surface perpendicular to the B-pillar position of the Buick. The tape was marked in 2-in. intervals, and different gap sizes were obtained by positioning the post closer or further away from the Buick along the tape. These marks were such that they could not be seen by the subjects. The experimental car (1969 Chrysler Newport) was parked in front of the gap so that there was either a viewing distance of approximately 46 ft or 300 ft from the subject's eyes to the perpendicular B-pillar gap line. The 46-ft viewing distance was considered as the minimum safe stopping distance when approaching the gap with a speed of 20 mph. The 300-ft viewing distance was selected as an upper limit since pilot eye movement experiments indicated that gaps located further away had little or no influence on the driver's information-seeking activities when approaching the gap at 20 mph.

Arrangement for Driving-Skill Experiments

The experimental arrangement for the driving-skill experiments is shown in Figure 4. Frequent grazing of the obstacles was expected when gaps with rather small clearances were presented. Thus, for safety reasons, as well as for economic reasons, the car and the wooden post making up the gap in the perception and risk-acceptance experiments had to be simulated in the driving-skill experiments. The Buick at the gap was simulated by 2 white 4-ft high, 2-ft wide, 1-in. thick Styrofoam plates placed 10 ft apart from each other, and the wooden post was replaced by an identical Styrofoam post. The softness and the light weight of the Styrofoam obstacles prevented any damage to the experimental car and the car occupants when contact with the obstacles was made.

A heavy steel plate was used to hold the Styrofoam post in place on the road. Two U-shaped steel posts were driven into the ground at the pavement edge to hold the Styrofoam plates. Three black rubber mats, approximately 7 in. wide and 24 in. long, were placed inside the gap in front of the 2 plates and the post. The mats were kept slightly wet so that the tire tracks of the experimental car could be seen. The 3 tire-track measurements were used subsequently to determine the relative gap position of the experimental car for each gap run. Gaps of different sizes were obtained by positioning the steel plate holding the post closer or further away from the 2 Styrofoam plates. To facilitate the accurate positioning of the steel plate holding the post, the same masking tape arrangement used in the perception and risk-acceptance experiments was used. The position of the gap along the road was again approximately at the midway point.

Procedure for Perception and Risk-Acceptance Experiments

Each subject was given a 2-hour introductory field session in which the subject was introduced to the perception and risk-acceptance aspects of the gap situation and to the driving skill requirements of the simulated gap situation. It was expected that this introductory session would provide a framework where initial learning with respect to the risk-taking task could take place and thus provide a more homogenized group for the subsequent DSI experiments. The order of the DSI experiments was not systematically determined and was of a somewhat random nature due to the availability of the subjects and the experimental equipment. Some of the subjects had their skill experiments between the perception and risk-acceptance experiments, whereas others had their skill experiments after the perception and risk-acceptance experiments were completed.

The experimental procedure used for the perception and risk-acceptance experiments required 2 experimenters. One experimenter was stationed at the gap while the other experimenter was sitting beside the subject in the experimental car. The 2 experimenters were able to communicate with each other using radios. At the beginning of the experiment the subject was given the appropriate set of instructions. The subject's gap judgments or the risk-acceptance decisions were recorded by the experimenter sitting beside the subject and then communicated via radio to the experimenter at the gap. The experimenter at the gap recorded the judgments too and determined the next gap size based on the previous judgments or decisions made by the subject. A new gap was subsequently set up by the gap experimenter by moving the post into a new position. The experimenter sitting in the subject's car then told the subject to look at the new gap after the gap experimenter disappeared behind the Buick. A series of 60 to 100 gap presentations took approximately 1 hour.

The Up-and-Down Transformed Response (UDTR) rule (31) was used to estimate the mean and the standard deviation of the psychometric functions. This rule is a generalization of the Up-and-Down (UD) rule (10). The 2 selected UDTR rule patterns provided estimates for the 70.71 and 29.29 percentage points of the psychometric functions. Both rules were presented alternately. Under the first pattern, 2 positive or "L" responses at a given stimulus level, or gap size, move the gap size 1 step down (smaller) for the next presentation, whereas a negative response always moves the gap size 1 step up (larger) for the next presentation. Under the second pattern 2 negative or "S" responses at the same level move the gap size 1 step upward (larger) for the next presentation, whereas a positive response "L" always moves the gap size 1 step down (smaller). During the course of experimentation the subjects were usually complimented with respect to their performance but were never told specifically how accurately they perceived or what type of risk-acceptance decisions they made. It was found that the thresholds of some of the subjects shifted considerably during a given experiment.

Procedure for Driving-Skill Experiments

The driving-skill experiments were conducted using the simulated gap situation consisting of 2 Styrofoam plates and a Styrofoam post. The gap was always set at 90 in. and the vehicle speed was instructed to be 20 mph. The overall width of the experimental car (Chrysler) was approximately 80 in., which left a total gap clearance of about 10 in. Previous pilot driving-skill experiments had indicated that a gap size of 90 in. represents a rather challenging gap situation for most drivers. Thus, contact with the obstacles could be expected in approximately 5 to 25 percent of all gap runs. In order to obtain some base data with respect to temporal information-seeking behavior, most of the driving-skill experiments were also used to collect TV data about a driver's temporal information-seeking activities. The experimental car was equipped with a TV eye-movement recording system and other electronic recording equipment. A detailed description of this TV eye-movement recording system (3 TV cameras, monitor, video recorder) is given elsewhere (27).

The gap was approached from both sides, which increased the efficiency of the data-collection process. Three experimenters were used to conduct the driving-skill experiments and to collect the TV data about the temporal information-seeking activities. One experimenter was at the gap, measuring and recording the tire tracks on the 3 rubber mats after each gap run. Further, in the case where the experimental car made contact with the obstacles, the damages were recorded and the damaged obstacles had to be replaced. The tire tracks were recorded to the nearest $^1/_{10}$ in., measured from the end of the obstacle toward the center of the gap. The other 2 experimenters were in the experimental car. The experimenter sitting beside the subject had to be prepared to use the dual braking system in case of an emergency. The other experimenter operated the TV equipment and the Honeywell recorder used to record the vehicle speed. At the beginning of each experiment the subject was again given a set of appropriate instructions. The subjects were instructed to read out loud as many speed values from the speedometer as they could while approaching the gap. A driving-skill experiment consisting of approximately 40 to 50 trials required usually about 2 hours.

Results of DSI Experiments

The estimates of the means and standard deviations for the 3 DSI components are given in Table 1. The comparison of gap means and standard deviations obtained from the perception and risk-acceptance experiments are shown in Figure 5.

The DSI sample values obtained under the stationary viewing distance of 46 ft and the DSI sample values obtained under the stationary viewing distance of 300 ft are shown for each subject in Figure 6. In Figure 6 we see that subjects E.T. and R.F. exhibited under both viewing distance conditions rather low DSI sample values. Subject M.P. exhibited ultra-conservative risk-taking behavior under the 300-ft viewing distance condition. The perception means in Table 1 indicate that all 4 subjects decreased their mean estimates under the 300-ft perception distance condition (E.T., 6.3 in.; M.P., 2.4 in.; B.B., 4.1 in., and R.F., 8.1 in.). The same holds true for the risk-acceptance means with the exception of subject M.P., who exhibited ultra-conservative risk-taking behavior (E.T., 13.1 in.; M.P., -34.9 in.; B.B., 12.0 in.; and R.F., 4.6 in.).

Other effects, such as driving speed, a different gap setup and environment, and a 2-dimensional reduced-scale ($^1/_{12}$ and $^1/_{24}$ scale) laboratory gap display, on the DSI components were experimentally investigated in an exploratory manner. The results of these experiments and other driving-skill and information-seeking experiments are discussed elsewhere (32).

Figure 3. The gap situation for the visual-perception and risk-acceptance decision experiments.

Figure 4. The simulated gap situation for the driving-skill experiments.

Table 1. Estimates of means and standard deviations for 3 DSI components.

				Perception[b]				Risk Acceptance[c]					
	Driving Skill[a]			46 Ft		300 Ft		46 Ft		300 Ft		DSI	
Subject	μ_S (in.)	σ_S (in.)	σ_S' (in.)	μ_P (in.)	σ_P (in.)	μ_P (in.)	σ_P (in.)	μ_{RA} (in.)	σ_{RA} (in.)	μ_{RA} (in.)	σ_{RA} (in.)	46 Ft	300 Ft
E. T.	0.06	4.05	4.05	73.34	3.13	67.03	2.78	82.95	1.19	69.84	3.73	2.4	0.7
M. P.	0.00	2.81	2.81	78.23	1.21	75.80	2.36	95.44	2.35	130.32	3.86	6.1	19.4
B. B.	-0.98	2.99	3.14	62.96	1.71	58.90	2.08	93.56	2.96	81.58	4.12	9.8	7.2
R. F.	-1.55	1.98	2.45	70.71	1.26	62.60	1.97	74.19	1.31	69.58	2.75	1.4	2.9

[a] Gap size 90 in., speed 20 mph, 80-in. wide car.
[b] Gap size perceived as equal to 79-in. wide car at 0 mph.
[c] Gap size accepted for 79-in. wide car at 0 mph.

Figure 5. Comparison between the means and standard deviations of the visual-perception and risk-acceptance psychometric functions obtained under the 46-ft and 300-ft viewing distances for all subjects.

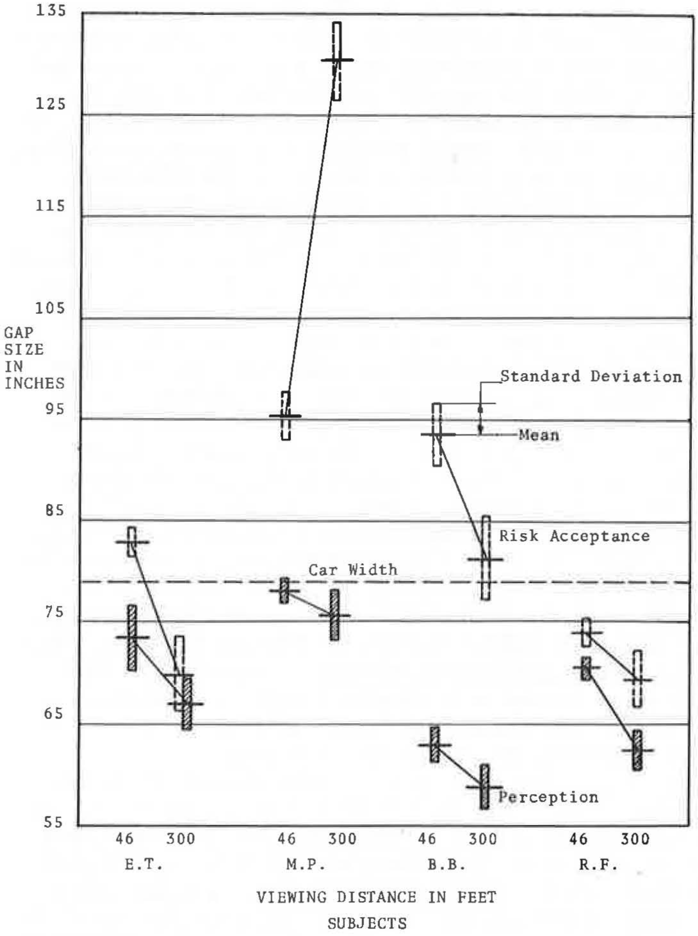
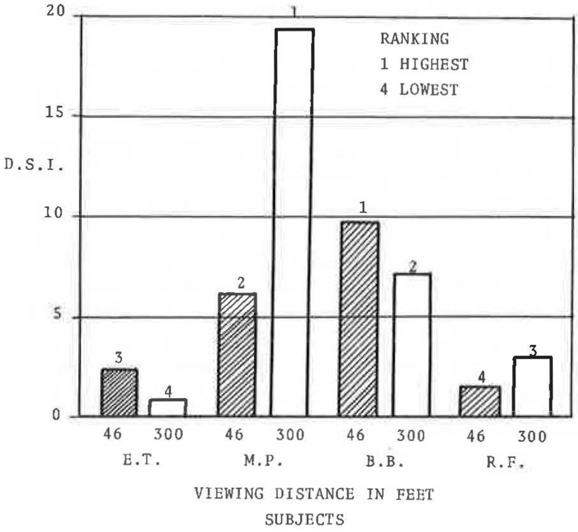


Figure 6. Comparison of DSIs obtained under the 46-ft and 300-ft viewing distances for all subjects.



CONCLUSIONS

As pointed out previously, the concept of the DSI is based on the assumption that a driver's "safety distance" between the mean of his psychometric risk-acceptance function and the mean of his psychometric visual-perception function for a gap, expressed in multiples of the standard deviation of his driving-skill distribution for centerline-path deviations in the gap, is a representative measure of his risk-taking behavior. The experiments conducted with respect to the DSI concept provided several major findings. First, the DSI methodology was successful in detecting rather large DSI differences among the individual drivers when tested under the same experimental conditions. In addition, Figure 6 shows that the 2 drivers who exhibited a rather low DSI under the 46-ft viewing distance exhibited again a rather low DSI under the 300-ft viewing distance, whereas the 2 drivers who exhibited a considerably higher DSI under the 46-ft viewing distance exhibited again a considerably higher DSI under the 300-ft viewing distance. Due to the small number of subjects tested and the observed magnitudes of the intrasubject variability, no really significant association between the 46-ft and the 300-ft viewing distances can be demonstrated (Kendall rank correlation coefficient: +0.333, significant only at the 0.375 level). Another interesting finding is the fact that the obtained standard deviation estimates for the psychometric risk-acceptance functions were generally only slightly larger than the obtained standard deviation estimates for the corresponding psychometric visual perception functions. The rather modest observed increases in risk-acceptance judgment variability seem to suggest that the gap clearance that drivers consider as "safe" to drive through seems to be a rather stable and distinct quantity in their minds. Thus, based on these rather exploratory experimental findings, we may tentatively conclude that the DSI methodology appears to be a promising tool for classifying drivers with respect to their risk-taking behavior. Further, the values of the 3 individual DSI components could make it possible to predict whether a particular driver would incur hazard in a gap risk-taking situation more likely due to his perceptual limitations, due to his limited skill ability, or due to a rather biased value judgment with respect to the consequences of failure.

If a satisfactory predictive accuracy and generality of the DSI, as well as an economically feasible testing procedure is assumed, the DSI methodology could be applied to all segments of the driving public and serve as a screening and/or diagnostic device. The DSI methodology could make it possible to direct the educational or improvement efforts to the specific area (risk acceptance, visual perception, driving skill) where modification seems most needed and of most benefit. Should a broad application of the DSI methodology prove to be politically or economically infeasible, it might be applied on a limited basis for the selection of bus drivers or other special-vehicle drivers where somewhat higher safety considerations would offset the rather high cost of testing. The basic concept of this methodology is by no means limited to the particular driving situation investigated. The methodology could easily be adapted and used in any other risk-taking situation where some visual perceptual capability and some degree of skill are required to engage in a particular activity.

In all the DSI perception experiments, a considerable variability among the drivers with respect to how they perceived the width of a given gap was found. This rather unexpected result [contrary to the findings of Gilinsky (15) for similar perception experiments] is considered to be of major importance. If it is assumed that future research would confirm the observed large perceptual judgment variability among drivers, the relationship between accidents and perceptual judgment capabilities should be investigated next. Should a significant relationship exist, driver education and improvement could be changed to include and provide adequate perceptual judgment training, and the driver licensing procedures could be changed to include perceptual judgment tests.

Before we conclude this discussion with respect to the DSI concept, we should point out once more the limitations and the exploratory nature of this investigation. Before the DSI concept can be applied successfully as a screening and/or diagnostic device in such areas as driver licensing, much more research will be needed to validate its generality as well as its satisfactory predictive accuracy.

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EXPERIMENTAL MEASUREMENTS OF PERCEPTUAL THRESHOLDS IN CAR-FOLLOWING

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A series of experiments was carried out to measure perceptual thresholds of drivers in car-following. Early results from pilot experiments revealed 2 basic difficulties associated with previous attempts reported in the literature to measure relative motion thresholds in car-following: First, it was sometimes possible for the subject to perceive the pitching of the lead car in response to the initiation of an acceleration or deceleration maneuver and thereby infer immediately that a change had occurred. Second, permitting the subjects to respond when they were sufficiently confident that they had detected a change introduced an unmeasurable variable. This unmeasurable variable arises because a subject wishing to make no errors might wait for larger stimuli than one wishing to register quick responses, even though both might have the same sensitivity. An experiment was designed to circumvent these difficulties. By means of an occlusion device, subjects seated as passengers in a following car traveling at 45 mph were given controlled looks, normally of 4-sec duration, at a lead car moving at a constant speed. For each exposure the subjects indicated whether they perceived negative (that is, the cars came closer) or positive relative motion. The results indicate that (a) the dominant cue used to judge the sign of relative motion is the average value of relative speed divided by spacing; (b) there is response bias in favor of indicating negative rather than positive relative motion; and (c) there is a high level of sensitivity to relative motion. For example, if a lead car were closing on a following car at 3 mph, the following driver's probability of correctly identifying the sign of relative motion as negative rather than positive after a 4-sec observation is 0.99 when the spacing is 200 ft.

•ONE of the most frequently occurring situations confronting an automobile driver is following another vehicle. This situation occurs on 2-lane roadways and multiple-lane highways when passing is difficult or restricted and whenever a motorist is "content" to follow another vehicle with approximately the same desired speed. For more than a decade a number of investigators have attempted to construct theoretically and validate experimentally mathematical models of this driving task (1). Such models focus on the longitudinal task and neglect all other subsidiary tasks such as steering and routing. The form of these models is principally a stimulus-response type of equation. While the stimulus has been expressed by using several different mathematical forms, the relative speed (the difference between the lead-vehicle speed and the following-vehicle speed) as well as the intervehicle spacing have been shown experimentally to be important variables in the process and correlate well with the acceleration and braking of a vehicle.

Brown (2) as early as 1960 pointed out that, in the light of the results of experiments on car-following, there was need for information regarding the driver's sensitivity to, or discrimination of, relative motion. Indeed, the ability of a driver to estimate quantities such as spacing or changes in spacing and relative speed are implicitly assumed

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in "car-following" equations. The implication of the existence of thresholds to the perception of such quantities is that they establish limits to the applicability of such models.

Over the past several years a number of studies have been devoted to quantifying perceptual cues involved in longitudinal pursuit, not only in following an automobile but also in the closely related perceptual task of effecting a rendezvous in space by direct visual sensing.

These previous studies have been conducted in the laboratory (3, 4) using simple geometrical figures in an otherwise featureless environment, in simulators (5, 6), and in the field (7, 8, 9, 10) using automobiles. One of the major sources of difference between the real-world situation and that of laboratory experiments is that the driver, or subject, is moving through a visual environment that is crowded with extraneous details. This difference might well have a significant effect on detection of relative motion and underlines the need to conduct experiments in the real world. All the previous real-world experiments have used a similar technique. Two cars were driven at constant speed with the subject in the following vehicle. At some instant the lead car adopted a constant acceleration or deceleration, and it was the subject's task to indicate when he perceived some dynamic change. The results from these field experiments do not indicate good agreement with each other or with laboratory results. There was, therefore, a need for further experimental investigations.

PILOT EXPERIMENTS

One series of pilot experiments was conducted to investigate, at different following distances, a driver's ability to reproduce speed changes of a lead vehicle whose speed oscillated sinusoidally in time about a fixed value with a period of 20 sec and an amplitude of 7 ft/sec. Spectral analysis applied to the results showed that the maximum value of the cross-correlation coefficient decreased from 0.98 at a following distance of 75 ft to about 0.3 at 750 ft. The time lag (i.e., the value which maximized the cross-correlation) increased from 1.5 sec at a spacing of 75 ft to 7 sec at a spacing of 750 ft. Data were collected at following distances up to 1,280 ft. However, beyond 750 ft the results were erratic, sometimes with the cross correlation increasing and the time lag decreasing as the spacing became greater. It was difficult to determine from the vehicle trajectories or speed histories when the driver applied a control input. A major difficulty with this approach was that it was impossible for the subject to maintain a spacing that did not drift by large amounts during the run. A different approach was therefore adopted.

In this approach the subject rode as a passenger, observed the lead car that executed random changes in speed, and indicated by means of a 3-state switch whether he thought he was going faster, at the same speed, or slower than the car in front. The spacing (i.e., distance from front bumper to front bumper) was varied between 80 ft and 550 ft. The results from 2 subjects analyzed in detail showed clearly the pitfalls in offering subjects a 3-state choice (that is, permitting a "zero" or "don't know" option). For relative velocities too small to be reliably judged, one subject indicated zero relative motion approximately 20 percent of the time, independent of spacing, whereas the other subject indicated zero relative motion 80 percent of the time when the spacing was 140 ft. This figure decreased to 50 percent at a spacing of 500 ft. Such variability in the way subjects choose to perform the task makes it impossible to derive a clearly defined threshold value. A third choice allows each subject the degree of freedom to set his own level of performance. However, the results did indicate that, when the value of relative velocity divided by spacing exceeded a value of about ± 0.03 sec^{-1} independent of spacing, it was detected 75 percent of the time. The corresponding threshold value of angular velocity decreased from 13×10^{-4} rad/sec at a spacing of 140 ft to 2.2×10^{-4} rad/sec at a spacing of 460 ft.

RESPONSE TO PITCH OF LEAD VEHICLE

Upon examining the data for individual responses in the foregoing experiments, it was apparent that in many cases, independent of spacing, the response to an acceleration of the lead vehicle was almost instantaneous. It appears that in some cases the subject was able to perceive a change in attitude or pitch of the lead car at the onset of an acceleration. This was not readily apparent to subjects or experimenters during the initial experiments, but further tests in which such an effect was consciously looked for did reveal that frequently it was indeed possible to perceive the initiation of an acceleration through this mechanism. When a vehicle with a nonrigid suspension initially moving at constant speed starts to accelerate (or decelerate), the rear of the vehicle drops (or rises). This is particularly pronounced on acceleration because an attempt to manually produce a constant level of acceleration usually produces an instantaneous initial value higher than intended. If the driver is able to perceive this pitch, he could immediately infer a change. Such an effect would explain why, with the oscillatory speed profile experiment, the overall time lag decreased for large spacings, if one assumes that as the spacing increased the fraction of all responses of this type also increased. It is worth commenting that, in acceleration, exhaust cues could provide additional unintended information, although we did not observe any such effects in our experiment.

The observation of this pitch effect led us to consider if it had been present in any earlier work. A distribution of all the reaction times measured in the field by Torf and Duckstein (8) and Whitty and Duckstein (9) was examined and seen to have a distinctly bimodal shape, with one peak at about 1.7 sec and another at about 2.8 sec. It seems plausible that responses to lead vehicle pitch might have contributed to the peak about 1.7 sec, especially as the reaction times reported were not reduced by the time required to press a response button. Many responses to very small values of the stimulus are apparent in Figures 1 and 2 of Snider (10). It again seems plausible that some of these may be responses to vehicular pitch.

The findings from our pilot experiments underlined several difficulties associated with attempts to measure threshold information in the real driving situation. In the light of these, an experiment was designed to circumvent them.

EXPERIMENT

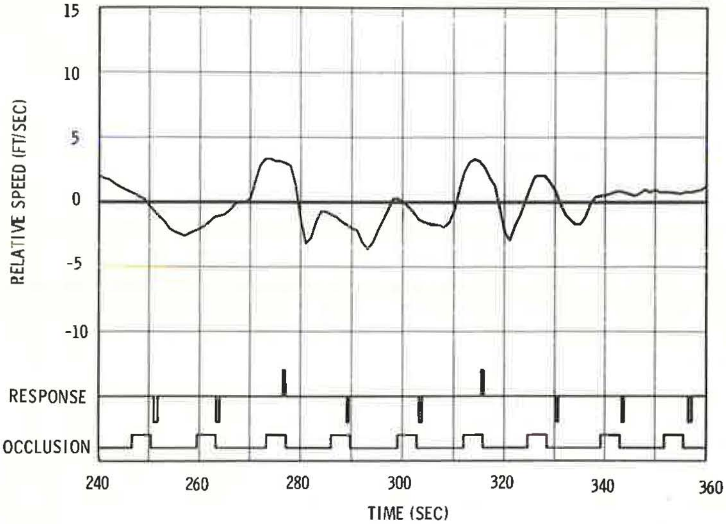
Two vehicles were driven on a single lane of roadway. By means of the eye occlusion device shown in Figure 1, subjects seated as passengers in a following car were given controlled looks, normally of 4-sec duration, at a lead car. The following car traveled at a nearly constant speed of about 45 mph, and during each exposure the lead car also traveled at a nearly constant speed close to this value. The subjects were thus presented with nearly constant relative speed stimuli. It was the lead driver's responsibility to control spacing and relative speed. Small random deviations from constant speeds led to measurable accelerations that were also analyzed. The subject's task was to judge whether the cars moved further apart (i.e., positive relative motion) or came closer together during the exposure period and to register his positive or negative response by moving a lever into one of two positions. No other options such as "zero" or "don't know" were permitted; in all cases the subject responded with his best estimate.

Ten subjects performed a total of 42 runs, each consisting of a 10-mile trip on a public freeway. Approximately 50 judgments per run were obtained (Table 3). Of the total of 2,170 judgments made, 1,923 had a 4-sec exposure time and 247 (data set 10^c in Table 3), a 2-sec exposure time.

Both lead and following cars were fitted with fifth wheels that generated a pulse for each foot of forward travel, pulses for the lead vehicle being telemetered to the following car. The trajectory information, state of the occlusion device, and the subject response, together with a 3,000-Hz clock signal, were recorded synchronously by a multichannel magnetic tape recorder. The data were later reduced to digital format for computer analysis. A 2-min sample of the information recorded, representing about $1\frac{1}{2}$ miles of forward travel, is shown in Figure 2, in which the state of the occlusion device ('up' indicates the subject was permitted to see), the subject response ('up' indicates that positive relative motion was judged), and the relative speed are plotted versus time. The plotted response time has been corrected to take into account a delay of 0.4 sec between the subject's decision to respond and the recording of the response. This value was obtained by using the instrumentation in the car to measure the time difference between a simple event (a light coming on) and the recorded subject response.

Figure 1. Eye occlusion device: (a) vision unobstructed; (b) vision occluded.

Figure 2. Sample (2 min, about 1½ miles) of computer plot of relative speed, state of occlusion, and subject response versus time. Numerical details for the exposure are given in Table 1 (top 9 rows).



The pertinent information concerning the judgments was punched on data cards, one card per response, and the analysis was performed using this data set. A short sample (which includes the nine judgments in Fig. 2) of this information is given in Table 1.

ANALYSIS

We assume that when the subject makes a judgment he is responding to some function of the dynamic variables to which he has been exposed. We refer to such functions as stimulus functions. One of our main aims is to identify which stimulus function most simply, consistently, and completely describes all the effects present in our data. The criterion adopted is that a good stimulus function is one for which the probability of judging positive relative motion (as distinct from negative relative motion) depends only on the value of the stimulus function and not explicitly on any of the independent variables, such as spacing. Ideally, all such dependence would be incorporated into the stimulus function.

The comparative ability of 9 different stimulus functions to explain the detection of the sign of relative motion, as recorded in our data, was investigated. The functions studied included 3 previously discussed in the literature—acceleration (7, 8, 9), angular velocity (11), and spacing change divided by spacing, $\Delta S/S$ (10)—as well as others indicated in Table 1. Scatter diagrams showing the values of these stimulus functions to which the subjects were exposed were plotted versus spacing. One such plot, for the stimulus function average relative speed divided by spacing (U/S), is shown in Figure 3 for all 2,170 items of data collected in the experiment. The subject response is represented by the symbols plotted; an "x" indicates that the sign of relative motion was correctly judged and an "o" indicates that it was incorrectly judged. The data clustered around 3 target spacings of 125, 250, and 500 ft. The distribution of the values of relative speed, U, was essentially the same at different spacings. The decreasing numerical value of the stimulus with increasing spacing in Figure 3 occurs because it is U/S and not U that is plotted. The reason for plotting U/S will be discussed later.

Figure 4 shows only those values of U/S whose sign was incorrectly judged. When the magnitude of U/S is greater than about 1×10^{-2} sec^{-1}, errors are rare. However, small positive values of U/S are more likely to be incorrectly judged as negative than small negative values are to be incorrectly judged as positive. To examine these and other questions in a more quantitative manner the technique described in the following was adopted.

Technique

The range of the stimulus function of interest was divided into about 20 intervals of equal size, and the fraction of exposures in each cell that were judged positive, P^+, was plotted as a bar graph. A large number of such response plots were produced and formed the basis of our analysis. One example of such response plots is shown in Figure 5. Smooth curves were visually fitted to the bar graphs. The first, second, and third quartile points, Q_1, Q_2, and Q_3, were estimated from the fitted curves, that is, the values of the stimulus function when P^+ was 0.25, 0.5, and 0.75 respectively. The first quartile point, Q_1, is the value of the stimulus that is perceived negative 75 percent of the time and will be referred to as the negative threshold. The 0.5 point, Q_2, gives the value of the stimulus that is equally likely to be perceived negative or positive. As we shall see, Q_2 is not generally equal to zero but has a positive value that increases with spacing. As a result of this response bias, Q_3 is larger than the absolute value of Q_1 by an amount that also increases with spacing, thus rendering these quantities unsuitable for sensitivity-comparison purposes. A more suitable quantity that characterizes sensitivity is the intercategory threshold (12), defined as $I = Q_3 - Q_1$, which in our case measures the stimulus region in which the sign of relative motion cannot be detected correctly as often as 75 percent of the time.

In the foregoing we have considered the threshold to be the value that is correctly judged with probability 0.75. This choice is essentially arbitrary, and different levels have been adopted. The intercategory threshold at a given level will always be the difference between the positive and negative thresholds at the same level.

Table 1. Sample of the response data.

Subject Response	Time at End of Observation (sec)	Following Car Speed (ft/sec)	Values at Beginning of Observation			Values at End of Observation				Angular Velocity (10^{-4}rad/sec)	ΔS (ft)	$\frac{\Delta S}{S}$ (percent)	Exposure Time (sec)
			S (ft)	U (ft/sec)	A (ft/sec^2)	S (ft)	U (ft/sec)	A (ft/sec^2)	U/S (10^{-2} sec^{-1})				
-	250.4	67.4	181	0.7	-0.22	182	-0.5	-0.51	-0.3	-0.9	1	0.4	3.8
-	263.2	67.7	165	-2.2	0.17	158	-1.2	0.23	-0.7	-2.8	-6	-4.1	3.8
+	277.2	68.7	162	3.3	0.09	172	3.1	-0.12	1.8	6.2	10	6.0	3.8
-	289.7	68.7	168	-1.0	-0.21	164	-1.8	-0.21	-1.1	-4.0	-4	-2.6	3.8
-	302.8	67.4	145	0.3	-0.15	144	-1.2	-0.44	-0.8	-3.4	-1	-0.9	3.8
+	315.6	68.4	134	2.1	1.18	145	3.0	-0.52	2.1	8.5	11	7.3	3.8
-	328.4	67.5	142	0.6	1.08	149	1.8	-0.39	1.2	5.0	7	4.5	3.8
-	343.0	68.7	145	0.5	0.11	148	0.8	-0.03	0.6	2.2	3	1.8	3.9
-	355.6	68.6	154	0.8	-0.05	157	0.7	0.12	0.5	1.8	3	1.7	3.8
-	368.2	68.2	166	1.2	-0.06	170	0.8	-0.21	0.5	1.7	4	2.4	3.8
-	382.7	67.2	153	-5.4	-0.69	139	-4.7	1.18	-3.4	-14.7	-14	-10.4	3.9
+	395.9	68.8	127	1.6	0.97	138	3.2	-0.21	2.3	10.2	11	7.7	3.8
-	408.4	67.8	146	0.1	0.04	147	-0.1	-0.34	-0.1	-0.3	1	0.3	3.8
-	420.4	68.5	142	-0.6	0.00	141	0.2	0.31	0.2	0.7	-1	-0.7	3.7
+	433.7	67.5	141	-0.1	0.70	144	1.4	0.08	1.0	4.1	3	1.8	3.8
+	447.5	68.4	251	17.1	-1.68	278	13.7	-1.96	4.9	10.6	27	9.8	3.8
-	461.4	68.3	329	0.0	0.25	331	0.8	0.22	0.2	0.4	1	0.4	3.8
+	474.6	68.5	345	1.8	-0.03	349	0.9	-0.75	0.3	0.5	5	1.3	3.8
-	486.5	68.2	340	-0.6	0.21	337	-0.9	-0.26	-0.3	-0.5	-2	-0.7	3.7
-	498.7	65.9	325	-1.0	0.17	323	-0.4	0.04	-0.1	-0.2	-2	-0.5	3.7
+	511.8	68.9	317	0.1	-0.32	316	-0.9	-0.33	-0.3	-0.5	-1	-0.3	3.8
-	532.2	69.9	308	-1.5	-0.33	303	-2.4	-0.16	-0.8	-1.5	-5	-1.7	4.1
-	545.4	68.0	288	-1.0	0.05	285	-0.5	0.12	-0.2	-0.4	-3	-0.9	3.8
-	558.1	67.3	291	2.4	0.11	301	2.8	-0.07	0.9	1.9	10	3.4	3.8

Figure 3. Scatter diagram of average value of relative speed divided by spacing (10^{-2} sec^{-1}) versus spacing (feet) for all data collected in the experiment. The "x" indicates that the sign of the relative motion was correctly identified and the "o" indicates it was incorrectly identified.

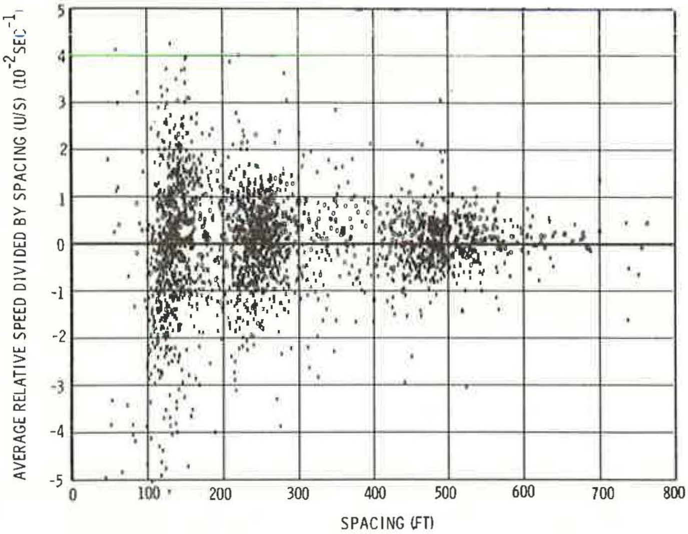


Figure 4. Scatter diagram of average relative speed divided by spacing (10^{-2} sec^{-1}) versus spacing (feet) for all exposures whose sign of relative motion was incorrectly judged.

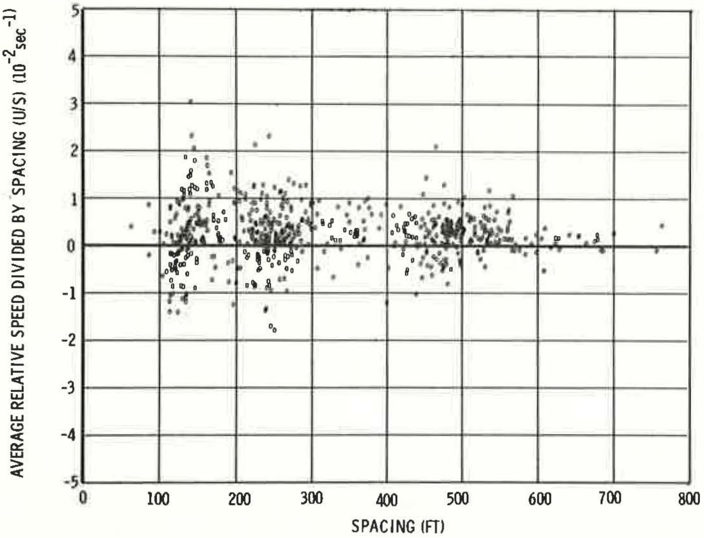


Figure 5. Response plot for the stimulus function average relative speed divided by spacing (10^{-2} sec^{-1}) for all the 4-sec exposure time data.

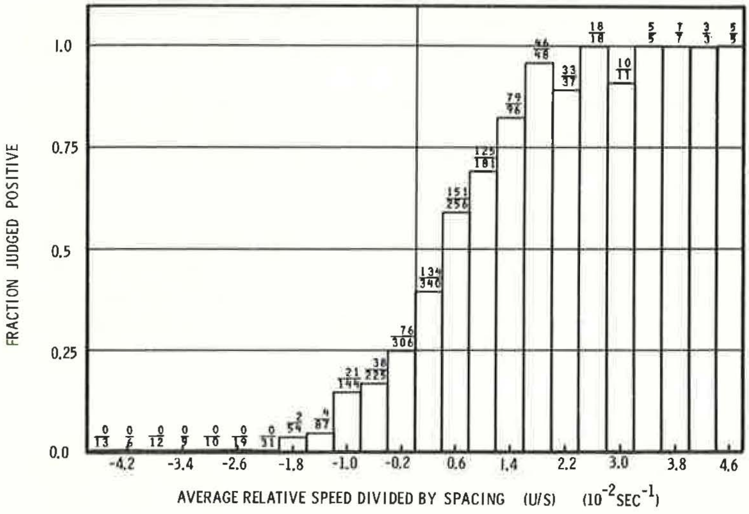


Table 2. Dependence on spacing of the value equally likely to be judged positive or negative (Q_2) and the intercategory threshold at the 0.75 level ($I = Q_3 - Q_1$) for the stimulus functions of relative speed, relative speed divided by spacing, and angular velocity (values are for end of observation).

Spacing Interval (ft)	No. of Data	Mean Spacing (ft)	Std. Dev. (ft)	Relative Speed (ft/sec)		Relative Speed / Spacing (10^{-2} sec^{-1})		Angular Velocity (10^{-4} rad/sec)	
				Q_2	I	Q_2	I	Q_2	I
131 ≤	317	115	16	0.1	1.8	0.15	1.4	1.8	7.4
131-156	283	142	7	0.4	1.8	0.5	1.8	2.3	5.8
156-226	332	192	24	0.6	2.9	0.5	1.6	1.7	4.1
226-256	302	240	8	1.0	3.0	0.45	1.45	1.0	2.9
256-350	315	286	26	1.2	5.0	0.5	1.6	1.2	2.9
350-484	318	439	37	3.4	7.0	1.0	1.9	1.2	2.6
>484	303	540	58	3.8	6.6	0.65	1.2	1.0	2.2

RESULTS

Spacing Dependence

All 2,170 responses were divided into 7 spacing intervals, and the intercategory thresholds, I, and response bias, Q_2, were measured (Table 2) for the stimulus functions of relative speed, relative speed divided by spacing, and angular velocity, in all cases using the instantaneous values at the termination of the observation. By angular velocity we mean the rate of change of the angle subtended by the lead car at the subject's eyes. These 3 functions are essentially US^n, where n has the values 0, -1, and -2 respectively. Only when $n = -1$ is the intercategory threshold independent of spacing. Therefore, on the basis of the criterion discussed earlier, we reject all functions with an S^{-2} spacing dependence (angular velocity) and all with an S^0 spacing dependence (relative speed and spacing change). The constancy of the intercategory threshold of relative speed divided by spacing indicates that the stimulus function that best describes the detection of the sign of relative motion has reciprocal spacing dependence.

Acceleration and Exposure Time Dependence

Small variations in the speed of both cars produced measurable accelerations. The probability that an exposure with a given value of acceleration was judged positive was independent of acceleration within the range covered by our data (approximately -1 ft/sec^2 to 1 ft/sec^2). It is therefore concluded that acceleration is not a major cue to the sign of relative motion. However, acceleration did systematically influence the perception of other stimulus functions. For example, the dependence on acceleration led to rejecting the hypothesis that the subject was responding to the value of the relative speed at the beginning of the observation divided by the spacing. The response plots for 2 reciprocal spacing functions were independent of acceleration. These are the average value of the relative speed divided by spacing (U/S) and spacing change divided by spacing ($\Delta S/S$).

Comparing the data from a 2-sec exposure with those for a 4-sec exposure indicates that the responses to both of these are exposure time-dependent. Preliminary results indicate that the dependence for U/S is perhaps slightly less. The remaining results will therefore be presented as responses to U/S, bearing in mind that the same value of U/S is more likely to be correctly judged after a longer exposure. Figure 6 shows the quartile points and intercategory threshold of U/S plotted for the data divided into 11 spacing intervals. The constancy of the intercategory thresholds for this function over a wide range of spacing is apparent. The response plot for all the 4-sec data is shown in Figure 5. The stimulus values are readily converted to $\Delta S/S$ (in percent) by multiplying by 4 since $(U/S)T = \Delta S/S$ where T is the exposure time.

Response Bias

There was a pronounced and consistent bias in favor of indicating negative, rather than positive, relative motion. For there to be an equal probability of indicating negative or positive relative motion a positive relative motion must be present. All values of Q_2 in Table 2 are positive, whereas in the absence of a bias we would expect them to be distributed around zero. The response curves for all the data in the current experiment indicate that, when presented with zero relative motion, the probability that negative motion is judged is 0.66 and not 0.5 as we would expect in the absence of any bias. This bias in favor of indicating negative relative motion is much larger than could be explained by an effect resulting from physical asymmetry in the closing as compared to the opening situation. The magnitude of the response bias for stimulus functions with reciprocal spacing dependence increases with spacing (Table 2 and Fig. 6).

Individual Subject Results

The data for individual subjects were divided into the 3 spacing intervals, 100-190, 200-320, and 380-640 ft. The quartile points, Q_1, Q_2, and Q_3, were estimated for the stimulus function U/S and $\Delta S/S$. The values of the intercategory threshold, I, and re-

Figure 6. Response bias, positive, negative, and intercategory thresholds for the stimulus function average relative speed divided by spacing (10^{-2} sec^{-1}) plotted versus spacing (feet). This was obtained by dividing all the data into 11 spacing intervals.

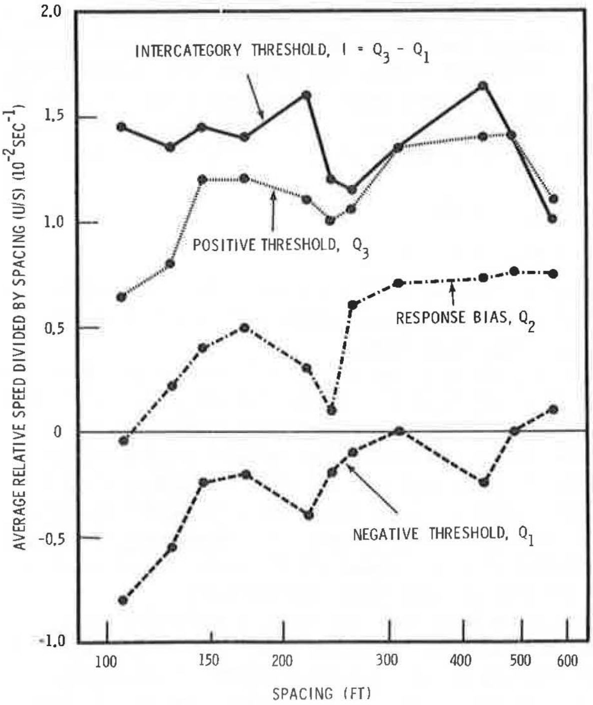


Table 3. Values equally likely to be judged positive or negative (Q_2) and intercategory thresholds at the 0.75 level ($I = Q_3 - Q_1$) for the stimulus function $\bar{U}/S$ (10^{-2} sec^{-1}) for the individual subjects in 3 spacing intervals and for all spacings combined.

			Spacing Interval							
			S = 100 to 190 $\bar{S}$ = 139 ft		S = 200 to 320 $\bar{S}$ = 249 ft		S = 380 to 640 $\bar{S}$ = 489 ft		All Spacings $\bar{S}$ = 279 ft	
Subject No.	Data Set	No. of Data	Q_2	I	Q_2	I	Q_2	I	Q_2	I
1	1	63	-0.1	1.4	0.5	0.5	—	—	0.1	1.6
2	2	99	0.3	1.2	0.6	0.6	0.6	1.1	0.4	1.6
3	3	208	0.1	0.6	0.5	1.1	0.5	1.5	0.4	1.0
4	4	200	-0.2	1.0	-0.1	0.9	0.4	0.7	0.1	0.9
5	5	208	0.6	1.6	0.3	1.4	0.4	1.4	0.7	1.7
6	6	97	0.6	0.3	0.4	1.0	—	—	0.6	0.8
7	7	211	0.7	2.0	0.1	1.3	0.4	1.5	0.3	1.6
8	8	214	0.6	0.9	0.3	1.7	0.3	1.5	0.5	1.4
9	9	196	-0.3	1.3	0.3	0.8	0.7	1.1	0.3	1.1
10	10[a]	207	-0.2	1.5	0.9	1.2	0.9	1.6	0.6	1.7
10	10[b]	220	0.8	1.2	0.6	1.3	1.0	0.7	0.7	1.0
10	10[c]	247	0.6	2.0	0.7	1.2	0.7	1.4	0.9	1.8
Mean			0.29	1.24	0.42	1.08	0.59	1.25	0.47	1.36
Standard deviation			0.41	0.53	0.27	0.34	0.23	0.33	0.25	0.36

[a] Four runs with procedure identical to that used for other subjects.

[b] Four runs with 4-sec exposure from extra session.

[c] Four runs with 2-sec exposure from extra session.

sponse bias, Q_2, for the variable U/S are given in Table 3 for the 3 spacing intervals and for all spacings combined. Wherever a blank entry occurs in this table it indicates insufficient data. The constancy of I and the increase of Q_2 as the spacing increases, as previously shown for all the data, are apparent for individual subjects. For all spacings combined, each and every subject has a positive value of Q_2. The values of I obtained by combining all spacings tend to be larger than the mean from the 3 spacing intervals. This is because the increase of Q_2 with spacing contributes additional variance to the response curves. For all spacings combined, the variation in I between subjects is slightly more than a factor of 2. However, when one subject was tested twice, a variation almost as great as this was observed (see results for data sets 10^a and 10^b in Table 3). This suggests that the observed variations could reflect both varying performance levels for each subject or differences in sensitivity from subject to subject.

CONCLUSIONS

There are three major conclusions from this study:

1. The response of the subject in detecting the sign of relative motion is to the average value of relative speed divided by spacing (U/S). The same level of U/S is more likely to be judged correctly after a longer exposure time.
2. There is bias in favor of indicating negative, rather than positive, relative motion. In addition, this negative response bias is an increasing function of spacing. The bias is in the direction of increased safety, in that the driver sometimes will think he is gaining on the car in front when in fact he is not. The unsymmetrical nature of the risk associated with different control decisions is not a plausible explanation of the observed bias, because the sign indicated by the subject under the conditions of the experiment in no way affected any control input to the following car. However, it is still conceivable that such a bias, learned through driving experience, is so strong that it continued to operate for each subject even though they were passengers.
3. The results of the experiment indicate a high level of sensitivity to the sign of relative motion. For example, the response curves indicated that, if a lead car were closing on a following car at 3 mph, the following driver's probability of correctly identifying the sign of relative motion as negative rather than positive after a 4-sec observation is 0.99 when the spacing is 200 ft. It therefore seems unlikely that driver limitations in the detection of the sign of relative motion could be a serious contributor to rear-end collisions or such accidents as a stationary car on a freeway being struck from the rear. Such accidents are more likely manifestations of problems of attention and the inability to correctly judge the magnitude of relative motion. That is, the driver has no doubt he is gaining on the lead car but is insufficiently aware of the rate at which he is gaining. The results also indicate that little improvement in smoothness of flow or safety is likely to be obtained by providing the driver with information on the sign of relative motion without also giving its magnitude.

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DISCUSSION

Rudolf G. Mortimer, Highway Safety Research Institute, University of Michigan

It is certainly important to learn more about driver sensitivity to various cues and to be able to define which cues he may be using in carrying out various driving tasks. The longitudinal control task of the vehicle, as in car-following, is one that requires considerable attention because it occurs with high frequency under most driving conditions in this country and in others having large vehicle populations.

The cues used for relative motion thresholds have, as pointed out by Evans and Rothery, been studied by a number of researchers, and different absolute levels of driver sensitivity have been found because of methodological differences. Unlike the authors, I find that, although different methods have been used in these previous tests, there appeared to be a reasonable degree of correspondence in the findings for describing the perceptual process involved although not necessarily in the interpretations offered by the authors of those papers. For example, Braunstein and Laugherty (7) concluded that subjects were responding to the occurrence of an acceleration or deceleration in sensing relative velocity. But Hoffman (1966) reviewed their data and concluded that a Weber ratio model, $\Delta H/H$, where H is the distance headway between the vehicles, could explain the data quite well. According to this the drivers were responding to the change in the headway spacing between the vehicles.

Evans and Rothery have used a different methodology from that employed before because they felt that laboratory studies or field studies utilizing fairly conventional psychophysical methods run into difficulties because of either the simulation involved or the factors influencing the driver's judgments. However, their own method would reduce the driver's normal scanning behavior by providing limited opportunities for viewing the vehicle ahead. In addition, the subject is made aware of the fact that a judgment is required of him at a certain time, which is not analogous to the manner in which a driver would direct his attention to certain cues in normal driving. It is probably useful, overall, to conduct investigations using different methodologies, each of which can tap some aspects of the actual task.

The findings obtained in this study are of interest. The authors have concluded that the driver is highly sensitive to detecting the sign of a spacing change. Most of their experiment was carried out using a 4-sec exposure, which produced a high level of sensitivity, such that a relative speed of 3 mph at 200 ft was detected 99 percent of the time. The detection probability did decrease when a 2-sec exposure time was used.

We have conducted similar studies, using other procedures. One method used a laboratory simulation in which 2 lights, simulating the taillights of a vehicle, were moved toward or away from the observer at a constant speed. More recently we have used a dynamic car-following driving simulator for the same type of study. We have also conducted studies on the road in which a driver followed another vehicle, with both cars moving at the same speed but with the lead vehicle beginning to coast down at random intervals. The following car driver had to detect the onset of coasting. Incidentally, we used the same technique for measuring intervehicle headway by means of distance pulses obtained from fifth wheels. We commiserate with the authors of this paper in having suffered the tribulations associated with this method, even though it ultimately did work for us as it apparently did for them. Each of our experiments showed that a Weber ratio of the form $\Delta H/H$ was a good model for explaining the driver's detection of relative motion.

The authors have presented their results in terms of a model of average relative speed (U) divided by spacing (S) and have found that this is independent of the initial spacing. Since the function U/S is equivalent to the function $\Delta S/ST$, it can be seen that they have results that can be explained by the Weber model such as described earlier. This shows agreement with previous studies except for the value of the constant expressing the driver's sensitivity. For example, in my 1971 study the 50th percentile value of $\Delta H/H$ was about 0.12, whereas the 99th percentile performance, as reported in their study, was about 0.10. As mentioned previously, it was expected that greater sensitivity would be found in their study because of the use of the visual occlusion method and because their subjects were not also driving the vehicle or carrying out any side tasks.

The greater sensitivity of the method used by the authors leads them to conclude that driver limitations in detecting the sign of relative motion are not likely to be a serious contributor to rear-end collisions. While I would basically agree with this conclusion, our own data have shown that Weber ratios of as high as 0.4 were obtained in our test situations for less than 1 percent of responses, indicating an infrequent, but potential, hazard. As pointed out by the authors, there is little question that other problems such as poor visibility, expectancy, attention, and the inability to correctly estimate relative speed are important contributing variables.

From a more theoretical standpoint the choice of a "stimulus function" of U/S by the authors causes some difficulties to me as a psychologist. This is because it suggests that the driver is directly sensing the relative speed and the absolute headway spacing. The problem arises with the former, i.e., relative speed detection. The equation suggests that the driver can detect relative speed in some direct manner. It seems much more probable that drivers would estimate relative speed on the basis of the rate of change of the headway spacing. Thus it would appear much more satisfying to utilize the stimulus that is probably sensed by drivers in an underlying model that seeks to explain drivers' behavior. For this reason, and because the value U/S is difficult to grasp for intuitive meaning (at least the value S/U would be better, since this is the time headway), it would be recommended that the data be also represented by an alternative, but equivalent, model.

In conclusion, the authors have reported a good experiment using a method that should provide data with relatively low variability, although almost certainly overestimating the sensitivity of drivers in the traffic stream. For the benefit of other behaviorists, a performance measure in the form of a Weber function would be preferable to the one they have used.

John N. Snider, Department of Industrial Engineering, University of Tennessee

A basic consideration that must be weighed heavily in designing experimentation dealing with man's perceptual characteristics in automobile driving is that of the fidelity of the task presented to the subjects—i.e., are we studying man in the automobile driving context or are we generating an artificial task and hoping for a strong correlation between his performance on the artificial task and in the automobile driving task? In this paper, Evans and Rothery chose wisely in conducting their research in a "free field" environment with its wealth of related perceptual cues, which can only be guessed at in simulation. However, by restricting the subject's view of the leading vehicle physically through a visual occlusion device and temporally to a 4-sec "peek" (additional trials involving 2 sec were run with one subject), they have generated a task that is quite unlike the normal visual perception task in automobile driving. The authors' rationale for taking this approach is that indirect cues may be presented either from the leading vehicle's exhaust or from vehicle pitching due to spring wrap-up. However, the authors state that they were unable to maintain a constant relative velocity during the short time interval the subject had view of the leading vehicle and consequently considered acceleration itself as a possible cue in the course of their data analysis. Although the authors suggest that the direct perception of vehicle pitching during acceleration may have influenced subject performance in a study reported by me (10), subsequent research has demonstrated this not to be the case (13).

The basic advantage in using a modified method of constant-stimulus psychophysical technique, as Evans and Rothery have employed it, is that a forced choice response may be obtained in which the subject's subjective confidence in his response is eliminated from consideration—the data yield directly to probabilistic analysis, in which case a given threshold may be identified with a corresponding probability of detection (assuming the subject does not change markedly from one experimental session to the next). On the other hand, the method of adjustment technique allows the subject to respond when he is confident of what he is perceiving (perhaps at a level analogous with a 0.99 probability of detection threshold). I argue that the threshold appropriate for use in this context is a level that the subject views as necessary for initiating a response—after all, a driver will undoubtedly only initiate a control action in driving when he views that control action as necessary, based on his perception of the situation. The method of adjustment, when employed with carefully prepared instructions, appears to most adequately meet this need.

A review of the data shown in the authors' Figure 6 serves well to illustrate some of the conceptual problems associated with the probabilistic analysis of relative motion perception data. For example, the 0.75 negative response threshold, Q_1, is reported as corresponding with a value of average relative speed divided by spacing, U/S, of zero for data taken in the vicinity of 300 ft while the corresponding threshold is found to be either zero or actually positive for data taken for headways in excess of approximately 500 ft. In other words, as a consequence of using a binary forced-choice procedure, the subjects respond 75 percent of the time that relative motion is negative when it is in fact zero or positive at these separation distances. Now, if the authors believe this, and if a threshold level of 0.75 is selected, this implies that a driver would be either decelerating or preparing to do so whenever the relative velocity of his vehicle with respect to a leading vehicle is zero and the headway or separation is in the vicinity of 300 ft or greater than 500 ft. I have considerable difficulty in accepting this finding.

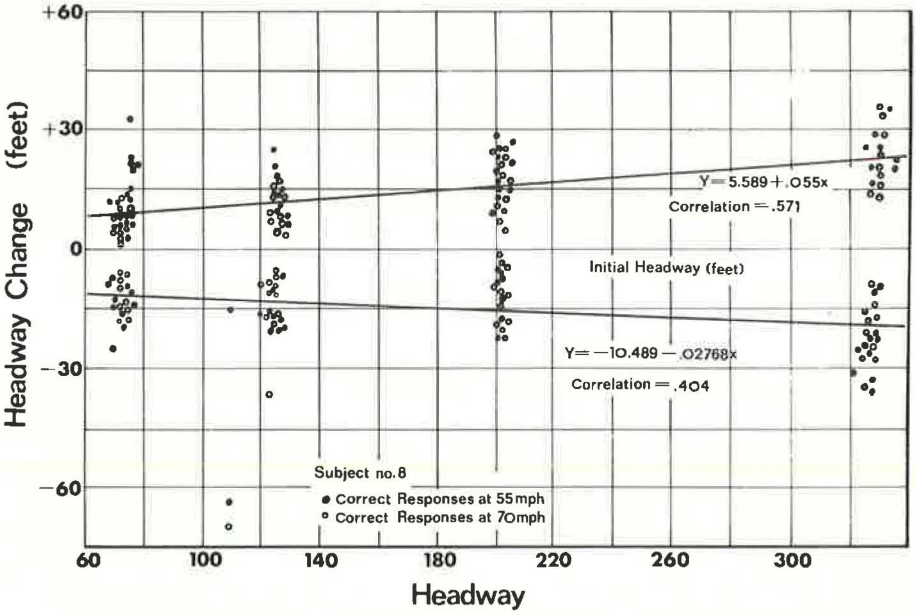
A stated conclusion of this research is that the probability of the subject's responding to a given stimulus is biased in the direction of favoring a response indicating a closure of the 2 vehicles. It is worth noting again that the subjects were forced to indicate either a positive or negative relative motion. In this context, because closure represents potential hazard and is the direction of change that is of more immediate concern to the driver, it appears both reasonable and likely that the driver's response would be biased in this direction when forced to respond at levels below his "level of confidence."

A major purpose of this paper has been to "identify which stimulus function most simply, consistently, and completely describes all the effects present in our data." Based on the fact that the ratio of average relative speed, U (feet per second), divided by spacing, S (feet), produces a function that has a relatively consistent intercategory threshold with respect to separation distance, the authors conclude that this function best describes all effects in the data. However, they note that this function does not describe the effects associated with the 2-sec exposure. Hence, the data are time-dependent. The authors further point out that, if their threshold value for this function is multiplied by exposure time, the resulting threshold is expressed in terms of a percent change in headway. In the case of the data presented in the authors' conclusions, this 0.99 threshold with a 200-ft separation corresponds with a $\Delta S/S$ of 8.8 percent or, in this case, a decrease in headway of 17.6 ft. It is of interest to note that, in a similar study (13) that involved constant relative acceleration (negative) coupled with a method of adjustment stimulus presentation, a mean headway change for detection was found to be 11.25 ft for original headways in the 180- to 190-ft range. This is the pooled average of 245 data points obtained from 8 subjects who performed while both driving and riding as passenger in the research vehicle. No statistical difference could be determined between the subject's performance when driving or riding as a passenger in the vehicle. It should be further noted that this writer has investigated (13) and reported on the effects of relative velocity as well as relative acceleration on the perception of relative motion between a leading and following vehicle at distances ranging from approximately 50 ft to 300 ft. These studies strongly indicate that for this range of separation distances, within which most car-following occurs, a stimulus function of the following form quite adequately describes all observed effects:

$$\Delta S = K_1 + K_2 S$$

Figure 7 shows this relationship with both raw data and corresponding stimulus functions. In the opinion of this writer, the authors' data would be more meaningfully described by this form of stimulus function, which is not time-dependent. (This assumes, of course, that the change occurs within a short enough time period so that the subject's memory trace of the initial separation distance is intact—changes taking longer than approximately 45 sec appear to exceed man's memory span.)

Figure 7. Relative velocity study—headway versus headway change.



Finally, the authors conclude that "there is a high level of sensitivity to relative motion." The authors' example to support this conclusion is that the probability of correctly identifying the polarity of a negative relative motion involving an initial separation of 200 ft with a closing relative velocity of 3 mph and a 4-sec observation is 0.99. As previously noted, this corresponds to an 8.8 percent decrease in separation distance; thus, based on the authors' findings, the separation distance must decrease by 8.8 percent for us to be 99 percent confident that the subject perceives the change. Couple this finding with man's motor response time and a realization that this type of data describes the best performance that man is capable of and then you begin to understand the underlying factors that result in the behavior exhibited by mass traffic flow. In this writer's opinion, the data do not support the authors' conclusion. In fact, just the opposite conclusion is indicated by both their data and the research of others.

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AUTHORS' CLOSURE

In our paper we have consciously striven to emphasize those aspects of driver perception that are of most concern to traffic theory and experimentation and therefore have avoided delving into the psychological and psychophysical aspects. Those aspects have been discussed in detail in a separate paper being published elsewhere (14). There we present our results in terms of analytical response functions to 2 stimulus functions, namely, average relative speed divided by spacing (U/S) and spacing change divided by spacing ($\Delta S/S$). An analytical response curve is necessary because a simple Weber ratio does not take account of the response bias. We have made (15) detailed comparisons between the predictions of the analytical response functions obtained from the experiments reported here and a number of laboratory, simulator, and field results reported in the literature. In particular, we find that the results of Braunstein and Laugherty cited by Mortimer agree well with ours if one assumes that the percentage of erroneous responses they report correctly measures the response level the subjects were choosing. The results of Braunstein and Laugherty (as well as others) have embedded within them a response bias not only of the same sign as we observed but also of the same magnitude.

In the interests of brevity we have chosen in this paper to present our results only as a response to U/S, as opposed to the essentially equivalent $\Delta S/S$ interpretation favored by Mortimer. The quantity U/S appears as the stimulus in the most successful of the analytical car-following models, namely the reciprocal spacing model (16). Intuitively, this function implies that the subject senses relative speed directly, his judgment being scaled by a spacing factor.

The instrumentation that we used to measure vehicle trajectories is a very effective research tool and has been successfully and conveniently used since 1963 (17-22). Apart from the obvious advantage of no mechanical link between the cars, it offers a degree of flexibility and precision not obtainable with earlier devices. Spacing changes were measured to within 0.2 ft and speed to within 0.2 ft/sec in these experiments, and further development of this equipment since then has increased its precision.

The comments of Snider appear to stem from a misunderstanding of the goals, execution, and conclusions of the experiment we have described. The longitudinal control of a vehicle can be considered to require 3 distinct tasks from the driver. First there is perception, then decision, and finally execution of a control input. All these, as well as the mechanical response of the vehicle, are lumped together as one grand system response in car-following models. The overall driver-vehicle system lag, τ, has contributions from all these sources. Car-following models do not yield information on the separate processes of perception, decision, control input, and vehicular response. It was the purpose of the present study, as indicated by the title, to experimentally investigate the perceptual aspects of the problem, and only the perceptual aspects. Precise measurements on the perceptual process require isolating it from the other processes.

We reiterate that, if a subject is permitted to view an increasing stimulus and respond when he chooses to do so, what is measured is a function of both his perceptual sensitivity and his willingness to make a decision. Without prior knowledge of one of these, it is impossible to say anything about the other. Because sensitivity and willingness to decide are both involved in the measurements cited by Snider, they are characterized by large variance, as is apparent in the plot submitted by him. This variance is much greater than would permit discrimination between one interpretation or another, such as a response to vehicular pitch. For example, in Snider's graph (which is, incidentally, for his most consistent subject), at a spacing of 200 ft there is one response to spacing change of under 2 ft whereas in other cases there was no response until the spacing change had exceeded 25 ft. The variability at other spacings is similarly large. In general, when the standard deviation is considerably greater than the mean, it is very difficult, if not impossible, to distinguish the underlying process.

Our data do indeed imply that, if 2 cars traveling at 45 mph are about 300 ft apart, a driver in the following car will perceive at the 0.75 level after a 4-sec look that he is gaining on the lead car. There is no reason why the driver should decide to do anything as a result of this perception. If he is content with his current speed, he will continue to maintain it. If he desires to go faster he will catch up to the lead car and enter a car-following mode. We might stress that the experimental car-following work indicates that the lagged response is proportional to the stimulus for stimulus values well above threshold. There is no reason for supposing that there are very small responses to near-threshold stimuli. In fact, observations indicate that we should not expect such behavior.

We are at a loss to understand the nature of Snider's objections to our example. At a closure rate of 3 mph from a distance of 200 ft, the time to collision is over 45 sec—more than an order of magnitude greater than even the slowest motor response. Our conclusion was that limitations in the ability of an alert driver to detect the sign of relative motion were unlikely contributors to accidents. We did not state that other factors, such as inattention or vehicle response, do not contribute to accidents.

The technique we have used permits sufficiently clean and precise measurement of perceptual thresholds in car-following so that our results can be directly compared to laboratory-measured thresholds. When this is done the quantitative agreement (including spacing dependence and exposure time dependence) is sufficient to suggest the conclusion that a disc moving in a featureless environment simulates well the perceptual task in following a vehicle. The most prominent difference is that there is no response bias in the laboratory studies. It is our conjecture that the origin of the response bias arises from the subject's motion through his environment.

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SKID SIMULATOR FOR USE IN DRIVER TRAINING AND RESEARCH

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A large portion of accidents involve some type of skidding, yet most drivers lack knowledge of the procedures for avoiding skids or for bringing a skidding vehicle under control. The vehicle skid simulator being developed will provide a laboratory model of a skidding automobile in which the driver can experience the visual inputs and the yaw motions and learn how best to use the brake pedal, accelerator, and steering wheel to control his vehicle. The simulator rotates about a pivot point at the center of gravity of the skidding vehicle. The driver is placed in a potential skidding situation and told to keep the vehicle centered in a simulated lane. Manipulations of the controls are converted into voltages by transducers and fed into an analog computer programmed to represent the yaw responses of an actual automobile on various types of surfaces. The computed heading is compared to the actual heading, and the error signal is fed into a drive system that rotates the mock vehicle in the appropriate direction. Where friction demands are excessive for the simulated surface, speed, and tire conditions, a skid will be initiated. The simulator will be used for research to define the characteristics of control and skidding and to determine the potential for skid training. It will also be useful for studying some human-factors aspects of motion and acceleration effects on perception.

•IT IS quite obvious, even to the beginning driver, that some pavements are slipperier than others. The same pavement also varies from time to time with the presence of other materials, and recently the intense advertising and discussion of the virtues of snow tires, studded tires, belted tires, and radial-ply tires has made the general public aware that there are differences among tires. Although it is quite difficult to obtain reliable skidding accident data, there is a strong indication that the skidding accident rate is on the increase and that something beyond what is presently being done is required. For example, Miles and Shelton (1) report that skidding was a primary cause of accidents in at least 35 percent of all wet-pavement accidents in Virginia. A British study (2) reported that skidding was involved in approximately one-third of all wet-road accidents in Great Britain. Because of the variations in regional climate, pavement maintenance, and pavement composition, and because of differences in methods of obtaining the estimates of various causes in the United States, skidding accidents reported have ranged from 0 to 34 percent of the total at different times in different states (3).

Baker (4), in discussing single-vehicle accidents, concludes that most accidents appear to have numerous contributing factors, but "The factor which most commonly combines with others is a wet or slippery roadway. It is combined with almost every other listed factor, especially with lack of skill. . . ."

There also are seasonal variations in skidding accidents. Most wet skidding accidents happen in the summer and fall, obviously related to rainfall and to heat, which

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affects both the pavement surface and the characteristics of the rubber tires. As more reliable and faster methods for assessing the slipperiness of pavements are developed, it may be possible to modify or treat surfaces that become slippery at specific times of the year.

There are obvious differences in the requirements of friction at different situations in driving. On curves and intersections, especially where stop signs artificially increase the frequency of high friction requirements, a greater coefficient of friction is required and the greater wear results in faster smoothing of the pavement. Thus, any treatment of the existing surface is likely to be temporary because the wearing is a continuous process.

SOURCES OF DATA

Although it may be possible to discover useful information about skidding by investigating, in detail, a large number of skidding accidents, there are more direct studies of driver behavior that could provide information as a function of highway type, highway appearance, vehicle type, traffic, weather, average speeds, acceleration and acceleration patterns, tracking error and consistency, and similar variables. The driver, in addition to gathering information visually about the road surface, has other means for obtaining information about the surface and incipient skidding. For example, peripheral streaming patterns as cues to tracking performance and speed estimation have been investigated in a few studies (e.g., 5, 6), but much remains to be discovered on the uses and capabilities of cues from peripheral vision.

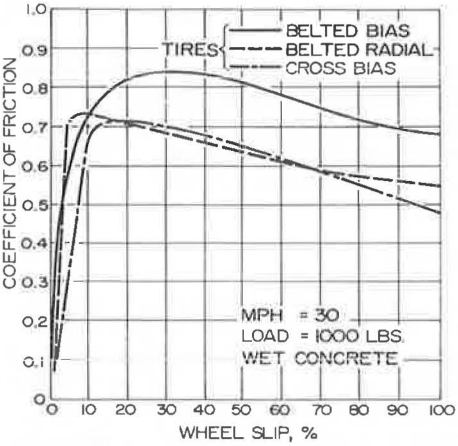
One of the potentially most useful sources of knowledge of roadway condition and available friction is the feedback from the road to the driver by means of the steering wheel. For example, the State Highway Patrol of California purchased over 1,500 vehicles with police specifications for use in the 1969 model year, choosing a moderately heavy vehicle, often a large Dodge model, specifying manual steering in all vehicles (personal communication, 1968). Discussion with the officer in charge of equipment disclosed that this was not a matter of cost or maintenance but strictly for the reliability, feel, and handling differences, which were felt to be important in high-speed driving under all road conditions. Undoubtedly, the highway patrolman is physically able to handle the occasional heavy torque demands of manual steering where a considerable portion, perhaps 20 percent, of the driving population would have difficulty. However, the strong preference for manual steering, even in a heavy car, indicates that some professional drivers feel that there are advantages.

Obviously, there are driver preferences as well as driver abilities that must be considered in developing a steering mechanism. Some sports cars have a reputation for their handling or feel. Racing drivers have developed preferences for individual types of steering, and there are many possible variations in the steering mechanisms, both power-assisted and manual. Driver preference for steering ratio or quickness has been considered, but there is no body of data relating steering ratio to accident rates or the effectiveness of evasive maneuvers.

Although there is a common feeling among many of the more mechanically inclined, especially young male drivers, that certain models are "good" and other models are "bad" in the way they handle, there is little known about the types or amounts of information that could be fed through the steering wheel to the driver. The dither signals generated by a driver during ordinary tracking can have very noticeable variations in the amount of torque feedback provided by different surface conditions and various speeds. Very likely there are cues that are used by drivers, even though they may deny knowledge of these cues.

Driver alertness and expectancy are serious problems in skidding emergencies. There are relatively few accidents on icy roads where the conditions are constant over a wide area, partly because drivers elect to stay off the road and partly because they adapt sufficiently to obvious conditions. It is unlikely that a driver will fall asleep when the conditions are obviously hazardous, but it is likely that the occasional patch of refrozen snow-bank melt will not be expected or observed by the driver who has been completely unchallenged for a long period of driving on dry, clear roads. The sudden change

Figure 1. Effect of tire construction on slip curve (from 8 as cited in 7).



of conditions is likely to produce a skid and unlikely to alert the driver in time.

Another area where driver expectancy could lead to loss of control is the range of effects of tire construction on handling qualities. Except for a slight increase in harshness of ride in some vehicles, the radial tire seems to have gained a reputation as the tire for all purposes. There are some indications that this reputation is not fully deserved. For example, many emergency maneuvers will result in some wheel slip. The maximum braking force occurs with a moderate rate of wheel slip. Generally, without automatic skid controls, a locked-wheel stop will result in a shorter stopping distance than is possible for most drivers attempting to use controlled-slip rates. In any event, once a skid has begun, a high coefficient of friction is still desirable. Figure 1 shows the effect of tire construction on the coefficient of friction with tire slip (7, from 8); the belted bias tire appears to be superior to the belted radial tire by a factor of 20 percent or more when slip has developed. Since the driver has need of this friction advantage in emergencies, the conservative choice for safety seems to be the belted bias tire. In any case, the more gradual change of coefficient with slip for the belted bias tire should give the driver a better degree of control than the abrupt peaking characteristic of the radial or regular bias tire. Its more consistent and predictable friction force for all degrees of slip is easier to handle.

The data on skidding and friction properties are complex and often display large variances. Most important, the theoretical conclusions from skid resistances and slip curves are not necessarily generalizable to driver behavior and vehicle reaction on the road. Whatever the characteristics, there should be methods for making the driver aware of the qualities of the various vehicles, tires, road surfaces, and road conditions that he may encounter or choose to avoid. In addition to setting performance standards for tires, the methods can involve improved or augmented feedback to the driver or widespread skid training and experience. The most effective technique would probably involve both improved feedback and skid training, although many basic questions have yet to be answered.

Recognition of the part training can play in controlling skidding is not new; there have been "skid schools" in Britain for many years. Although it may not be possible to operate skid schools at a profit in this country, it certainly would profit highway users as a group if everyone who drives had some knowledge of skidding control and prevention. In 1964, Liberty Mutual Insurance Company established their Skid Control School (Hopkinton, Mass.) to show how emergency training could be brought into advanced driver education programs. Other groups, including major auto manufacturers, also sponsor skid and winter driving courses. Research programs can be established in any area by the Department of Transportation, but it is a strong selling point for the utility of a program when it is established by a commercial firm such as an insurance company that stands to profit directly from an effective program. Liberty Mutual has sent their specially equipped cars and a driver trainer to several communities to illustrate the type of training involved and to help local jurisdictions set up skid schools. They recently have expanded their efforts along these lines by providing information on training and by demonstrating these skid-school concepts to groups involved in driver performance. Their program consists of sealing existing surfaces available to local groups to provide a low-friction surface and training local instructors in the skid techniques. These programs alone, however, cannot reach any large part of the driving public.

THE SKID SIMULATOR

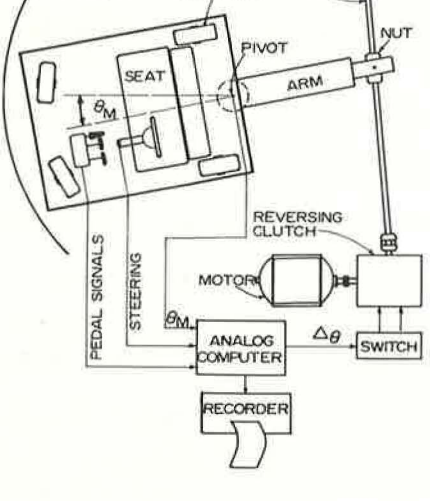
At Penn State, the skidding control and prevention program has several aspects: studies of road friction and surface wear, tire-pavement interactions, a vehicle skid simulator, and facilities for experiencing actual skids in a driver education training center driving range. Skid prevention obviously depends on road and surface design, and there is a considerable amount of study of these topics at Penn State and elsewhere. However, the field of driver behavior in skidding and awareness of skid potential has hardly been tapped. For this reason, a skid simulator is currently being developed with in-house funding at Penn State's Transportation Center. This one-degree-of-freedom simulator will require the driver to cancel random left and right yaws by means of the steering wheel and to control simulated skidding using the wheel and the pedal controls. By proper programming and use of motion, control, and visual variables, it should be possible to signal a potential skid to the driver and to train him to react properly to this feeling of "breakaway," counteracting the skid before it develops into loss of control. Correlation between driver behavior in the simulator and on the skid pad may provide some of the missing information. In addition, a simulator allows mathematical modeling and replicable training conditions that are difficult to achieve in an actual vehicle.

The skid simulator consists of the forward sections of an automobile mounted on a pivot to provide yaw at the command of an analog computer. The vehicle used was sectioned from just behind the front seat back and from the firewall forward, leaving the front bench seat, floor boards, front doors, dashboard, steering wheel, brake pedal, accelerator pedal, and roof intact. It rotates on 4 hard-rubber wheels, which are tangent to circles about a pivot point located just behind the front seat of the vehicle.

The drive system is shown in Figure 2. It consists of a rotating arm attached to the undercarriage of the vehicle and extending 5 ft out from the pivot point. At the end of the arm is a nut assembly free to rotate in the horizontal plane. The nut assembly is driven by a 1-in. diameter standard threaded steel rod that is attached to a universal joint and driven by a reversing electric clutch. The input to the reversing clutch comes from a constant-speed, 2-hp, 3,600-rpm ac motor.

The reversing clutch drive consists of an input shaft and an output shaft with two field and coil assemblies. By activating the appropriate coil, the output shaft is rotated either clockwise or counterclockwise. The analog computer will produce an output error signal $\Delta\theta$. This error is the difference between the desired yaw angle as computed by the mathematical analog and the actual yaw angle as measured at the pivot point. Transducers mounted on the steering wheel, brake pedal, accelerator pedal, and pivot point provide inputs for the computer simulation.

Figure 2. Skid simulator schematic diagram.



ANTICIPATED RESEARCH PROGRAM

Although the ultimate test is the driver's behavior in his own car during an unexpected skid, a simulator of this type may help to establish a behavior pattern that is appropriate to skid prevention without the time, expense, and possible hazard of actual training. After operational definitions have been developed, comparisons of trained and untrained drivers in actual skid-pan operations will be necessary for beginning the validation research. Long-term validation studies are likely to be the only source of statistically significant data relative to the effectiveness of training on a skid simulator.

One serious practical problem is that the frequency of skidding during driving is low enough that the potential value of training may be lost after a relatively short intervening period. Cost-effectiveness of skid training will undoubtedly require a low unit cost for periodic retraining, and practical programs must optimize the training cycle for convenience and potency over time.

A research program in skid simulation and training should include the following:

1. An expanded definition for vehicle handling "feel" with objective correlates;
2. A definition of, and threshold values for, incipient skid detection or "breakaway";
3. Development of a simple heuristic mathematical analog for realistic yaw motions in a skid simulator;
4. Validation of driver behavior in a vehicle after training in a yawing skid simulator and after various time lapses;
5. Theoretical integration of subjective qualities into a formal skid simulation analog based on the heuristic; and
6. Development of skid training programs that are both practical for widespread use and effective in teaching skid prevention and control.

It should be possible to simulate different types of vehicles and even different models within a vehicle type. A further extension of the modeling may include the skidding of articulated vehicles, where the trailer first swings freely and then influences the course of the vehicle pulling it. The different types of skids may also be demonstrated, including the power skid and recovery of steering control during and after a skid.

CONCLUSION

The in-car phase of driver skid training is necessarily expensive. Although any large-scale training of drivers could be done more economically on a simulator, the simulation must first be validated in the real driving situation. It is likely that actual experience will provide further refinement to the necessary skills, and emergency drivers such as police, firemen, ambulance drivers, and rescue teams will continue to require some in-car experience, even with a useful simulator. In addition, heavy vehicles, especially articulated vehicles, will present problems that will make simulation more difficult.

Commercial drivers of all types probably could benefit from skid training and practice, whereas wholesale in-car training of private drivers is less likely to be cost-effective. Since the potential saving in accident losses attributable to skidding probably exceeds 2 billion dollars per year, a reasonable investment, nationally, is indicated in skid prevention and control.

Little is known about driver perception of, or reaction to, incipient skidding or about the effectiveness of various types of skid training. The skid simulator, if it proves to be a valid representation of an actual vehicle skid, may provide both definitive data and a technique for convenient, low-cost training for emergency drivers, for problem drivers, and, ideally, for the general driving public upon routine renewal of driver licenses.

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