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Studies of Automobile and Truck Rear Lighting and Signaling Systems

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This report consists of 4 studies related to vehicle rear lighting problems:

Accident Data Analysis
Interpretation of Signals
Responses of Naïve Drivers to Presence and Stop Signals of Experimental Rear Lighting Configurations
Perception of Relative Velocity

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CONTENTS

Page

List of Tables

List of Figures

Objectives

Summary of Findings

Foreward and Acknowledgements

Page

Page

LIST OF TABLES

Number Page

TABLES (cont.)

TABLES (concl.)

LIST OF FIGURES

FIGURES (cont.)

FIGURES (cont.)

FIGURES (concl.)

OBJECTIVES

The four studies here reported had the following objectives:

STUDY I. Conduct an analysis of accident data in an effort to discern the information needed by drivers to avoid rear-end collisions.

STUDY II. Evaluate the ability of drivers to identify the intended information content of conventional and certain novel signal systems.

STUDY III. Evaluate a technique to unobtrusively measure the response of naïve drivers to conventional and novel rear marking and signaling displays.

STUDY IV. Evaluate the ability of drivers to detect changes in the dynamic relationship between their own vehicle and a lead vehicle, and analyze the way in which this information is used in car following.

SUMMARY OF FINDINGS

I. ACCIDENT DATA ANALYSIS

1. Crashes between vehicles oriented in the same direction constitute half or more of all traffic accidents.

2. In almost half of same-direction accidents involving a fatality, one vehicle was parked, stopped, stopping or starting.

3. Parked vehicles were involved in about 5% of all two-vehicle crashes in a Washtenaw County accident sample.

4. The relative speed between pairs of vehicles moving in the same direction is positively related to the probability of a rear-end crash occurring.

5. On grades, rear-end collisions increase compared to other two-vehicle collisions, showing the effect of variability in traffic speed.

6. The rates of rear end collisions are higher on wet roads than dry and higher still on wet roads at night.

7. Rear-end crashes into parked vehicles more frequently result in injury at night than day, indicating such collisions are more severe at night.

8. Most rear-end injury crashes into parked vehicles occurred at night (62% on dry, 74% on wet roads). Other types of rear-end injury crashes occurred much less often at night (30% on dry, 39% on wet roads).

9. Turning vehicles appear to be involved in more than the expected frequency of rear-end injury crashes, as compared to non-turning vehicles.

10. Trucks, especially tractor-trailers, were found to be overinvolved in fatal rear-end collisions by comparison with cars, being the striking vehicle in 20% and struck vehicle in 27% of interstate highway fatal accidents.

11. Twenty-eight percent of rear-end collisions on interstate highways occurred on up-grades, compared to 5% on downgrades. Of these collisions, 88% involved trucks, with the truck being the struck vehicle 82% of the time. When fatalities occur in car-truck accidents, 96% were riding in the car.

II. INTERPRETATION OF UNIQUE SIGNALS

12. Drivers readily identified the intended meaning of the novel rear lighting displays tested, which provided high deceleration, velocity, stopped and slow-moving vehicle signals.

13. Some conventionally used signals, such as hazard warning signals and back-up signals, were not identified as frequently as was expected.

III. FIELD STUDY OF RESPONSE TO UNIQUE SIGNALS

14. A technique of unobtrusive observation of vehicles approaching from the rear of a test car was useful in evaluations of novel rear lighting systems.

IV. PERCEPTION OF RELATIVE SPEED

15. In car-following, drivers responded with accelerator or brake actions primarily to detected changes in headway, making little use of relative velocity information.

16. It was determined that drivers' perception of relative speed was so poor that they could do little more than identify whether the gap between theirs and a lead car was opening or closing.

17. Mean thresholds for angular velocity in two different experiments were 2.8×10^{-3} and 5.2×10^{-3} rad/sec, with an overall mean of 3.5×10^{-3} rad/sec.

18. In car-following by drivers in a simulator the mean bandwidths of following car acceleration, relative velocity and change in headway were 0.092 Hz, 0.096 Hz and 0.060 Hz, respectively.

FOREWORD AND ACKNOWLEDGEMENTS

This report is one of a series which have been issued under the general contract title "Passenger Car and Truck Signaling and Marking Research", and consists of work conducted on Phases I-III of that project. Prior reports issued under this contract include the following: "Evaluation of Rear-End Collision Data for Determining Vehicle Rear Lighting and Signaling Priorities", Hit Lab Reports, 3, No. 4, 1972; "The HSRI Part-Task Driving Simulator for Research in Vehicle Rear Lighting and Related Studies", 1972; "Passenger Car and Truck Signaling and Marking Research: Regulations, Intensity Requirements and Color Filter Characteristics", 1973; "Automobile Rear Lighting System Malfunctions: Surveys of Their Extent and Driving Simulator Studies of Some of Their Effects", 1974; "Development of a Computer Simulation to Evaluate the Effectiveness of Vehicle Rear Marking and Signaling Systems", 1974.

The studies described in this report were carried out during the period 1971-74, and had the overall objective of providing basic information concerned with the definition of information which may be useful to drivers in avoiding rear-end collisions.

During the conduct of this study, periodic meetings were held with members of the VLC Research Fask Force (Signalling and Marking) consisting of: Mr. J.F. Meldrum, Chairman, Ford Motor Company; Mr. P. Lawrenz, American Motors Corporation; Mr. T.G. Tallon, Chrysler Corporation; Mr. R.J. Comparet, International Harvester Corporation; Mr. W.E. Barth, Mr. P.W. Maurer and Mr. R.J. Donohue, General Motors Corporation. We are pleased to acknowledge the assistance received from the Task Force in various aspects of this project.

Dr. E.R. Hoffmann was Visiting Research Scientist at HSRI, September 1973 to January 1974, from the Department of Mechanical Engineering, University of Melbourne, Australia.

INTRODUCTION

There has been a substantial amount of research, development and evaluation completed concerned with motor vehicle rear lighting systems. Much of this work involved the evaluation of displays which were derived on the basis of the application of psychological principles involving human perception and information processing. Thus, emphasis was placed, initially, on displays which would provide improved detectability and identification of stop and turn signals (Finch, 1968; Case et al., 1968; Mortimer, 1970). Other studies were concerned with providing improved information, coded by rear lamps, of changes in headway with a preceding vehicle (Rockwell and Banasik, 1968; Mortimer, 1970a). Evaluations have also been made of signals which provide information that a preceding vehicle is coasting, i.e., with the accelerator released, without the brakes being applied (Mortimer, 1971). This concept was extended in the form of a display which presented a signal at the rear of the vehicle when the accelerator was depressed and a different signal when the accelerator was released, as well as conventional stop signals (Rockwell and Banasik, 1969). Signal systems which provided information of the level of deceleration in braking, by the illumination of various numbers of rear signal lamps, have also been evaluated (Rutley and Mace, 1969) in driving tests, and by means of a simulator (Wallner, 1969). In addition, studies of traffic flow and car-following behavior of drivers resulted in some theoretical models to describe this performance (Herman and Potts, 1961), and suggested that the driver of the following car respond to the relative velocity and the instantaneous headway.

Other researchers (e.g., Nickerson et al., 1968) have evaluated the effectiveness of displays which provide information of the speed of preceding vehicles by illuminating various numbers of lamps on the rear of the vehicles. On this basis, relative speed information could be derived by the driver of the following vehicle by taking account of his own vehicle's speed.

Using the findings of various experimental and theoretical studies, Mortimer (1971b) derived the elements of an integrated rear lighting system and described its various components. It was recognized, however, that additional basic information was needed, followed by further evaluation of the overall concept that he proposed, to insure that the information provided by the system was that which was most essential and which could be effectively used by drivers.

It had been evident for some time, that drivers are poor judges of relative speed - one of the augmenting cues incorporated in the rear lighting system proposed by Mortimer (1971). This poor capability of drivers has been demonstrated in accident data such as that of Solomon (1964), which showed that vehicles which were traveling at increasingly disparate speeds were more likely to be involved in rear-end collisions. In addition, studies which were concerned with the ability of drivers to make overtaking decisions in the face of oncoming traffic (e.g.,Farber and Silver, 1967) clearly showed that drivers are almost completely unable to estimate the speed of approaching vehicles. This has also been found in a number of European studies which were recently completed (Rumar and Berggrund, 1973). An experimental study by Olson, Wachsler and Bauer (1961) provided some initial experimental data confirming the fact that drivers are able to process little information of relative car velocity in car-following.

At the same time, it must be recognized that there are no data available to indicate that there would be a reduction in rear-end crashes if drivers were presented with relative velocity information. However, an attempt to derive such information utilized a computer simulation (Carlson and Mortimer, 1974) and found that the utilization of such information could be expected to lead to a reduction in certain classes of rear-end crashes.

The studies that are described in this report were concerned with the development of additional knowledge of the type of information which should be displayed on the rear of vehicles to the drivers of following vehicles which would be most effective in reducing rear-end crashes and maintaining a smooth flow of traffic. The studies consist of analyses of accident data, particularly those concerned with trucks, for which no significant accident data analysis had been completed at the time that the work was initiated. In addition, the ability of drivers to comprehend innovative display formats, which were intended to provide specified types of information, was experimentally evaluated. Experimental studies were also carried out in the laboratory and in driving tests, concerned with the ability of drivers to process information of relative velocity.

ACCIDENT DATA ANALYSIS

ABSTRACT

This survey was conducted to determine whether accident data contain any indications of the importance of various vehicle signals and can offer any insights regarding possible additional signals of benefit.

The data indicate that rear-end collisions are 40-60% of those involving two or more vehicles. About 15% of rear-end collisions involve a parked vehicle. The data indicated that a slow-moving or stopped vehicle is frequently involved in rear-end crashes. Parked vehicles are more likely to be struck at night than in the daytime, compared to other classes of rear-end collisions.

ACCIDENT DATA ANALYSES

OVERVIEW OF COLLISIONS INVOLVING VEHICLES TRAVELING IN THE SAME DIRECTION

INTRODUCTION. In assessing accident causation, it is usually very difficult to evaluate the role played by various vehicle characteristics; such is the case with rear lighting systems. It is indeed likely that many accidents would not have occurred, and conversely that many accidents that did not occur would have if various vehicles had been equipped with different rear lighting systems than they actually had. The investigator can only assume the implication of rear signaling systems in these accident types in which such systems may have been a factor, and assess the potential for safety gains by the magnitude of losses among such accident types.

Accidents occurring between vehicles oriented in the same direction of travel, including cases where one vehicle is stopped or parked as well as those in which both vehicles are moving, are those in which rear signaling systems are most likely to have played a role. The rear-end collision is, of course, the most prevalent accident type occurring between vehicles oriented in the same direction of travel.

The questions addressed in this section are: How serious is the problem of rear-end collisions (or more generally, same-direction accidents)? Is this problem increasing or decreasing in size relative to other accident types? What causes or predisposing factors have been associated with the occurrence of rear-end collisions? Based on such evidence, is there reason to conclude that improvements in rear signaling systems would lead to significant gains in safety through reductions in the number and severity of such accidents?

During the year 1969, approximately 5,400 people were killed in accidents involving collisions between vehicles oriented in the same direction of travel (Accident Facts, 1970).

They constituted 10% of all traffic fatalities for the year, and 25% of all fatalities resulting from two-car collisions (Table 1). Such figures, however large, would serve as gross underestimates of the relative size of the same-direction accident problem. About 7,750,000, or half of all traffic accidents reported in 1969 involved same-direction vehicles, and well over half, or 65% of all two-vehicle collisions involved such vehicles (Table 2). Two years earlier, in 1967, there were about 6,850,000 same-direction accidents, which constituted about 62% of all two-vehicle collisions (Accident Facts, 1968). The underrated growth in this accident category may be real, because the rear-end accident is the most prevalent multiple-vehicle accident type on interstate highways (Hosea, 1969; Vecellio, 1967) which are growing rapidly in roadway mileage and in volume of traffic accommodated (Ford Automotive Safety Research Office, 1970).

There is little doubt that collisions between vehicles oriented in the same direction of travel constitute a large and perhaps growing problem for auto safety planners. The next question, then, is whether there is evidence among the data from such accidents that more clearly implicates rear signaling systems among the causes of these accidents. Looking again at the data from Accident Facts (1969), one finds, among fatal accidents involving same-direction vehicles (9.6% of all fatal accidents), nearly half (49.3%) involved one vehicle which was parked, stopped, stopping or starting (Table 3). Moreover, among all (fatal, injury, property damage) same-direction two-vehicle accidents (50% of total accidents), nearly two-thirds (65.8%) involve one such vehicle (Table 4). It should be pointed out that, in Tables 3 and 4, the third column, containing the percentage of like-oriented vehicle collisions in which both vehicles are moving, also includes all such collisions in which one vehicle is slowing to turn,

TABLE 1. Percent of Fatal Accidents Involving Like-Oriented Vehicles (1969).

	% of Total	% of Rural	% of Urban	% Total Two Car	% Rural Two Car	% Urban Two Car
Intersection	1.1	1.0	1.4	2.9	2.4	4.3
Non-Intersection	8.5	8.9	7.4	22.1	21.4	22.8
Total	9.6	9.9	8.8	25.0	23.8	27.1

TABLE 2. Percent of all Accidents Involving Like-Oriented Vehicles (1969).

	% of Total	% of Rural	% of Urban	% Total Two Car	% Rural Two Car	% Urban Two Car
Intersection	10.7	7.8	11.9	13.8	13.7	13.9
Non-Intersection	39.3	26.9	44.3	50.8	47.3	51.7
Total	50.0	34.7	56.2	64.6	61.0	65.6

TABLE 3. Percent Distribution of Fatal Accidents for Like-Oriented Vehicles Only (1969).

	One Vehicle Parked	One Vehicle Stopped, Stopping, Starting	Both Vehicles Moving
Intersection	---	18	82
Non-Intersection	18	36	46
Total	15.6	33.7	50.7

TABLE 4. Percent Distribution of All Accidents for Like-Oriented Vehicles Only (1969).

	One Vehicle Parked	One Vehicle Stopped, Stopping, Starting	Both Vehicles Moving
Intersection	---	39.3	60.7
Non-Intersection	28.7	44.3	27.0
Total	22.6	43.2	34.2

or has just entered the traffic stream. Thus, although Table 3 lists 82% of fatal like-oriented vehicle collisions at intersections to have been between two moving vehicles, far fewer such collisions can be presumed to have occurred between two vehicles moving at their normal traffic speed. In fact, only 27% of intersection same-direction collisions involved two such vehicles. Such statistics underscore the need for rear signaling systems to convey information that a vehicle is parked, rapidly decelerating, or proceeding at a very slow speed or stopped.

SPEED DIFFERENCES. More data indicating the need for some kind of velocity information in rear signaling systems comes from Solomon (1964), who performed an extensive analysis of a large sample of accident involvements covering an area of several states. One of his findings was that 47% of two-car, rear-end collisions involved cars traveling at a speed difference greater than 20 mph, whereas in normal traffic only 7% of randomly selected following vehicle pairs traveled at such differential speeds. The overinvolvement rate of 600% at greater than 20 mph differential speeds rises to over 3000% at 30 mph. For although fewer than 1% of random following vehicle pairs exceed a 30 mph differential speed, 32% of accident involved pairs were traveling at discrepant speeds of that order or higher.

More recent evidence for the importance of speed differential is supplied by a study performed for NHTSA by Triangle Research Institute (1970). These researchers found that vehicles whose speed deviated from the mean traffic speed (on selected Indiana highways) by more than ±15.5 mph were twelve times as likely to be involved in an accident as traffic deviating from the mean by less than ±5.5 mph.

Several other studies could be cited to support the argument that initial speed differential between following vehicles is a major precondition for the occurrence of a rear-end collision or other same-direction accident (Mitchell, 1966; Taylor, 1965). The argument for the implication of differential speed in same-direction accidents is also documented in another section dealing with truck accident involvement. That study also shows the exceptionally high involvement of trucks on hills in rear-end collisions. Such a finding follows directly from the implication of differential speed in such collisions, since trucks suffer relatively greater velocity loss on hills than do passenger vehicles, thus increasing the expected speed differential between some randomly selected truck-car following pairs.

If the speed of car traffic becomes more variable on grades the expected speed differential between any randomly selected car-following pairs would average zero, as it would on level roads, but the proportion of vehicle pairs traveling at 20 and 30 mph speed differentials would increase. One might then expect relatively more same-direction accidents to occur on grades.

In order to pilot test this proposition, we took recourse to some accident data that have been collected by HSRI and stored on magnetic tape from which they can be readily retrieved for statistical analyses. The data used in this analysis were of accidents that occurred in Washtenaw County in Michigan. They consisted of a sample of approximately 11,000 accidents reported during 1968 and 1970.

The accident data were drawn from the computer in the form of bivariate frequency table to show how rear-end collision rates compare with other two-vehicle collisions on grades (Table 5). A Chi-square test indicated that rear-end collisions were significantly over-represented on grades.

The data in Table 5 further indicate the important role of initial speed differential in the causation of same-direction collisions. It is possible that improved rear lighting systems could prevent or reduce the severity of many such accidents.

TABLE 5. Rear-End vs Other Two-Car Collisions as a Function of Roadway Grade.

Type of Collision	Number of Collisions		
	Graded Roadway	Level Roadway	Total
Rear-End Collisions	Actual 671 Expected 607	Actual 1835 Expected 1899	2506
Other Two-Car Collisions	Actual 1136 Expected 1200	Actual 3621 Expected 3557	4757
Total	1807	5456	7263

LICENSE PLATE STUDIES. In a well-controlled investigation into the effects of reflectorized license plates, Campbell and Rouse (1968) found that when various states switched to reflectorized plates, parked-car accidents were greatly lessened. However, the authors point out that other factors could be implicated besides reflectorization, so they undertook a much better controlled study, collecting data on parked-car accidents during the changeover to reflectorized plates, when some cars were still equipped with non-reflectorized plates. In order to assure that any accident differences found were the result of the plates and not because a different type of driver bought his new plates earlier, Campbell and Rouse used for their measure the percentage of _all_ accidents for each group (reflectorized and nonreflectorized) which were parked-car collisions in which the subject's car was that struck. Thus, if differences are found, they will not be due to the fact that people who buy license plates early are simply a different population whose overall accident involvement is low. The results showed a decrease in parked-car accidents for those cars with reflectorized plates, and no significant difference in other accident involvement. A more recent study, in Virginia (Stoke, 1973), did not find a reduction in crashes into the rear of cars which were fitted with reflectorized license plates than those without such plates.

Irrespective of whether or not reflectorized license plates can reduce crashes into parked cars at night, the hazard posed by this type of crash warrants remedial measures to be devised. An analysis of accident data by Mortimer and Post (1972) showed that the incidence of injury-producing rear-end crashes involving parked vehicles relative to moving vehicles is considerably greater at night than in the daytime. They suggested that a rear display which indicates a vehicle to be parked may be warranted. Parked-vehicle crashes are investigated in greater depth in the next section.

PARKED CAR ACCIDENT STUDY

OBJECTIVES. The conditions under which parked-car crashes occurred were further investigated in this study in order to evaluate the effects of dry and wet pavements, and the ambient lighting.

METHOD. The approach used was to make comparisons between all two- or more-vehicle accidents, all rear-end accidents based on the accident diagram interpretation, and parked vehicle rear-end accidents based on vehicle movement as interpreted from the accident diagram, as a function of road surface and ambient lighting conditions. A parked vehicle was defined here as one which was not in the main thoroughfare. Thus, a vehicle stopped at a traffic signal was not parked nor was one which had been abandoned in a lane of traffic.

The present study was conducted on the updated (1969-1972) Washtenaw County Accident File. In these runs accident severity was classified as a function of ambient light condition and road surface condition. The accident severity categories were mutually exclusive and were coded first by fatality, next by injury, and finally by property damage. The four ambient light conditions were daylight, dusk or dawn (no artificial lighting), darkness with no street lights, and darkness with street lights (continuous or intermittent spacing). Accident cases which contained missing data on any one or more of the variables were excluded. From a file of 30,577 cases, 9121 were excluded because only one vehicle was involved or pertinent data were missing. Because of the low frequency of fatalities in rear-end collisions and the underreporting of property-damage accidents (Carpenter et al., 1966), injury-producing accidents are probably the most valid and reliable criteria of severity and are used for that purpose.

RESULTS. Table 6 shows the frequencies of rear-end crashes into parked vehicles, and those excluding parked vehicles, in daytime and at night, and when the road was dry or wet. These data form the basis for the subsequent analyses.

TABLE 6. Frequency of Rear-End Crashes with Parked Vehicles and Those Excluding Parked Vehicles (Washtenaw County Data, 1969-1972).

Rear-End Crashes in Parked Vehicles

Pavement	Severity	Day	Night	Total
Dry	Injury	57	93	150
	PD + Injury	306	336	642
Wet	Injury	23	65	88
	PD + Injury	165	231	396
Total	Injury	80	158	238
	PD + Injury	471	567	1038

Rear-End Crashes Excluding Parked Vehicles

Dry	Injury	1078	454	1532
	PD + Injury	3140	1072	4212
Wet	Injury	546	344	890
	PD + Injury	1700	944	2644
Total	Injury	1624	798	2422
	PD + Injury	4840	1998	6838

Figure 1 shows the distribution of crashes on dry and wet pavements. Within the day and night those rear-end crashes involving a parked vehicle as well as those which exclude parked vehicles are in about the same proportion on dry and wet roads. But, it is clear that there are relatively more crashes of both types on wet roads at night than in the day.

The probability of an injury resulting from these rear-end crashes, whether a parked car is involved or not, is the same whether the pavement was dry or wet, since the relative proportions of injury accidents and all accidents is the same in the same combination of ambient lighting and pavement conditions (Figure 1).

Also, Figure 1 shows that there was precipitation recorded on 68 days, on average, which represent 19% of the days of the year.[1] Thus, the pavement was wet no more than 19% of the time, yet an average of 37% of the rear-end collisions occurred on wet roads, it is concluded that, both in the day and at night, more collisions occur on wet roads than would be expected if precipitation had no effect.

Table 7 shows the percent of rear-end crashes, both including and excluding those into parked vehicles, which resulted in injury.

It will be noted that the percent of rear-end crashes into parked vehicles which resulted in injury is less than those in other rear-end crashes, but is greater at night. Also, in the same pavement (or precipitation) conditions, there are proportionally more injury accidents at night than in daytime when a parked vehicle is involved, whereas this is less the case in other rear-end crashes (Table 7).

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[1] Washtenaw County had a mean of 68 days of precipitation per year based on the years 1939-1969 (Michigan Weather Service, 1971).

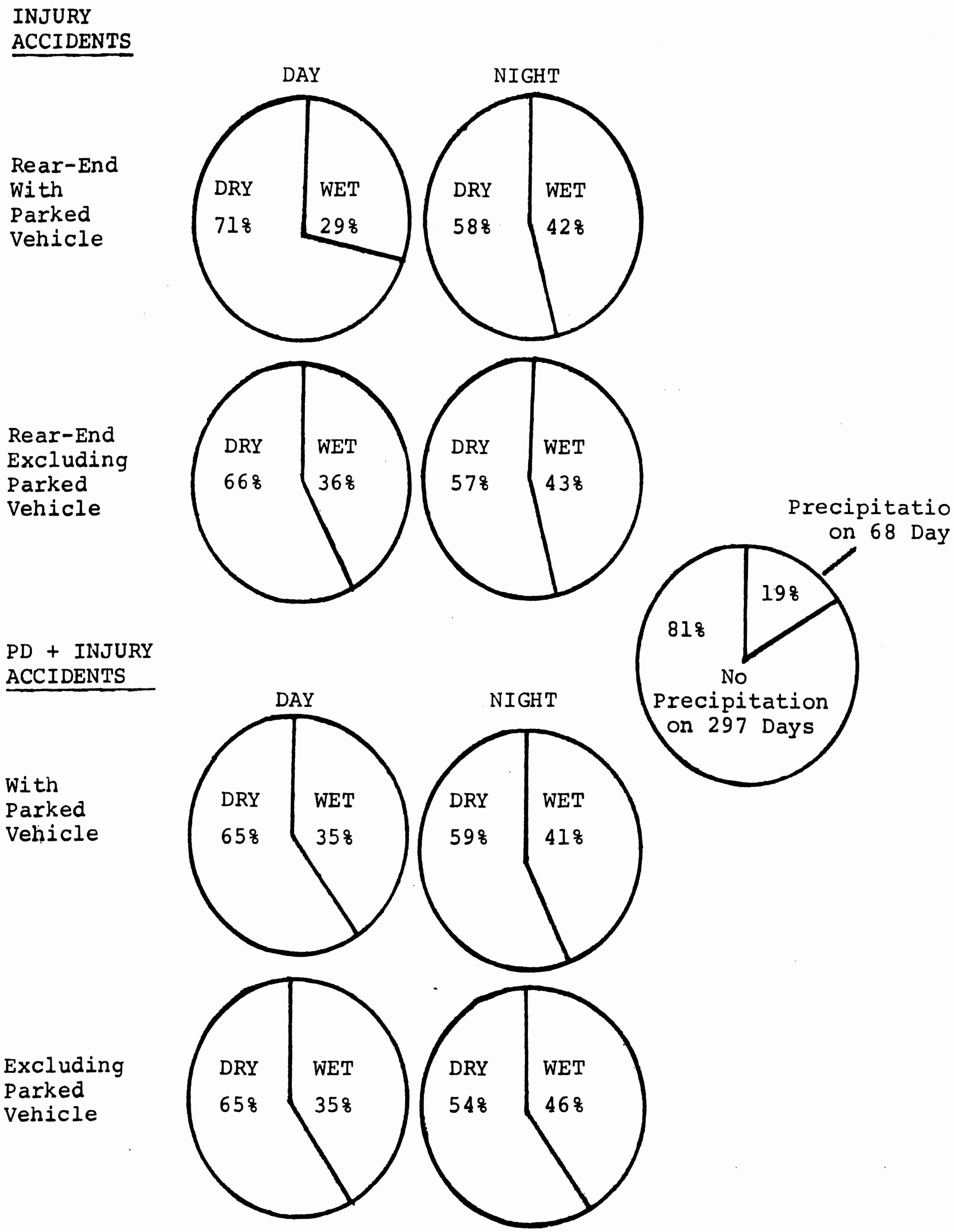

Figure 1. Percent of crashes producing injuries in rear-end crashes involving parked vehicles and excluding parked vehicles, on dry and wet roads.

TABLE 7. Percent of Rear-End Crashes Resulting in Injury.

Type of Rear-End Collision	Road (Precipitation)	Day	Night	Night-Day Difference
With Parked Vehicle	Dry	19	28	+9
	Wet	14	28	+14
Excluding Parked Vehicles	Dry	34	42	+8
	Wet	32	36	+4

Figure 2 shows the percent distribution of rear-end crashes which occurred in the day and at night. At night, the proportion of rear-end crashes into a parked vehicle was about twice as great as those for other rear-end crashes. For example, 74% of crashes into the rear of parked vehicles occurred at night on wet roads, while only 39% of other (i.e.,excluding parked vehicles) rear-end crashes occurred at night on wet roads.

In fact, over half of all types of rear-end crashes into parked vehicles occurred at night (53% on dry roads, 59% on wet roads) and well over half of those resulting in injury (62% on dry roads, 74% on wet roads). By comparison, 26% to 39% of the other rear-end crashes occurred at night.

Figure 3 provides an overall perspective of the relative magnitude of rear-end collisions which do not involve parked vehicles and those rear-end collisions with parked vehicles, compared with all types of collisions involving two- or more-

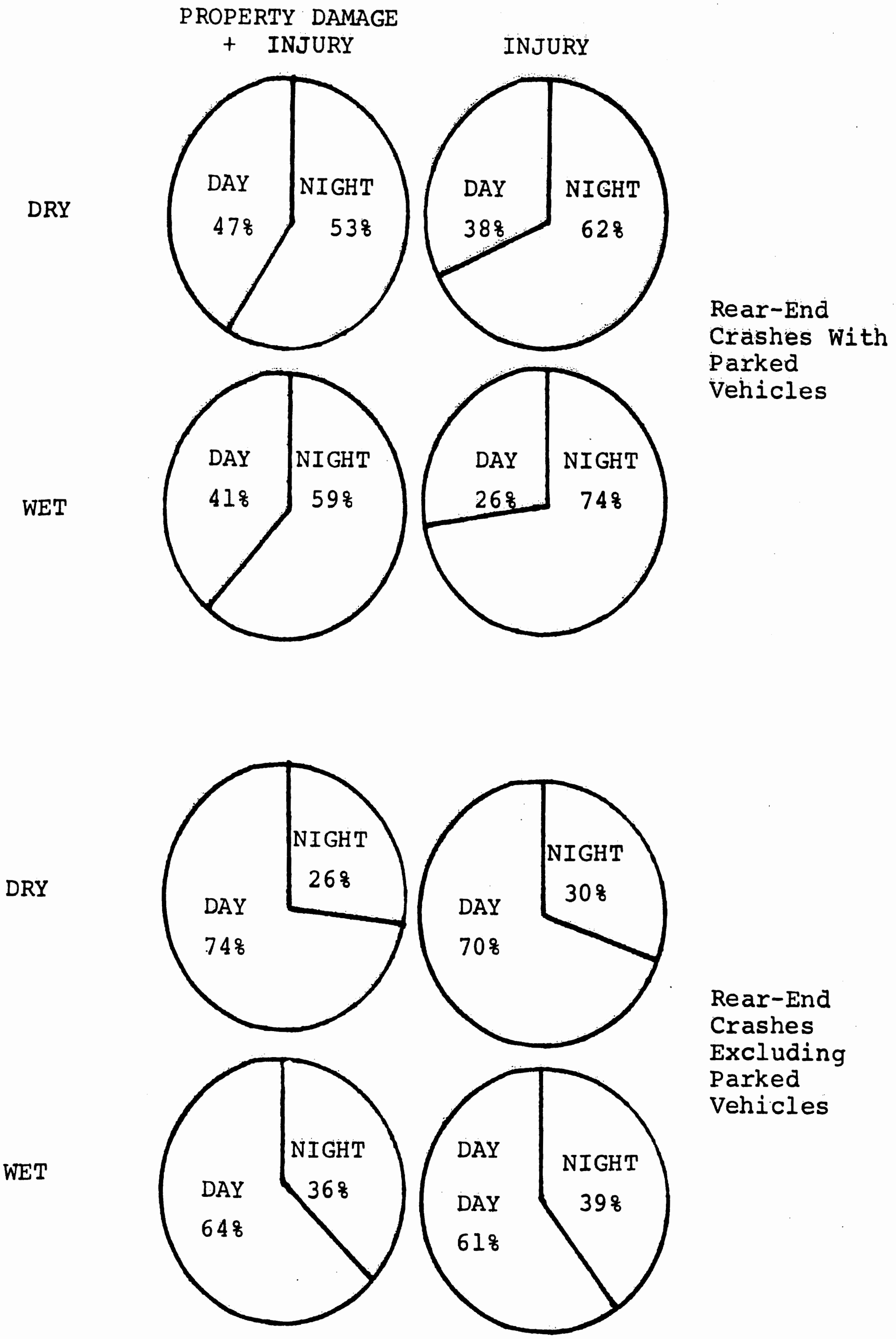

Figure 2. Percent of rear-end crashes involving parked vehicles and those excluding them in the day and night.

vehicles. It will be seen that a total of 37% of collisions involving at least two vehicles are rear-end types, with 32% of them being rear-end collisions into vehicles that are not parked and 5% into parked vehicles.

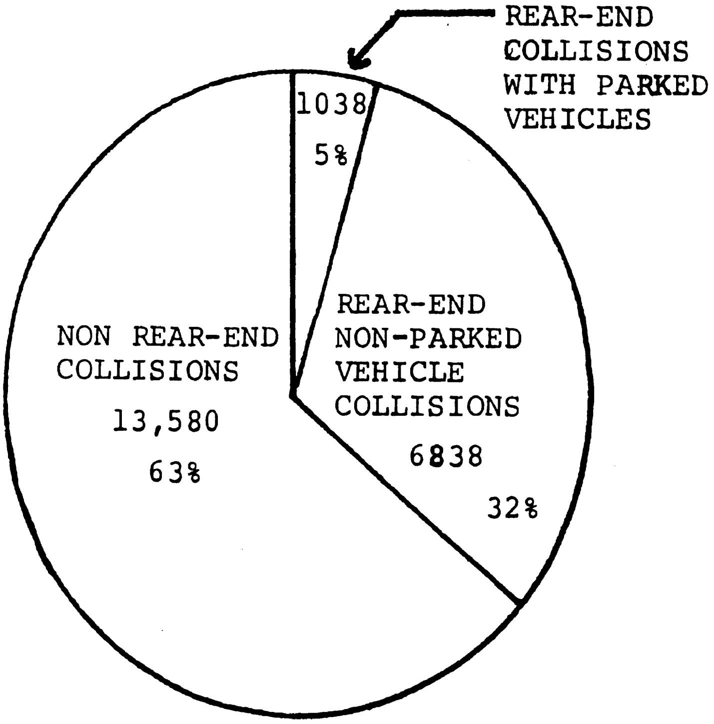

Figure 3. All two- or more-vehicle collisions (21,456).

DISCUSSION OF PARKED CAR ACCIDENT STUDY. Rear-end collisions were about 37% of the accidents involving at least two vehicles. About 15% of this total of rear-end accidents involved collisions with parked vehicles. This problem is either one of location, with moving and parked vehicles being placed too close to each other, or one of driver perception, with the parked vehicle not being recognized soon enough as being present or parked.

On average, about twice as many rear-end crashes of all types occurred on wet roads than would have been expected based on the proportion of time that precipitation was reported. Precipitation is defined as one-tenth inch or more of liquid. One inch of snow equals one-tenth inch of liquid.

Rear-end accidents with parked vehicles occurred in about the same proportion on dry and wet pavements as other types of rear-end collisions (as shown in the top half of Figure 1). Thus, pavement wetness does not appear to contribute differentially to crashes into parked vehicles, compared with other types of rear-end collisions.

There was a greater increase in the probability of an injury resulting in a rear-end crash into a parked vehicle at night than in daytime, than in other rear-end crashes at night compared with daytime. Thus, the severity of rear-end crashes into parked vehicles is heightened at night, whereas the percent of other rear-end crashes resulting in injury is increased less at night.

On average, 55% of rear-end crashes into parked vehicles occurred at night, while only 29% of other rear-end crashes occurred at night. Thus, parked vehicles are more likely to be involved in a rear-end crash at night. Further, 66% of rear-end crashes into parked vehicles which resulted in injury occurred at night. Thus, the parked vehicle, rear-end collision is largely a nighttime problem both in terms of frequency and severity.

The findings of this analysis confirm those of an earlier study (Mortimer and Post, 1972) inasmuch as parked vehicle, rear-end crashes are concerned, and provide further details of the conditions in which they occur. Since it was found that the relative frequency and severity of rear-end crashes with parked vehicles is considerably increased at night, compared to daytime, visibility and recognition of such vehicles as parked seems to be a factor. That the situation is aggravated by poor visibility conditions is confirmed by the elevated involvement of vehicles in all types of rear-end crashes when the road is wet, since the driver's visibility is impaired at those times due to dirt on headlamp lenses, water on the windshield, increased glare from headlamps of oncoming vehicles, reduced reflectivity of pavements, etc.

ACCIDENTS INVOLVING TURNING VEHICLES

An analysis of accident data reports for Washtenaw County, Michigan, was made (Mortimer and Post, 1972) to discern the relative involvement of vehicles that are struck in the rear while turning or waiting to make a turn. It was found that about 15% of rear-end injury collisions on urban and rural roads, that do not have limited access, involved a turning vehicle in the day and at night. On limited access roads about 3% of such crashes occurred in daytime and 1% at night. While the exposure of turning vehicles is not known, it is doubtful that they constitute 15% of traffic maneuvers on non-limited access roads or 1-3% on limited access roads, suggesting that turning vehicles are overinvolved in rear-end collisions compared with other vehicles in the traffic stream.

It cannot be inferred from these data whether the turn signals were adequately visible, or whether the turn and stop signals masked each other. It is also known that drivers frequently fail to signal turns (Zoltan, 1963; Mortimer, Domas and Moore, 1974). These factors make it difficult to show the role of vehicle rear marking and signaling systems in these crashes. However, rear lighting displays should minimize ambiguities and masking between signals. The turn signal should be clearly visible as well as the stop lamps when both are on simultaneously.

TRUCK ACCIDENT INVOLVEMENT

INTRODUCTION. The objective of this analysis is to evaluate the need for truck rear lighting systems which provide more or different information than current systems. Such a need will be shown by the following arguments: (1) truck accidents comprise a sizeable proportion of all vehicle accidents; (2) truck accidents on the average cause considerably more deaths and property damage losses than passenger car accidents; (3) trucks are involved in a higher percentage of accidents than would be expected as a function of the percentage of vehicles they comprise on American roads; (4) trucks are also overinvolved in accidents as a function of their mileage, as compared to passenger cars; and (5) a disproportionately high percentage of truck-involved accidents are of the rear-end collisions type, indicating that improved, more informative, truck rear lighting systems should be investigated for their value in reducing the loss of life and property caused by such accidents.

On almost every dimension of vehicle description, trucks vary across an immensely wider range than automobiles. For instance, the 500 pound Mailster used by the Post Office is a truck, as is the 150,000 pounds-plus trailer and double-trailer combinations now appearing on American roads. These two vehicles are less like each other than any two automobiles. Along with such weight and size differences, and their concommitant handling and braking disparities, there are many more subtle variations which are central to an appreciation of the special problems of truck safety research.

First of all, the type of driving done in trucks seldom approximates the mix of country and city driving experienced in a typical passenger car. Some, like the mailster, see only city driving while many of the large combination vehicles are used almost exclusively on rural highways in interstate transportation.

The distribution of trucks on the road at different times of day and different days of the week varies from the distribution of passenger cars and is directly related to truck accident frequency. Studies have shown that, compared to cars, trucks have a disproportionately low accident rate during the hours of 2pm and 2am on Saturdays and Sundays, and a disproportionately high accident rate from 2 a.m. to 2 p.m. on weekdays (Stern, 1966; New York State Department of Motor Vehicles, 1965). This implies that the truck population does not comprise a static percentage of vehicles on the road at any one time. It is a separate population (or rather several separate populations) of vehicles dynamically interacting with the passenger vehicle population. Thus, in considering the following accident data, the fact that trucks comprise 20% of the traffic volume on the Ohio turnpike must be qualified by the knowledge that truck volume might actually be 2% at 3pm on Sundays and perhaps 35% or more at 4am on Wednesdays. Although most truck accident studies acknowledge that trucks do have their own distribution of accident times and days, they seldom consider this in relation to their analysis of truck traffic volume. An exception is a study (Scott and O'Day, 1971)[2] which was completed after this analysis was made. However, their overall findings are not dissimilar from the ones to be described.

Another variable that distinguishes trucks, especially the larger combination types, from other vehicles is the driver. Truck drivers are generally in the 25-45 age range, and overwhelmingly male. But much more important is the fact that driving is their job. This matter will be discussed further.

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[2] The reader is referred to that study, which is the most comprehensive made on the subject. An abbreviated version of that report can be found in J. O'Day and R.E. Scott. An analysis of Truck Accident Involvement, HIT-LAB Reports, 4, No. 8, April 1974, HSRI, University of Michigan.

The above discussion has not resolved the definitional problems of trucks. Unfortunately, the existing literature dealing with truck accidents does not permit a reviewer to make many fine discriminations between truck types. Some of the studies discussed in this paper simply refer to "trucks", others differentiate between combination vehicles (tractors will full- or semi-trailers) and rigid ("straight") vehicles, while a few studies make several distinctions between truck types, often on the basis of rigid vs non-rigid and the number of axles.

The truck accident problem is sizeable, and growing. About 20% of the vehicles on American roads today are classified as trucks. In the decade from 1960-1970 the number of trucks in use in the United States increased by 50%, compared with a passenger car registration increase of 35% (Automotive News, 1970). Over 60% of all trucks are small vans and pickups below 8000 pounds gross vehicle weight, and only 13% (or 2,200,000) are large straight trucks (20,000-40,000 pounds) or tractor-trailer (40,000-160,000 pounds). However, the heavier vehicles, especially tractor- and semi-trailer combinations, accrue a disproportionate percentage of total truck mileage, most of which is accumulated over major rural and interstate highways.

Two rough dichotomies, based on the size of truck (large vs small) and the type of driving (urban vs rural), will be considered. The greater part of the paper will deal with large trucks operating on rural roads, mainly because the most extensive studies of truck accidents focus on interstate highway and state turnpikes (Crosby, 1959; Eckhardt and Flanagan, 1955; Hosea, 1969a; Vecellio, 1967), and the truck traffic on such roadways consists primarily of large straight trucks and tractor-trailer combinations.

That an emphasis should be given to the study of interstate highway accidents is not unwarranted. Not only are the actual miles of freeways increasing at a faster pace than for any other roadway type, but the traffic density on these roads is growing even faster. It is expected that between 1969 and 1975 the number of miles of urban freeway in the United States will increase by 80% and that the miles of rural freeway will increase by 50% (Ford Motor Co., 1970). Moreover, it is expected that these freeways, which now carry about 12% of all U.S. motor vehicle travel, will carry 25% by 1975. Thus, even given the growth of freeway mileage, each mile of freeway will undergo a 40% increase in traffic density (Ford Motor Co., 1970). That is, for every 100 vehicles passing over a given mile of freeway today, there will be 140 vehicles crossing the same mile of roadway in 1975. In light of the fact that rear-end accidents are already the most prevalent multiple-vehicle accident-type on interstates and turnpikes (Hosea, 1969a; Vecellio, 1967), this expectation of increased traffic density bears ominous implications with respect to that accident-type in the near future.

TRUCK ACCIDENT SEVERITY. When a truck is involved in an accident it can be expected that there will be several times the number of fatalities and several times the property damage loss associated with an average accident sampled from the population of all motor vehicle accidents. In 1968, for all motor vehicles in the United States, the death rate reported in Accident Facts (National Safety Council, 1969) was 5.5 per 100,000,000 miles of travel. Unfortunately, that publication does not provide a breakdown of its data so that a direct comparison can be made between death rates for passenger cars vs that for trucks. However, Accident Facts does show that although large tractor-trailer combinations comprise only 0.8% of all U.S. motor vehicles they constitute 6.5% of all vehicles in fatal accidents. This means that a given tractor-trailer combination is nearly ten times as likely to be involved in a fatal collision than an average passenger car. Moreover, the greatest number of these fatalities are likely to be found in passenger cars involved in truck-car collisions, because for every truck driver killed in a truck-car collision, 35 passenger car occupants are killed (Interstate Commerce Commission, 1966; U.S. Department of Transportation, 1967). Reports on accidents involving large motor carriers (defined as interstate carriers of property having annual revenues of $200,000 or more) reveal fatality rates for such vehicles of about 15 per 100,000,000 vehicle miles (Interstate Commerce Commission, 1966; U.S. Department of Transportation, 1967), or approximately three times that given above for all vehicles. It must be taken into account too, that such motor carriers operate primarily on large freeways which generally have far better than average fatality rates, e.g.,as low as 2 per 100,000,000 vehicle miles on urban freeways (Ford Motor Co., 1970). The motor carrier accident reports noted above disclose an average property damage loss of $2000 per accident, which is approximately seven times the $300 per accident reported by Accident Facts as the average for all motor vehicle accidents in 1968.

It is clear from the preceding analysis that car-truck collisions are more apt to result in death or serious injury than collisions not involving trucks. It must be remembered, however, that in the data presented above the larger types of trucks are heavily overrepresented. Postal vans, milk vans, etc., tend to pull overall truck averages down to the point where the overall differences between all trucks compared to all cars become smaller. Even so, as shown in Table 8, trucks consistently account for 25-50% more fatalities per accident involvement than passenger cars. Using passenger car data as a base, Table 8 gives the fatalities per accident of trucks in various states (Arizona Highway Dept., 1969; New York State Dept. of Motor Vehicles, 1962, 1963, 1966, 1967; North Carolina Dept. of Motor Vehicles, 1968; Virginia Dept. of State Police, 1966, 1967, 1968, 1969). As an example in reading Table 8, the 720% in column 7 for Arizona means that the average tractor-trailer

TABLE 8. Car and Fatal Accidents vs Overall Accident Rate as a Measure of Relative Severity of Accidents Involving Each Vehicle Type.

(1) States & Years Covered	(2) Vehicle Type	(3) Total Number of Accidents	(4) Percentage of All Accidents	(5) Total Number of Fatals	(6) Percentage of All Fatals	(7) Severity Measure
Arizona 1968	Car	61.660	86.9	438	67.1	100%
	Tractor with semi-trailer	710	1.0	36	5.5	720%
	All other trucks	9,590	12.1	179	27.4	263%
New York 1961 1962 1965 1966	Car	2,491,000	91.8	10,163	86.2	100%
	Tractor with semi-trailer	27,140	1.0	520	4.4	468%
	All other trucks	193,700	7.2	1,107	9.4	140%
North Carolina 1967	Car	150,940	88.8	1,717	83.3	100%
	Tractor with semi-trailer	2,290	1.3	85	4.1	322%
	All other trucks	16,940	9.9	244	11.6	127%
Virginia 1965 1966 1967 1968	Car	531,850	88.2	4,248	82.5	100%
	Tractor with semi-trailer	9,070	1.5	289	5.6	400%
	All other trucks	61,690	10.3	612	11.9	124%

accident in that state for 1968 caused 720% or 7.20 times the fatalities suffered in the average passenger car accident. Thus, if 10 of every thousand car accidents led to a fatality, then 7.2 x 10 or 72 of every thousand truck-involved accidents led to such a fatality. Column 7 also shows that in Arizona accidents involving other trucks caused 263% of the fatalities for passenger car accidents, etc.

Table 8 certainly points to truck overinvolvement in serious accidents, but the data in that table are not based on mileage or even registration figures. Several published reports, however, do provide precise comparisons of car and truck accident rates, and they confirm the finding of truck overinvolvement.

TRUCK ACCIDENT RATES. Crosby (1959) conducted a study of accidents occurring over a six-year period on the New Jersey Turnpike. His report shows an accident overinvolvement rate for trucks which cannot be explained away as a function of the higher mileage of trucks. Turnpike records permit a very precise analysis of accidents as a function of miles driven, and Crosby's study showed almost twice as many truck accidents per million miles driven than was the case for passenger cars. (In this study, pick-up trucks and small vans were classified as passenger cars.) As a matter of fact, truck mileage on the turnpike accounted for only 9.8% of all turnpike mileage, and 10% of all vehicles which traveled the turnpike during the study period. However, during this same period these trucks were involved in 24.9% of all accidents which resulted in 43.6% of fatalities occurring on the turnpike over the six-year study period. That is, only 10% of the turnpike traffic accounted for nearly half of all fatalities.

In a similar study of accidents on the Ohio Turnpike between 1960-1965, Vecellio (1967) uncovered equally disturbing data on truck involvement rates. For instance, during that period passenger cars were involved in 97 accidents per hundred million vehicle miles, whereas the truck involvement rate was 190 accidents per hundred million vehicle miles. Like Crosby 1959, Vecellio reports that truck accidents, as a function of mileage, showed accident overinvolvement comparable to that based on number of vehicles. Cars were involved in 7.7 accidents per hundred thousand vehicles, and trucks had 14.7 accidents per hundred thousand vehicles which is again nearly twice the involvement rate of cars.

One great difference between Vecellio's and Crosby's data, resulting perhaps from the greater recency of the Ohio study, was that truck mileage on the Ohio Turnpike was 20.6% of all vehicle mileage, which is twice that which Crosby reports for the New Jersey study. If this discrepancy does represent a change in time more than a change in location (a conclusion supported by Hosea, 1969), and an ever increasing percentage of interstate highway miles being covered in trucks, then Crosby's statistics are understatements of the size of the truck accident problem as it exists today, considering the previously mentioned growth of the interstate system and the increase in traffic density that it is undergoing.

THE NATURE OF TRUCK ACCIDENTS. It has already been mentioned that truck traffic varies in density over hours of the day and days of the week in a manner distinctly different from passenger car traffic, and that truck accident occurrence parallels the truck traffic pattern. But, there is a much more important singularity in truck accident involvement - the incidence of rear-end collisions. Both as the striking vehicle and as the vehicle struck, trucks are highly overinvolved in rear-end collisions. Before presentation of the statistical support for the above statement, it should be pointed out that the rear-end collision is the predominant multiple-vehicle accident type on freeways and interstate roads (Crosby, 1959; Hosea, 1969a;

Vecellio, 1967). Thus, as the freeway and interstate system grows in size, and more especially as it grows in traffic density, the rate of rear-end collisions can also be expected to increase. The actual size of the rear-end collision problem will become clear below as the incidence of such collisions in truck-related accidents is compared with that of other motor vehicles.

In a study specifically directed to an analysis of fatal accidents on the interstate system, Hosea (1969a) found that 63% of all fatal multiple car collisions involved vehicles oriented in the same direction. Forty-one percent of all fatal two-vehicle collisions were rear-end, in which both involved vehicles were moving at the time of the accident. Such percentages may seem high for fatal accidents, because rear-end collisions are, on the average, much less serious than head-on and broadside collisions. Nationwide, collisions between vehicles oriented in the same direction of travel comprise about half of all multiple-vehicle accidents, but only 20-25% of all fatal two- or more-vehicle accidents (National Safety Council, 1969). It is likely, judging by the high percentage of fatals among like-oriented vehicle collisions on interstate highways, that an overwhelming percentage of all multiple-vehicle accidents on these roads are of this type.

Hosea's study showed that trucks were overrepresented in their involvement in rear-end collisions on the interstate highways (Hosea, 1969a; Hosea, 1969b). Property-carrying vehicles were involved in 18.6% of all fatal accidents reported in the study, but they were responsible for 31.4% of rear-end collision involvements, which is 70% higher than would be expected if their responsibility for accidents was proportionally distributed among accident types. Moreover, property-carrying vehicles were responsible for 21.8% of all collisions with parked vehicles, which is 1 1/2 times the number that would be expected, based on an overall involvement rate of 18.6%. Hosea subdivides property-carrying vehicles into the three categories: single unit (straight) trucks; panels and pickups; and combinations (tractor-trailers). Table 9 shows the percentage of total accidents, rear-end accidents, and parked-vehicle accidents for which each truck type and passenger car were responsible. Also in Table 9 are percentage figures for the truck involvements in the two collision types compared to the passenger car ratio as a base. From the table it can be seen that the vehicle-type most overinvolved in both types of collisions is the combination, which was responsible for 2.22 times, or 222%, the number of rear-end collisions in which a similar number of passenger cars were involved. As the table shows, the larger single unit trucks also show a characteristic overinvolvement in responsibility for parked-vehicle and rear-end collisions.

The above data, it must be remembered, refer only to the one vehicle in a two-vehicle accident which was judged, by investigative agencies, to have been responsible for the accident. In a rear-end collision, responsibility is almost always attributed to the striking vehicle (Hosea, 1969a, p. 220). Since trucks are more often struck than striking in rear-end accidents, the data above constitute no more than the tip of the iceberg. Fortunately, Hosea published a sequel to the quoted study (Hosea, 1969b) in which he more specifically detailed involvement in rear-end accidents of one truck type, the tractor-trailer. Table 10 is a reproduction of the table Hosea provides in that publication. His data show that such vehicles, which account for 10% of the total volume of interstate traffic, were involved in 47% of all fatal rear-end collisions occurring on completed sections of the interstate system in 1968. As Table 10 shows, tractor-trailers were classed as the responsible (i.e.,with few exceptions, the striking) vehicle in 80 accidents, which is 20% of all interstate

TABLE 9. Fatal Accident Responsibility Rates for Cars and Trucks Measured Against Mileage Accumulation on Interstate Highways in 1968[1].

(1) Vehicle	(2) Percentage of all Interstate Travel	(3) Percentage of all Multiple Vehicle Accident Responsibility	(4) Involvement Measure*	(5) Parked Vehicle Accident Responsibility	(6) Involvement Measure*	(7) Percentage of all Rear-End Accident Responsibility	(8) Involvement Measure*
Cars	79.7	75.7	100%	71.9	100%	68.6	100%
Combinations	10.2	13.2	136%	19.8	215%	19.5	222%
Panels & Pickups	6.8	7.7	119%	3.1	50%	7.5	128%
Other Single Unit Trucks	3.3	3.4	109%	5.2	175%	4.4	155%

* The percentage in this column represents a measure of the rate of accident involvement responsibility as a function of vehicle mileage, using the passenger car rate as a base. Thus in column 8 the 222% for combination vehicles indicates that, per hundred million miles driven, a tractor-trailer combination is more than twice as likely (2.22 times as likely) as a passenger car to be involved in a fatal rear-end collision as the vehicle responsibile for the collision.

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[1] Based on data reported by Hosea, 1969a.

TABLE 10. Fatal Accidents Involving Tractor-Trailer Combinations on Completed Sections of the Interstate System in 1968.

Type of Collision	Number of Accidents	Fatalities			Property Damage	
		Vehicle Number 1	Vehicle Number 2	Total	Total	Per Accident
Tractor-Trailer → Passenger Vehicle	35	4	48	52	$226,000	$ 6,474
Tractor-Trailer → Tractor-Trailer	26	22	4	26	$522,200	$20,077
Tractor-Trailer → Single Unit Truck	14	5	-	5	$116,000	$ 8,286
Tractor-Trailer → Pickup or Panel	5	-	7	7	$ 9,300	$ 1,860
Total Collisions → Tractor-Trailer Responsible	80	31	59	90	$873,100	$10,916
Passenger Vehicle → Tractor-Trailer	93	111	3	114	$337,500	$ 3,629
Single Unit Truck → Tractor-Trailer	5	5	-	5	$ 11,600	$ 2,320
Pickup or Panel → Tractor-Trailer	15	20	-	20	$ 73,800	$ 4,920
Total Collisions → Other (i.e., Non-Tractor-Trailer) Vehicle Responsible	113	136	3	139	$422,900	$ 4,106

* From Hosea, 1969b.

fatals, and was the second (struck) vehicle in 113 cases, or 27% of all interstate fatals. Moreover in 45 of the 80 accidents in which the tractor-trailer was the striking vehicle, the second (struck) vehicle was also a truck, most often another tractor-trailer. Table 10 further delineates the number and distribution of fatalities suffered in the reported accidents, and the large property damage losses associated with them. It is noteworthy that, of the 166 fatalities occurring in collisions involving both a passenger car and a tractor-trailer, 159 (96%) of the victims were passenger car occupants.

In further assessing Hosea's data, it might be helpful to consider the size of the disparity between the accident frequencies reported and what would be expected if tractor-trailers were a representative 10% of the interstate traffic volume. That is, if tractor-trailers were no more likely to be involved in a rear-end collision than any randomly selected vehicle, in what percentage of the 411 such fatal accidents would they have been involved? First, in 10% of all such accidents tractor-trailers would have been involved as the striking vehicle. Instead they were the striking vehicle in 20% of all rear-end fatals, or twice their proportion based upon their number (Table 11). Moreoever, in only 10% of those accidents (i.e., 1% of all rear-end fatals) would the struck vehicle have also been a tractor-trailer. Hosea's data show that both vehicles in fatal rear-end collisions were tractor-trailers in over 6% of all such accidents, or 6 times their expected involvement. Probably an even higher percentage of nonfatal rear-end collisions involve two tractor-trailers. Nine percent of all fatal rear-end collisions would be expected to involve a tractor-trailer striking some other type of vehicle (i.e., .10 x .90 = .09) In fact over 13% of rear-end fatals are of this type, an over-representation of almost 50% in a category in which one might expect, owing to the relatively lower speed and acceleration capability of these large vehicles, a much smaller involvement ra

TABLE 11. Fatal Rear-End Accident Involvement Rate for Tractor-Trailers on Interstate Highways Compared to a Simple Probability Model.

(1) Type of Collision	(2) Expected Percentage	(3) Actual Percentage	(4) Percentage of Expected
Tractor-Trailer → Car	8.0	8.8	110
Tractor-Trailer → Tractor-Trailer	1.0	6.3	630
Tractor-Trailer → Single Unit Truck	0.3	3.4	1130
Tractor-Trailer → Pickup or Panel	0.7	1.2	171
Car → Tractor-Trailer	8.0	22.7	284
Single Unit Truck → Tractor-Trailer	0.3	1.2	400
Pickup or Panel → Tractor-Trailer	0.7	3.7	529
TOTAL	19.0	47.3	248

The overinvolvement observed is discussed with a causal analysis in the next section. Nine percent involvement for tractor-trailers would also be expected in our simple statistical model for those rear-end fatals in which the truck was the struck but not the striking vehicle (i.e.,.90 x .10 = .09). In this category the actual involvement rate was just under 28%, three times that expected. It should be noted that the overinvolvement rate for tractor-trailers shown in Table 11 is much lower than it would be if their accident incidence were measured against that of automobiles as it was in Tables 8 and 9 because the rate of involvement of cars in rear-end accidents of substantially below what a simple probability model would predict (Table 12).

In the previously mentioned study of truck accident involvement on the Ohio Turnpike, Vecellio's analysis showed an overall truck accident involvement twice that which would be expected as a function of the percentage of turnpike mileage accrued by those vehicles. His data also show a strikingly higher over-involvement in rear-end collisions. Unlike Hosea, Vecellio's study does not provide discriminations between truck types, nor does it deal only with fatal accidents.

TABLE 12. Comparisons of Truck and Car Involvement Rates in Rear-End Accidents on the Ohio Turnpike* in Relation to a Simple Probability Model.

(1) Type of Collision	(2) Number	(3) Actual Percentage	(4) Expected Percentage	(5) Involvement Factor
Car to Car	67	37.8	64	100
Truck to Truck	47	26.6	4	1117
Car to Truck	43	24.3	16	255
Truck to Car	20	11.3	16	119
TOTAL	177	100	100	-

*From Vecellio, 1967.

The data from Vecellio's study were based on all Ohio Turnpike accidents occurring from 1960-1965. The detailed data on rear-end accidents cover only the year 1965. Table 12 shows the number of such accidents occurring in each of the four categories of car to car, truck to truck, car to truck, and truck to car. Next to the accident figures are the percentages they comprise of the total and next to that the percentages that would have been expected if trucks were a representative 20% of the Turnpike traffic (Vecellio states that trucks did account for 20% of all Turnpike mileage). Column 5 in Table 12 shows a measure of actual involvement in relation to the involvement in the car-to-car category. Thus, the 1117 figure in column 5 for truck to truck rear-end collisions means that there were 11.17 times as many of these accidents as one would expect based on the rate of car to car collisions. Table 12 serves to support Hosea's finding of the overinvolvement of trucks in rear-end accidents, and to extend that finding to a more general level not limited to fatality-producing collisions.

CAUSAL ANALYSIS OF TRUCK ACCIDENTS. In attempting to find the reasons for truck overinvolvement in rear-end collisions, it is helpful to learn as much as possible about the characteristics of such accidents. That is, do they occur with undue frequency on curves, upgrades or downgrades? Are rear lighting systems ever directly implicated? Is driver fatigue often a factor?, etc. When such information is cataloged, one can more fruitfully assess the possible implication of such special truck characteristics as size, weight, braking capacity, acceleration, etc.

Vecellio's (1967) data show that special circumstances do tend to be associated with truck-involved rear-end collisions. First of all it appears that any rear-end accident is more likely to occur on an upgrade than on a corresponding downgrade. Of the 1284 rear-end collisions which occurred during the study period, 28% were on upgrades and only 5% on downgrades. (For all accident types 19.5% occurred on upgrades and 6% on downgrades.) Vecellio reports that the extreme disparity between these two occurrence rates cannot be explained by any east-west traffic differential. It is interesting to note that the obvious upgrade hazard implied in the above figures was observed despite the fact that the maximum upgrade on the entire Ohio Turnpike is a gentle 2%.

Not unexpectedly, truck accidents comprise the bulk of all upgrade rear-end collisions on the Ohio Turnpike. In fact, a detailed analysis of the 1965 data showed involvement of at least one truck in 88% of these collisions. Cars were involved in nearly two-thirds of all rear-end collisions on straight or downgrade sections of roadway but in little more than one-third of upgrade rear-end accidents. Such data would tend to implicate truck speed holding ability and braking ability as contributory factors to this over-representation. In 53% of all upgrade rear-end collisions the striking vehicle was a truck, and in 88% of these cases the vehicle struck was also a truck. Car to car accidents accounted for only 12% of all upgrade rear-end collisions, and car to truck accidents comprised 35% of the total. Table 13 contains these statistics and compares them to the simple statistical model premised on involvement as a function of vehicle mileage (trucks accounting for 20% of all Ohio Turnpike vehicle mileage). A comparison of column 5 in Table 13 with the corresponding column in Table 12 gives some indication of the greater truck overinvolvement in upgrade rear-end collisions compared to their rear-end accidents and overall accident overinvolvement.

TABLE 13. A Measure of Actual Truck Rear-End Accident Involvement on Ohio Turnpike* Upgrades in Relation to a Simple Probability Model.

(1) Type of Collision	(2) Number	(3) Actual Percentage	(4) Expected Percentage	(5) Percentage of Expected	(6) Involvement Factor
Car to Car	4	11.8	64.0	18.4	100
Truck to Truck	16	47.1	4.0	1177.5	6052
Car to Truck	12	35.3	16.0	220.6	1134
Truck to Car	2	5.8	16.0	36.3	187
TOTAL	34	100.0	100.0	-	-

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* From Vecellio (1967)

The data in Table 12 are pertinent to the causal analysis of truck rear-end accident overinvolvement. Although there are only a small amount of data, a simple chi-square test shows that the overall involvement of trucks (46 involvements where a simple probability model would have predicted less than 14) versus that of cars (22 involvements compared to over 54 expected) is highly significant ($X^2 = 91.3$, ldf; $p < .001$).

The data supplied by Vecellio on upgrade accident involvements is supported, though with far less precise data, in a study by Eckhardt and Flanagan (1955) performed on accidents occurring on the Pennsylvania Turnpike over a fourteen-year period. They compared car and truck accidents, and found that the only large difference in the kind of accident involvement for each vehicle type was an overinvolvement for trucks in accidents occurring on straight, uphill portions of the turnpike -- 25% for trucks as compared to 15.5% for cars.

To recapitulate briefly, it has been shown above that trucks have more than their share of accidents, that these accidents are more serious and costly than the average accident, that the truck accident overinvolvement is largely attributable to a very high rate of involvement in rear-end collisions, and that within the category of rear-end collisions, trucks are overinvolved at a very high rate in accidents occurring on straight, uphill stretches of road. By definition, when an event occurs, the information contained in the event is an inverse function of the a priori probability that the event would occur. This is, the more unexpected an event, the more one can learn from observing its occurrence. It follows that, from the truck accident data presented above, the most fruitful line of causal analysis would pursue the factors contributory to the incidence of uphill rear-end accidents, since it is in that area that truck accidents deviate most markedly from predicted rates of occurrence, based on the simple probability model previously discussed.

Several factors which could conceivably contribute to the high incidence of trucks, both as striking vehicle and as vehicle struck, in upgrade rear-end collisions are: driver fatigue or inattentiveness, following too closely, comparative lack of speed and acceleration ability, rear lighting and braking inadequacies. Unfortunately, it is impossible to make any controlled and precise assessment of such factors with the type of after-the-fact accident data available to the author. The actual influence of such variables as rear lighting failures or inadequacies, and less than ideal braking or accelerative ability are bound to be greater than indicated by police reports of the accidents because investigators seek immediate, not proximate, causes in filing their reports. For instance if, on a hill, a truck's speed falls from 65 to 35 mph and is struck in the rear by a car which has been following it for some time, reduction in the truck's speed was obviously a precondition for the occurrence of the accident. Thus, it is a possibility that had the truck possessed a taillight system incorporating a dramatically visible speed indicator, the car driver might have been alerted in time to avoid the collision.

Granting then that the implication of such contributory factors as lighting or performance deficiencies are unlikely to be proportionally represented in accident reports, what is the evidence for their complicity in truck-involved rear-end collisions? First of all, consider the element of initial speed differential between following vehicle pairs on an interstate road. Certainly it is a trivial truth that some such differential is a necessary precondition to there being a rear-end accident.

There are three basic rear-end accident situations, not including consideration of merging or exiting traffic. First, two vehicles may have been going at the same speed one ahead of the other for some time, but for some reason a significant speed differential is introduced, as would be the case if a car were following a loaded tractor-trailer at about 60 mph and the vehicles entered an extended upgrade. In such a case the car driver would be forced, to avoid an eventual collision, either to slow down or pass the truck. Generally this is no problem assuming the car operator's driving is not impaired, but it is the rare possibility of an accident occurring that must be considered. Any differential in accident preconditions is in itself an accident "cause" and should be eliminated. Second, a change in the distance between two vehicles, which was initially quite small relative to normal traffic patterns, caused by a fairly small loss of relative velocity in the lead vehicle, will necessitate some input by the following driver. In such a case genuine alertness, as opposed to the mere absence of fatigue or inattentiveness, is required on the part of the following driver if a collision is to be avoided. There is evidence that trucks tend to follow each other in convoy fashion and maintain short headways. The third general case is that in which the pair of vehicles never was in an equal speed relationship, but where the following vehicle comes up on a lead vehicle whose speed is somewhat lower than its own. Again, an input is required for accident avoidance.

If any example of the above three situations is considered an incident, comparable to a lottery ticket where the prize is a rear-end accident, then the more of these incidents a vehicle accumulated over a given stretch of road, the more likely it is to be involved in a rear-end collision. It might be helpful at this point to consult some of the literature dealing with speed differential, traffic flow, and accident occurrence.

In attempting to assess the role of speed differential and traffic distribution as accident variables, Mitchell (1966) conducted a study of accident causation on an urban freeway. He found that most accidents on the freeway were between vehicles moving in the same direction, i.e. rear-end or sideswipe. Also, he reported that a major cause of such accidents was "stream friction" in the traffic flow which was partially caused by large speed differentials between slow-moving vehicles and those moving at normal freeway speeds.

Taylor (1965) argues that there is a relationship between the rate of accident occurrence and traffic speed distribution and that a normal distribution of speeds across vehicles leads to the lowest accident rate. For numerous reasons, trucks are not likely, in a mixed traffic situation, to form a normal distribution of speeds with other vehicles. First of all, as Wolf (1968) points out, the speed limits for trucks are generally lower than for cars on turnpikes and interstates. Moreover, there is the added variability in speed due to truck performance factors. In addition, truck traffic is heavy and light at different times and on different days than is automobile traffic. Such a situation might indicate that a good deal of "stream friction" would be generated because trucks tended to be entering or exiting from turnpikes during periods when cars were in steady travel.

An intensive study of the implication of vehicle speed differentials in rear-end accident causation was reported by Solomon (1964). He found an extremely strong relationship between the speed differential between two following vehicles and the probability that they would be involved in a rear-end collision. As this differential increases past 20 mph, the probability of such an accident soars, so that following vehicles traveling at a 30-35 mph differential are 30 times as likely to be involved in a rear-end collision than a vehicle pair traveling at a 15 mph differential or less. Solomon's finding is quite important, since the scope and precision of his data collection procedures, which include speed observation and/or interviews with nearly 300,000 drivers (he had the official cooperation of agencies in eleven states and the Bureau of Public

Roads) is almost unparalleled in the literature.

It appears that the speed differential between pairs of following vehicles is an important factor as a precondition for rear-end accidents, which are the most prevalent multiple-vehicle accident type reported on modern interstate highways. What then is the actual relationship between the speed of trucks and passenger cars on such roads? Speed limits on interstate highways are often lower for trucks than cars, by up to 15 mph. Because of findings such as Solomon's above, criticism has been directed at such differential speed limits (Crosby, 1959; Ferguson, 1968; Wolf, 1968). Ferguson (1968) studied the relationship between truck and car speed over all types of roads in the state of Virginia. His recommendations specifically pointed to interstate highways as presenting the greatest safety hazard with differential speed limits for trucks and cars. He found that on the interstates, where truck speed limits were 50 mph compared to 65 mph for cars, truckers generally disregarded their limits, with subsequent problems of decision making for law enforcement personnel. Ferguson also found that, regardless of speed limit differentials, trucks would of their own accord tend to travel on the average at a speed 5 to 7 mph slower than the average car speed on the interstates. It is not surprising that this 5 to 7 mph differential was not constant over all portions of the roadway, but varied as a function of road gradient. On some primary roads, the truck average speed on many downgrades exceeded the average car speeds along the same road portion. Moreover, a study of average speeds at 18 sites along the interstate routes disclosed that truck and car speeds often varied inversely from one site to another (Ferguson, 1968). In fact, this was so for the majority of the sites. That is, if the average truck speed tended to be higher at site m than at site m-1, it was very likely that the average car speed was decreasing over this same span. What this implies is that, for any randomly selected car-truck following pair, not only is there likely to be an average 5 to 7 mph speed differential between them (as opposed to a 0 mph average differential between a randomly selected car-car following pair), but in addition this speed differential is continually changing as the vehicles move over different road gradients. This suggests the necessity for a lot more vigilance and corrective inputs for the following driver in the car→truck pair compared to the following driver in the car→car pair, for the former is likely to find himself in a situation where his vehicle is experiencing an accelerating speed differential vis-à-vis the vehicle he is following. Combine that situation, experienced over and over again, with the evidence of inattentiveness reported above in association with rear-end collisions, and the rate of truck involvement in these accidents is not surprising.

In a study concerned with truck performance, Firey and Peterson (1962) studied the ability of trucks to maintain speeds on measured grades. Those authors found, for vehicles whose weight (in pounds) to horsepower ratio was in the vicinity of 400 to 1 (comparable to a normally loaded tractor-trailer), entering a steady upgrade of two or three percent (which is the maximum upgrade on the Ohio and Pennsylvania turnpikes, respectively) that speeds dropped from an initial velocity of 50 mph to 38 mph and 29 mph, respectively, at 2500 feet into the grade. At a point of 4500 feet into the grade the speeds were 32 mph and 23 mph, respectively. With larger grades, velocity drop-off was much sharper so that such a vehicle entering a five percent grade was down from 50 mph to 16 mph at 1900 feet into the grade. In a similar study, Williston (1967) collected data on the speed of traffic along a number of graded stretches of Connecticut highway. He studied three sites, each an extended three percent, four percent, or five percent grade, and measured the actual speed of passenger cars, pickup and panel trucks, large single-unit trucks, and tractor-trailers traversing them. His data show only small initial differences in the average speeds of the various vehicle types entering each grade. Passenger cars generally maintain their speed throughout the grades studied, whereas trucks, especially the larger ones tend to lose velocity. For instance, in the five percent grade studied, the mean speed of passenger cars, at 2500 feet into the grade, dropped from 57 mph to 55 mph. Over the same stretch, the average speed of panels and pickups fell from 54 mph to 44 mph; large single-unit trucks dropped from 53 mph to 33 mph, and tractor-trailers went from 54 mph to 26 mph. Moreover, an anlysis of the distribution of speeds reveals a much larger variation for the larger truck types. Whereas, at 2500 feet into the five percent grade, two-thirds of all passenger cars were maintaining speeds between 49 mph and 59 mph, a range of only 10 mph, the corresponding central two-thirds of all tractor-trailer speeds covered a span of 18 mph, from 17 mph to 35 mph.

The reported incidence of rear lighting failure or inadequacy as a factor in vehicle collisions is small indeed. However, what little evidence there is shows a much greater rate of accident reports implicating lighting or signaling deficiencies in truck-involved accidents in comparison to such reports in car-involved collisions (Crosby, 1959; North Carolina Department of Motor Vehicles, 1968). Moreover, Crosby's (1959) investigation into the "basic causes of the high involvement and severity of truck accidents" cited "inadequate and/or poor maintenance of rear lighting equipment" as the first of these causes.

As has been previously stated, driver inattention, fatigue, drowsiness, etc., are often cited as causal factors in rear-end accidents (Crosby, 1959; Eckhardt and Flanagan, 1955; Vecellio, 1967).

Eckhardt and Flanagan (1955),for example, report from their study of Pennsylvania Turnpike accidents that driver inattention or misperception appeared to be a primary contributory factor in over 25% of all accidents. Moreover, this factor of driver inattention was most highly implicated in the straight upgrade accidents in which trucks are so often involved. It would follow that many such accidents were rear-end collisions in which a high differential in speed between a truck and following car was a major contributory cause. In Vecellio's (1967) study of Ohio Turnpike accidents, the assigned primary cause for 43% of all rear-end collisions was driver sleepiness, inattention, or carelessness.

It is not surprising that the factors of driver inattention and fatigue should be so frequently assigned as causes for rear-end collisions. First of all, they are driver error factors, very salient and very easy to judge as causes. Moreover, by legal definition responsibility for a rear-end collision is almost invariably assigned to the driver of the striking vehicle, and slow reponse due to inattention is the most logical cause for an investigator to choose in justifying the foregone conclusion that a driver is at fault for running into the rear of another vehicle. Besides, a lot of drivers on the road are fatigued or drowsy, and many brag about driving long distances for extended periods without sleep. This phenomenon is not only unashamedly practiced by the general driving public, the same indiscretions can be found accentuated among interstate truck drivers. At least two of the above cited authors (Crosby, 1959; Vecellio, 1967) specifically referred to frequent violations among accident-involved truck drivers of Bureau of Motor Carrier Safety minimum safety statutes regarding driver physical condition and driver work hours.

A series of motor carrier investigation reports (Interstate Commerce Commission, 1953-1965) published by the I.C.C. demonstrates that driver and corporation noncompliance with I.C.C. statutes was rampant. The avoidable loss of life and property chronicled in those reports is sobering. Most of the truck drivers investigated in those reports were found to possess supplies of drugs for maintaining wakefulness over extended periods.

CONCLUSIONS. The conclusions to be drawn from the data and arguments above are not complicated. First, inattentiveness, fatigue, etc., are frequently factors in rear-end collisions. Moreover, because trucks cannot maintain their speed on hills as well as cars, they provide a hazard for a driver who is not alert. The only essential precondition for a rear-end collision is a non-zero relative velocity to close the gap between two following vehicles.

Finally, inadequacies and malfunctions of rear lighting systems, which are defects most often reported in connection with truck-involved accidents, can make it very easy for the fast-driving fatigued auto driver to crash into the slow truck toiling up a hill at 30 to 40 mph below his speed.

The disparity in speed between vehicles in the same lane, which leads to rear-end collisions in which trucks are so greatly overinvolved, suggests that a means of providing information of the speed of a vehicle being followed would be useful. Further work on systems of this type would be highly desirable.

CONCLUSIONS OF ACCIDENT DATA ANALYSES

The conclusions of this investigation are contained in the "Summary of Findings" section. The following suggestions are offered as reasonable avenues of investigation which may improve the accident problem dealt with in this section.

1. Improved performance of vehicle passive marking, such as retroreflectors and specific marking to denote parked vehicles.

2. Means to maintain clean rear lamp and reflectorized surfaces.

3. Headlamp washing or cleaning methods.

4. Rear signaling displays that minimize ambiguity and masking between presence, stop and turn signals.

5. A velocity display to provide information of the approximate speed of a vehicle to a driver following it.

INTERPRETATION OF SIGNALS
ABSTRACT

This was a laboratory investigation, the purpose of which was to determine whether naïve drivers could reliably interpret the meaning of unique signals as presented by various truck and automotive rear lighting systems.

The results indicate that, for most of the lighting systems tested, subjects could reliably interpret unique signals after brief training. Such errors as were made were not likely to increase risk.

INTERPRETATION OF SIGNALS

INTRODUCTION

In the development of rear marking and signaling displays it may be found that new types of information, such as suggested by the analysis of accident data, should be presented to drivers of following-vehicles so as to improve their performance in car-following and to reduce rear-end collisions. One of the major objectives of the research in vehicle rear lighting is to define the information which should be presented. Subsequently it will be necessary to determine the manner in which such information can be best displayed.

A prior consideration should be, however, to ascertain if drivers can comprehend the information intended to be conveyed by such signals, before much effort is expended on the derivation of the information required.

OBJECTIVE

The objective of this study was to determine the extent to which drivers can intuitively comprehend or deduce the meaning of new signals as they would be presented by a vehicle rear lighting system.

METHOD

SUBJECTS. A total of 100 subjects were run in this experiment. Forty-seven drivers viewed the lighting systems on trucks and 53 subjects viewed the lighting systems on cars. Subjects ranged in age from 16 to 49 with most of them between 17 and 28 years of age.

APPARATUS. Front and rear scale models (5/32 inch equaled 1 inch) of a car and a truck were made out of aluminum, and panel lights with interchangeable colored filters were mounted on the models to simulate vehicle lights. A control panel was constructed to provide voltage and on/off control to each lamp.

Each lighting system was set up on the model and photographed with a Super-8 movie camera. The surround of the model was dark to simulate night driving. The zoom lens was used to provide the cue of a change in distance between the vehicle the observer was supposed to imagine he was in, and the vehicle he was following or approaching.

Several film segments were made of each system, with each segment showing a different signal or combination of signals. The lighting systems were randomly ordered within the truck and car films, with the film segments for each system randomly ordered within each lighting system. Except for those cases where a hazard warning signal was shown on a stationary vehicle, each segment began with the rear presence lamps (or parking lamps and headlamps, in the case of an oncoming vehicle) being shown for the first few seconds, with any signals being added later in the same segment.

The Lighting Systems. Lighting systems on both the front and rear of cars and trucks were presented to observers for identification (Figures A-1, A-2. Appendix A). Thirteen car lighting systems and 14 truck lighting systems were presented. Once the truck film and car film were made, the order of systems or film segments was not changed from session to session.

Clipboards, with small lamps to illuminate the response sheets, were provided each subject. The response sheets indicated codes for a variety of possible signals that might be shown. Subjects responded by selecting those codes for signals which they believed were contained in each film segment. The subjects were not given any feedback as to the appropriateness of their responses.

PROCEDURE. The movies were shown to four groups of subjects a day over a three day period. Six groups of subjects saw the car film and another six saw the truck film, with the films alternated among groups.

The instructions (Appendix B) were read to the subjects, and included a description of their task ("identify the meaning, at the end of each film segment, of all of the signals you saw during that segment"), an explanation of the response sheets ("the rows indicate film segment numbers and the columns indicate the various types of signal presentations along with whether the front or the rear of the vehicle is shown"), and sample segments of film were shown to them.

Once the subjects were acquainted with the procedure the experiment began. The film was stopped after each segment of film and the observers were instructed to indicate all of the signals that had been presented by checking the appropriate columns. Once the complete film was shown, it was rewound and shown again.

RESULTS

IDENTIFICATION OF SIGNALS ON THE REAR AND FRONT OF THE CAR SIMULATION. Fifty-three observers viewed the marking and signaling displays on the simulated car, with each subject receiving two exposures to the film segments. The percent of correct observations are shown in Table 14. This table shows the percent of subject responses which were correct in identifying the intended meaning of the various signals on the first and second exposure.

An inspection of Table 14 shows that the subjects generally did well in identifying presence and turn indications, with the exception of system 23. The subjects did less well in identifying other signals. Most errors resulted from misidentification as a stopped slow moving signal.

TABLE 14. Percent of Correct Observations of Various Signals as Presented to Naïve Observers by Different Signal Systems on Cars.

	Observation Number	Vehicle Lighting Systems										
		20	21	22a	22b	23	24	26	27	28	30	25
Presence	1	80	92	65	95	65	92	83	92	82	75	
	2	97	92	92	92	67	94	92	95	92	90	
Turn	1	70	90	100	95	75	80	78	95	90	75	
	2	100	95	95	100	80	88	98	95	92	94	
Stop	1	64	32	42	58	53	26	55	73	65	50	
	2	72	72	70	61	64	38	75	68	65	66	
Hazard	1	72							70		70	58
	2	80							74		80	65
Stop & Hazard	1	60							50		38	36
	2	56							60		53	42
Stop & Backup	1	35									37	
	2	54									60	
Stop & Slow Moving	1	38					32	38			38	
	2	62					46	55			55	

The velocity display, or change-of-speed display, was shown to observers with the vehicle either accelerating or decelerating. Figure 4 shows the percent of observers who identified both the stop and velocity signals in system 29 on the first and second exposure, when the vehicle was accelerating and decelerating, respectively. While relatively few observers correctly identified the existence of both the stop and velocity display signals, the identification of the velocity display was greater than 90% when the vehicle was accelerating. When the vehicle was decelerating the identification of the velocity display reached about 80% by the second exposure.

In those film segments where the simulated vehicle was undergoing both increases and decreases in speed while displaying the velocity signal, Figure 5 shows that about 95% of observers correctly identified the velocity display on the first and second exposure, when no other signals than the presence lights were involved.

When the vehicle was presenting stop and turn signals and slowed down sufficiently for the stopped/slow moving signal to be lighted, relatively few observers (Figure 6) correctly identified all three signals. However, of interest to this study, is that by the second exposure, more than 70% of observers correctly identified the stopped/slow moving vehicle signal with the three systems that were used to display it.

Figure 7 shows the percent of signals correctly identified in the case where a vehicle equipped with system 25 applied the brakes and decelerated at a sufficient level to turn on the steady-burning high deceleration signal during the period of high deceleration, and to slow the car to a stop, illuminating the stopped/slow moving vehicle signal. Figure 7 shows that, on the first exposure, about 80% of observers correctly identified the high-deceleration signal and the stopped/slow moving

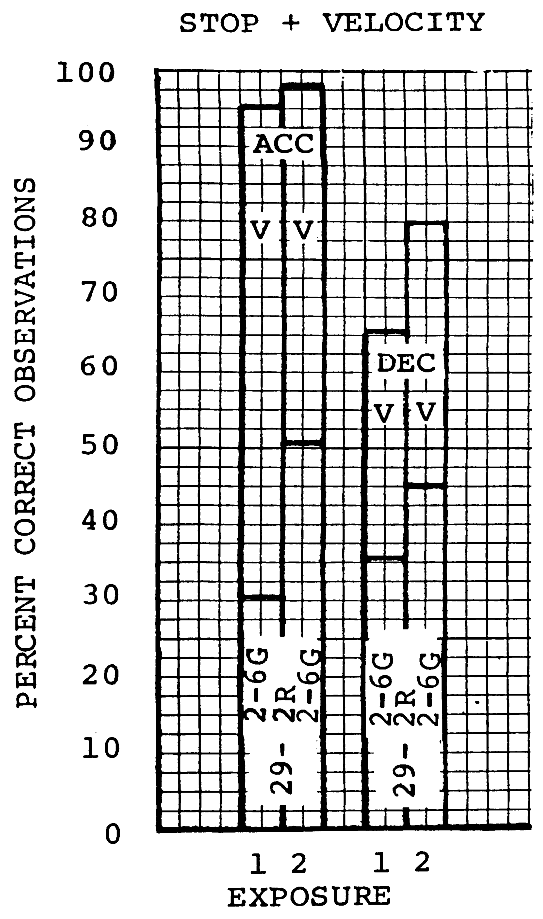

Figure 4. Percent of correct observations of stop and velocity signals on car. Percent of total velocity signal observations also shown, and for acceleration and deceleration.

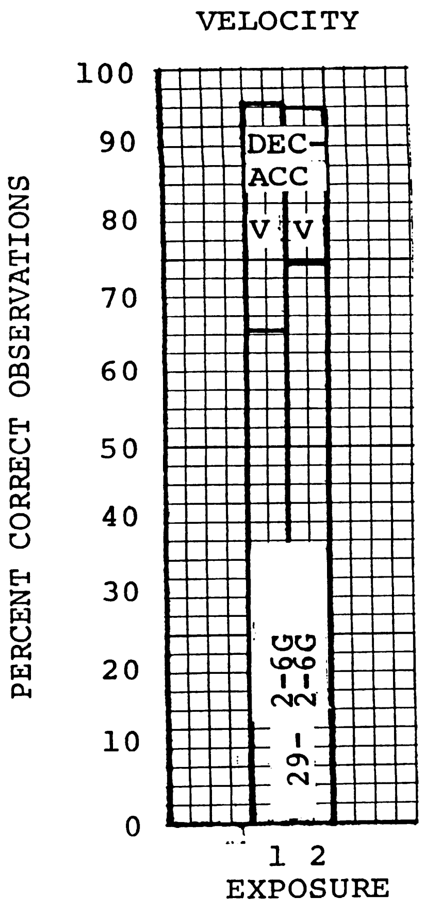

Figure 5. Percent of correct observations to changes in velocity signals on car. Percent of total change in velocity observations also shown. Deceleration and acceleration shown in same film segment.

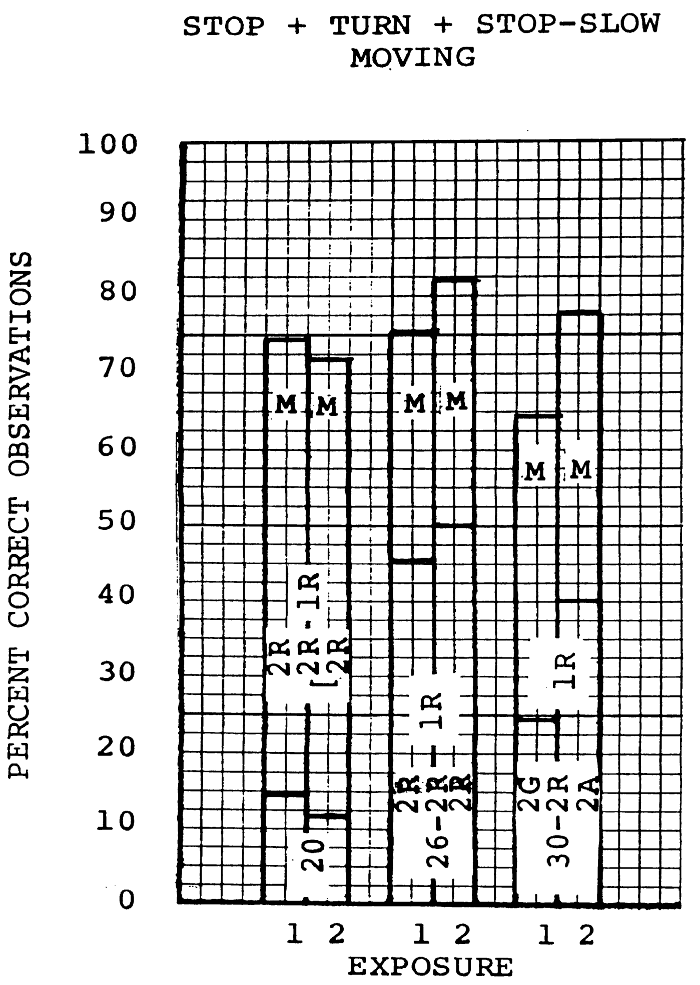

Figure 6. Percent of correct observations of stop, turn, and stopped/slow-moving signals on car. Percent of total stopped/slow moving observations also shown.

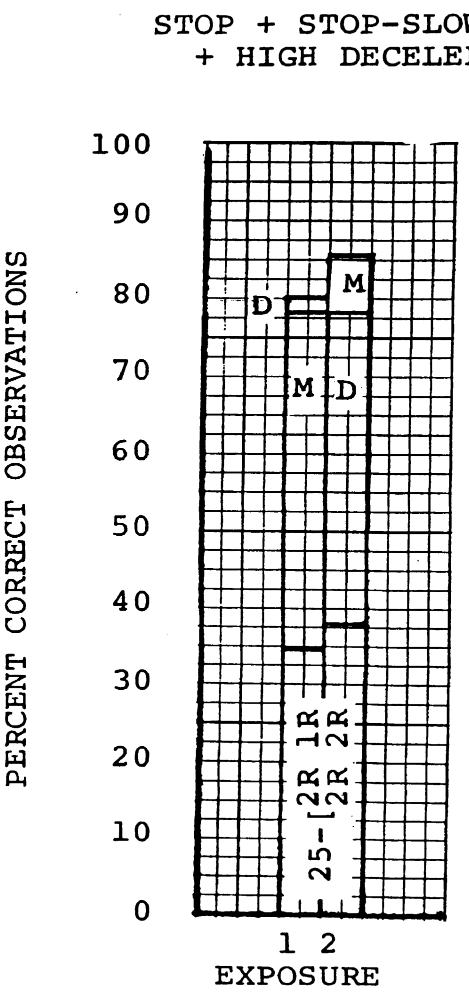

Figure 7. Percent of correct observations of stop, stopped/slow moving and high deceleration signals on car. Percent of total stopped/slow moving (M) and total high deceleration (D) signals observed also shown.

vehicle signal. There was a slight improvement on the second exposure, with up to 86% of observers identifying the stopped/ slow moving vehicle signal.

Figure 8 shows the percent of correct responses in identifying the existence of the high-deceleration signal when combined with the stop signal on system 25. About 80% of observations were correct on the first exposure.

Figures 9 and 10 show the percent of observers who correctly identified headlamps on an oncoming vehicle (Figure 9) and a front turn signal and headlamps (Figure 10), with over 80% of responses being correct in both cases.

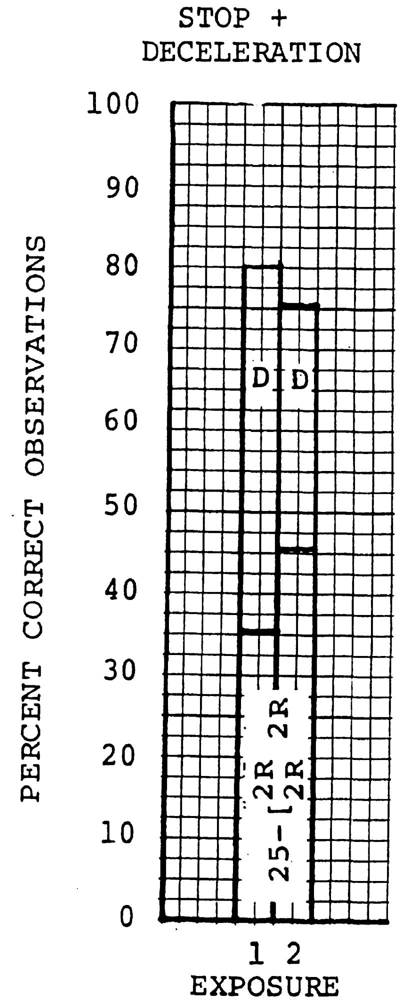

Figure 8. Percent of correct observations of stop and high deceleration signals on car. Percent of total high deceleration (D) signals observed also shown.

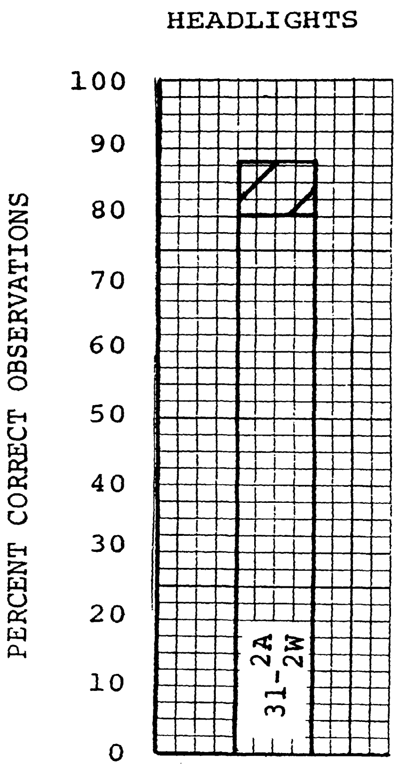

Figure 9. Percent of correct observations of headlights on car.

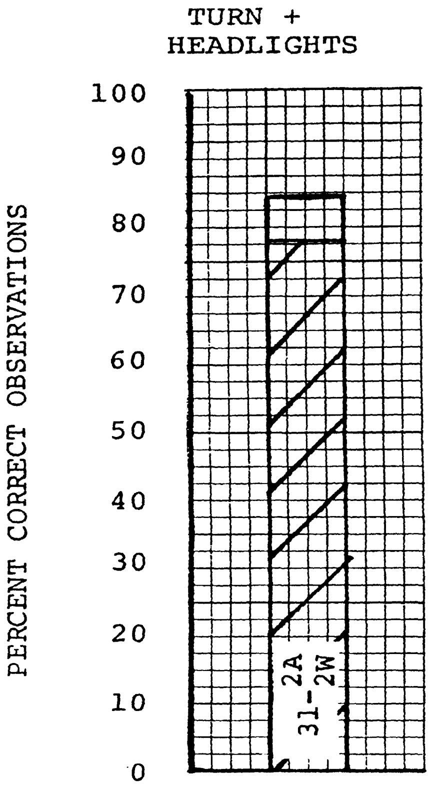

Figure 10. Percent of correct observations of turn signals and headlights on car.

IDENTIFICATION OF SIGNALS ON THE REAR AND FRONT OF THE TRUCK SIMULATION. Table 15 and Figures 11-15 show the results, analogous to those already shown for the car simulation, for the identification of signals shown in the truck simulation. In many respects the results are also similar.

Identification of the hazard warning signal on the truck simulation was relatively poorer than on the car. Similarly, the identification of a stop signal in conjunction with a hazard warning signal resulted in only about 45% of correct observations, less than for the car simulation. In both these signal modes the low percent of correctly identified hazard warning signals was primarily due to confusions with the stopped/slow moving vehicle signal or failure to identify both the stopped/slow moving and hazard warning signals.

Figure 12 shows identification of the stop signal combined with the velocity signal. In the case of the vehicle starting with the brakes applied and then accelerating, about 94% of the observers correctly identified the velocity signal in system 29. However, when the vehicle was initially in motion and then began to slow down by braking, about 66% of observers identified the velocity signal on the second exposure. The trend of fewer correct observations of the velocity signal when the vehicle was decelerating was also found in the car simulation.

In the case where braking was not involved with the velocity signal and the truck decelerated and accelerated, about 93% identification of the signal was obtained with system 29 (Figure 13).

In the two presentations involving the front of a truck, the identification of headlamps (Figure 14) reached 85% on the second exposure, and the identification of a turn signal in conjunction with the headlamps (Figure 15) was 73% on the second exposure.

TABLE 15. Percent of Correct Observations of Various Signals as Presented to Naïve Observers by Different Signal Systems on Trucks.

	Observation Number	Vehicle Lighting Systems											
		20	21	22a	22b	23	24	25	26	27	28	29	30
Presence	1	85	85	85	95	55	95		92	81	85		86
	2	95	98	85	95	72	95		98	83	91		96
Turn	1	85	96	90	93	62			95	87	87		91
	2	98	98	83	93	70			98	85	91		91
Stop	1	49	55	57	55	50	40		65	55	23		60
	2	55	65	61	59	61	50		60	68	47		61
Hazard	1	49						51		40			
	2	64						61		57			
Stop + Hazard	1	26						28		34			40
	2	45						43		44			40
Stop + Slow Moving + Hazard	1												34
	2												38
Stop + Turn + Slow Moving	1								36				38
	2								45				35
Stop + Slow Moving + High Deceleration	1							15					
	2							32					
Stop + High Deceleration	1							15					
	2							40					

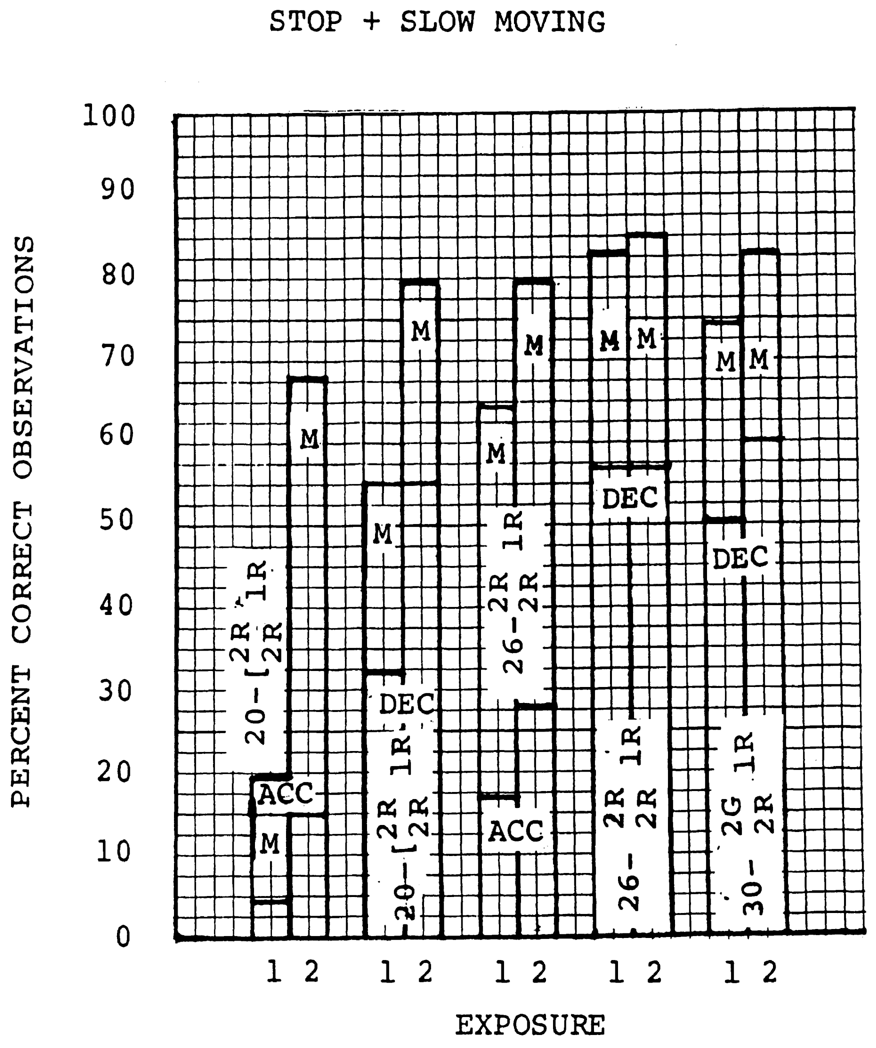

Figure 11. Percent of correct observations of stop and stopped/slow moving signals on truck. Percent of total stopped/slow moving signals (M) observations also shown.

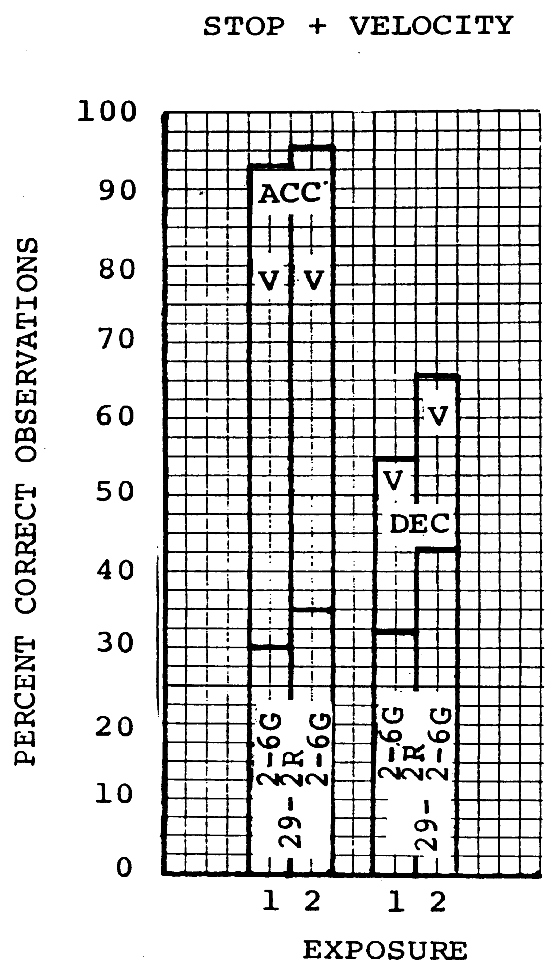

Figure 12. Percent of correct observations of stop and velocity signals on truck. Percent of total velocity signal observations also shown, and for acceleration and deceleration.

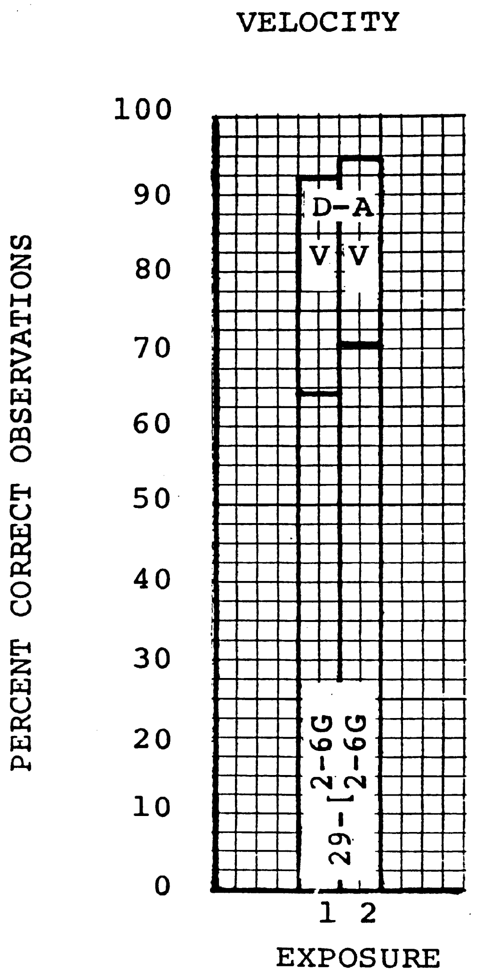

Figure 13. Percent of correct observations to changes in velocity signals on truck. Percent of total change in velocity observations also shown. Deceleration and acceleration shown in same film segment.

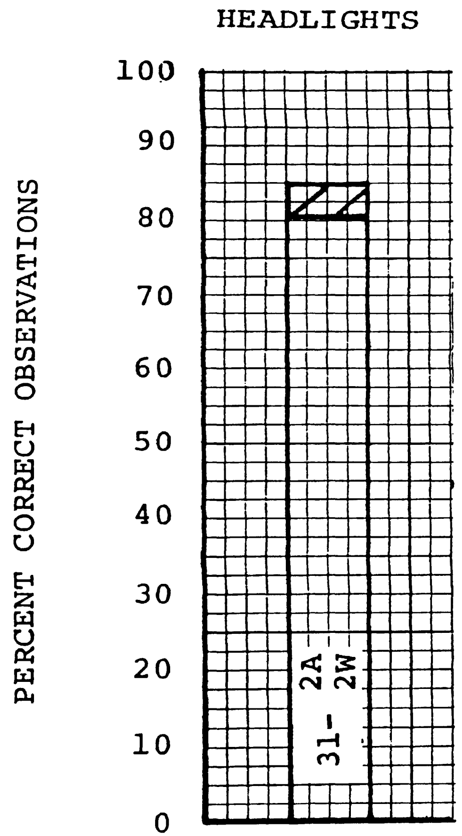

Figure 14. Percent of correct observations of headlights on truck.

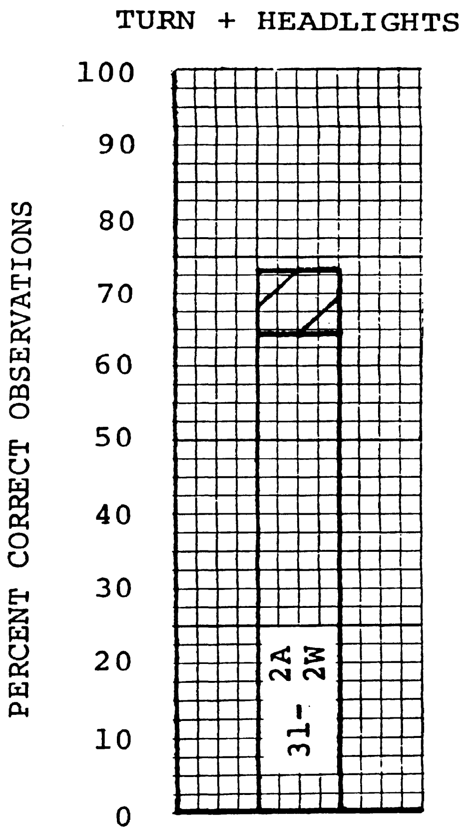

Figure 15. Percent of correct observations of turn signals and headlights on truck.

DISCUSSION

In both the car and truck simulation, there was a general improvement in the signals that were correctly identified in the second exposure compared to the first. This indicated that further exposure, in the normal course of driving, to signals of the type that were used in this study is likely to further improve the ability of drivers to intuitively and correctly interpret the meaning intended by these signals.

Thus, one of the major questions that was posed in the developmental stages of this study appears to be answered affirmatively, and suggests that drivers are likely to learn the meaning of new signals, which they have not seen previously, quite readily. It also suggests that such signals can be coded in a number of alternative ways, and successfully transfer the desired information. This is shown by the fact that various display formats were used in this study with relatively small differences in their effectiveness.

The correct identification of presence and turn signals was about 90% or better. The only exception to this was with system 23, primarily in affecting the identification of presence lamps, apparently due to this system using four red lamps positioned around the rear of the car. The other systems all used two lamps, and identification of the presence lights was good whether these lamps were red or green.

It was apparent that a number of the conventional signals were not identified with as high a frequency as might have been expected. For example, stop signals in the car simulation were identified correctly on about 60% of the presentations. The hazard warning signal was identified, when presented alone on about 75% of presentations. The combination of stop signals and back-up signals were only identified on less than 60% of the observations.

The relatively low identification of stop signals and hazard warning signals was due to the subjects reporting some of these signals as the stopped/slow moving vehicle signal.

It was also found, that some of the observers were unfamiliar with some of these conventional signals, particularly the hazard warning and the back-up signals. This shows that drivers may require some additional education in the meaning of such signals, which have been used on vehicles for a number of years.

By comparison, some of the novel signaling displays were correctly identified substantially better than the hazard warning signal and back-up signal. In general, the stopped/slow moving vehicle signal was identified on up to about 85% of the presentations in which it was combined with other signals such as the stop signal, the turn signal, and the high deceleration signal. When the velocity signal was presented in such a way that the vehicle was initially stationary, with the stop lamps lighted which were then extinguished as the vehicle began to accelerate, about 90% of the observers correctly identified it. Conversely, when the vehicle was initially simulated as running at a high speed and then slowed down, finally coming to rest with mild braking, about 80% of the observers correctly identified the velocity display. In other film segments, the velocity display was used with the vehicle undergoing increasing and decreasing changes in speed without other signals being shown, in which case about 95% of observers correctly identified the velocity display.

The high deceleration signal was also identified a relatively high proportion of the time. For example, about 80% of observers correctly identified it in the car simulation when it was presented in conjunction with the stop signal and the stopped/slow moving vehicle signal, with about 75% correctly identifying it in the truck simulation.

The front of the car or truck, identified by headlights and turn signals, was identified by about 80% of observers in both the car and truck simulation.

The results of this study appeared to show that novel signaling displays such as a stopped/slow moving vehicle signal, a velocity display, or a high deceleration signal can be expected to be readily identified by drivers with little introductory training required. It has been noted that some confusion occurred between conventional signals, such as the stop signal and hazard warning signal, and the experimental displays, in particular the stopped/slow moving vehicle signal. However, these misinterpretations would not be expected to have a deleterious effect upon safety. This is because the general information in any of these signals is fundamentally similar and would require that a driver exercise caution with respect to the vehicle ahead of him, which he would understand to be either slowing down or stopped.

The specific displays that were selected for use in this study are not necessarily those that would be most effective in presenting the particular items of information which they were intended to transmit, and further work might be done to evaluate alternative means of presenting the same types of information. Other studies done in this research program and elsewhere (e.g., Mortimer, 1971), have indicated that signals, which indicate the speed of a preceding vehicle to a driver, may be helpful in reducing rear-end collisions (Carlson and Mortimer, 1974). This study demonstrates that there are means to code such signals so that they can be interpreted by the drivers of following-vehicles quite readily.

RESPONSE OF NAÏVE DRIVERS TO PRESENCE AND STOP SIGNALS OF EXPERIMENTAL REAR LIGHTING CONFIGURATIONS

ABSTRACT

This study was conducted to check the feasibility of directly measuring the responses of naïve drivers to signals presented by nonconventional rear lighting systems in a normal driving situation.

The results provide reason to believe that the procedure is feasible and meaningful results can be obtained with reasonable experimental effort.

RESPONSE OF NAÏVE DRIVERS TO PRESENCE AND STOP SIGNALS OF EXPERIMENTAL REAR LIGHTING CONFIGURATIONS

OBJECTIVE

The objective of this study was to determine whether differences could be detected in the responses of naïve drivers to stop signals presented by normal and unique signal systems. If such response differences could be detected, this would provide a methodology for subsequent evaluations of the effects of experimental rear lighting and signaling systems, in normal driving conditions, on the behavior of drivers who are not solicited as test subjects.

METHOD

A station wagon was equipped with an array of eight lamps, four on each side, as shown in Figure 16. The lamps were four inches in diameter and equipped with single filament 32 cd bulbs with the exception of one pair which were equipped with double filament 3 and 32 cd bulbs. The topmost lamps on each side were yellow and used solely as turn signals.

Four configurations were employed, one on each of four consecutive nights.

Configuration 1:	All-red system one presence lamp on each side. No signal was given.
Configuration 2:	Same as one except that a stop signal was given as the subject driver approached. The stop signal was red and was accomplished conventionally by increasing the intensity of the presence lamps.
Configuration 3:	Green presence lamps, one lamp on each side. No stop signal was given.
Configuration 4:	Same as three except that a red stop indication was given as the subject driver approached. The stop signal was given by adding two red lamps on each side at high intensity, one above and one below the presence lamp. Subjectively, these lamps obliterated the presence lamp.

Figure 16. The lamps mounted on the test car.

Top lamp on each side yellow.
Second and botton lamp on each side red.
Third lamp on each side green.

A television camera(not shown in Figure 16) was rigidly mounted in the car, facing rearward and its output recorded on video tape. An electronic counter was mounted in the rear of the vehicle and so positioned as to be visible in the televised image. This unit counted time in milliseconds and provided a time base. The audio channel of the tape recorder was used for additional information such as might be noted by the driver or reported over the two-way radio link.

The car with the various rear lighting systems was driven on a rural freeway at a controlled speed of 60 mph*, at night. It was followed by another test car.

The two experimental vehicles were driven with a separation distance of about 1000 feet. When an isolated car passed the rear vehicle and moved back into the right lane behind the first test car the following experimenter's car speeded up slowly and the TV recorder was started. The following car attempted to pace the subject car closely enough to allow the driver to observe it without disturbing its driver. As a result, it stayed back about 300-500 feet. If a brake application was called for on the part of the lead car an attempt was made to do this at a separation of 300-400 feet. The brake signal was left on for about ten seconds and then shut off. No other actions of any kind were made. When the subject vehicle passed the lead car, the following car dropped back to the initial spacing to wait for the next subject.

The image of the subject vehicle was recorded continuously on videotape as it approached (all that could be seen were the headlights generally) until it changed lanes and went out of view. The intention was to re-create the speed trajectory of the vehicle by analysis of the lamp spacing changes on the TV

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*The speed limit was 70 mph.

image over time as given by the counter. To do this a calibration tape was made using a following car with relatively wide spacing between lamp centers (60 inches), for headways from 50 feet to 700 feet. Measurements were made of headlamp spacings of a number of cars and finally three spacings were used as rough classifications: wide (60 inches), medium (50 inches), and narrow (40 inches). As each subject vehicle overtook the first experimental vehicle its headlamp spacing category was noted on the audio channel of the recorder.

The data were digitized by running the video tape playback at 1/16th speed and measuring the distance, between the headlamps as seen on a 23" TV monitor, in millimeters, at intervals of two seconds. The measurement interval was reduced to one second as the subject vehicle closed to about 300 feet. These data were then transferred to time-distance plots. Data were obtained on 112 drivers.

DEPENDENT VARIABLES. An attempt was made to measure the following dependent variables:

1. Speed. Three typical plots of speed of the following car against headway are shown in Figure 17. The basic time-distance data were differentiated to yield speed. From such plots the following items were estimated.

   a. Initial speed - the speed of the overtaking car prior to any obvious change in speed.

   b. Speed change - the direction and approximate magnitude of speed changes.

2. Pass Point. As noted by the experimenter in the pursuit vehicle, the point at which the overtaking car's front wheels crossed the lane divider as it began to pass the experimental car.

3. Signals Given by Subject Car. Brake and turn signals were noted by the experimenter in the following car.

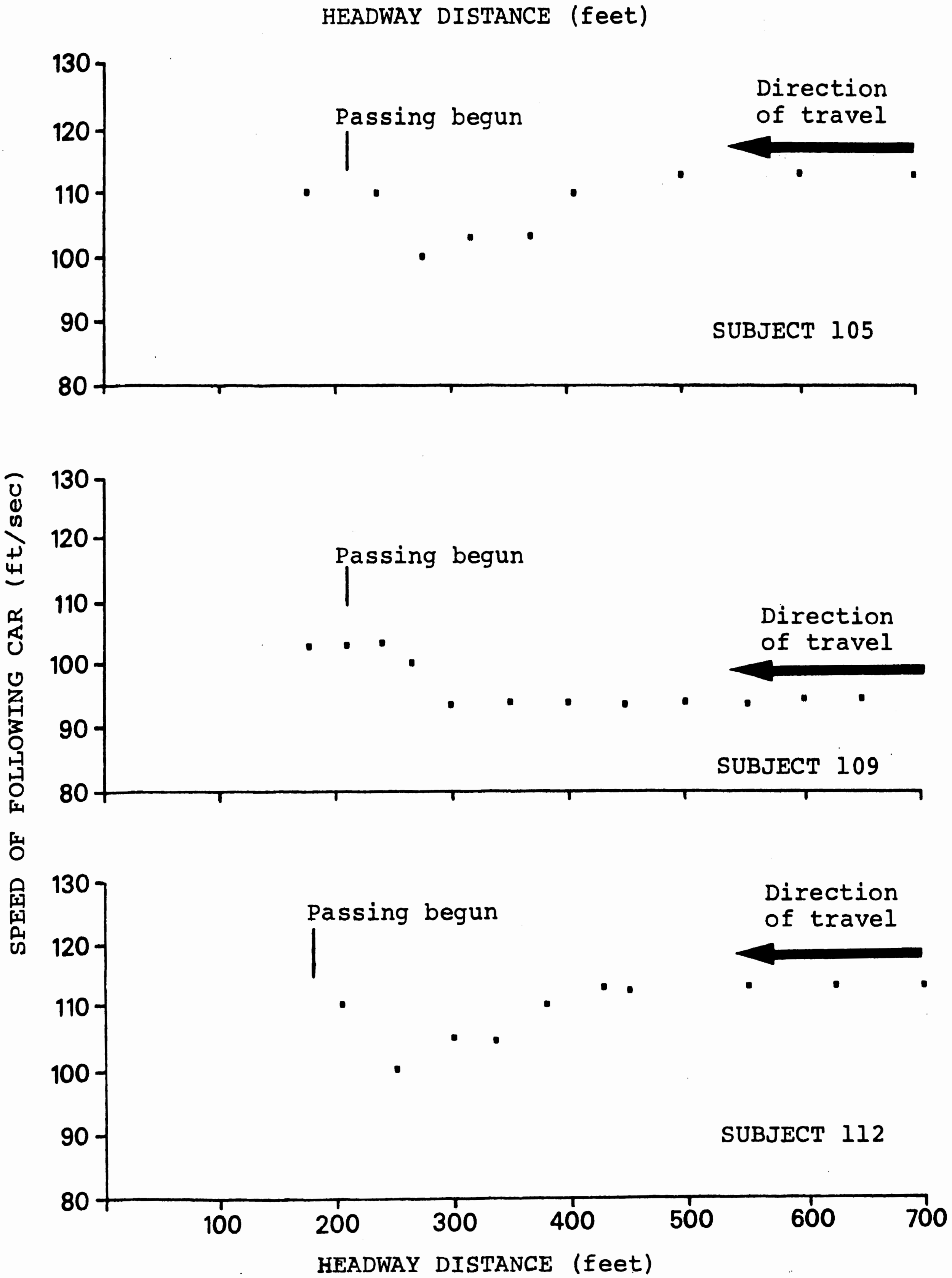

Figure 17. Typical speed-headway plots for three drivers prior tc passing the test car showing two red rear presence lam (configuration 1).

4. Distance at Which Brake Signal Given. For configurations 2 and 4, the distance of the subject vehicle behind the experimental vehicle at the time the brake signal was given was noted.

Data were collected between the hours of 8 p.m. to midnight, for 112 drivers.

RESULTS AND DISCUSSION

The results of the study are summarized in Table 16. In most respects the data are quite consistent, which may be surprising in view of the large variations shown. The most noteworthy differences are those noted under speed change behavior for configurations 3 and 4 and subject car signals for configurations 2, 3 and 4.

The results of this study provide some reason to believe that driver behavior may be influenced in ways that are relatively easy to measure by unique signal systems. A primary concern in planning this study was a possible "gawk" response solely attributable to the uniqueness of systems 3 and 4 which had green tail lights. This would have been expected to manifest itself as a slowing response. There were no consistent slowing responses associated with the unique systems. There was a great increase in the incidence of drivers who did not change their speed with systems 3 and 4, and a reduction in the percent of drivers who increased their speed as they neared the experimental car with system 4. There was also a slight increase in the incidence of brake applications in system 4 versus system 2.

Not shown in the data are two vehicles under system 4 that slowed and tracked the lead vehicle after the brake application. These indeed may have been "gawkers," but the rest of the subject drivers did not manifest any readily measurable interest in the unique configurations.

TABLE 16. Tabulated Results of Responses of Naïve Drivers to a Variety of Rear Lighting and Signal Configurations.

Description	1	2	3	4
Speed change by overtaking car (in %)				
None	6	20	43	42
Increase	52	40	43	19
Decrease	6	4	3	8
Increase - Decrease	10	8	7	8
Decrease - Increase	26	28	3	23
Mean pass point (in ft behind lead car)	203	265	253	253
Mean pass point standard deviation (in ft)	78	74	126	88
Mean initial speed of overtaking car (in ft/sec)	101	98	98	101
Mean initial speed of overtaking car standard deviation (ft/sec)	7	6	7	7
Mean distance at which brake signal given (in ft)	0	349	0	348
Mean distance at which brake signal given standard deviation (ft)	0	76	0	103
Subject car signals (in %)				
None	90	62	77	60
Brake	0	0	0	12
Turn	10	27	23	16
Brake and Turn	0	11	0	12
Subject car mean speed changes (in ft/sec)				
Increase	9	9	6	7
Standard deviation	5	4	2	4
Decrease - Increase				
Decrease	8	9	0	14
Standard deviation	4	4	0	4
Increase	9	11	0	7
standard deviation	4	2	0	2

1=All red - no signal
2=All red - stop signal given
3=Green presence - no signal
4=Green presence - red stop signal given

The results of the study show that it may be possible to evaluate novel rear lighting systems in terms of their effect on drivers who are not aware that they are participating in an experiment. There was no apparent novelty effect shown by the data, as can be inferred from the similar responses of the drivers to red and green presence lights.

There appeared to be an effect of the stop signals of configuration 4 in inducing cautious behavior as noted by the relatively fewer drivers who increased speed as they closed on the test car, and the increased number who applied their brakes. The latter findings could be attributable to the distinctive stop signal of configuration 4. Response to the stop signal of configuration 2 was quite similar to that of the presence lamps alone of configuration 1 with a 12% reduction in the number of vehicles that increased speed, indicating a more cautious approach, than to configuration 1. It is also noticeable that in their approach to the test car showing only green-blue presence lights (configuration 3) the drivers either increased speed or did not change their speed. A tentative explanation of this behavior is that drivers could clearly identify the test car as not braking, by the absence of red lights, and therefore did not hesitate to maintain or increase their speed during the approach. The greater mean and standard deviation of the distance of the pass point from the lead car with configuration 3 than configuration 1 may be partly attributed to the speed increase or maintenance of the drivers, necessitating a relatively greater mean pass distance for driver comfort considerations rather than safety. By comparison, the equivalent mean pass point distances for configurations 2 and 4, or 3, are probably due to the appearance of the stop signals and the expectation that the lead vehicle would decelerate. This would be expected to have the effect of increasing the mean passing distance and reducing the variability between drivers.

PERCEPTION OF RELATIVE VELOCITY

ABSTRACT

An extensive review of the literature was undertaken and three studies conducted in an effort to determine the cues to the detection of relative velocity as well as the sensitivity of normal observers to these cues.

The results indicate that the thresholds for angular velocity are about 3.5 x $.0^{-3}$ rad/sec, and that relative velocity can be perceived in short-glance times when it is above threshold. Drivers were able to scale relative velocity into just under three categories, but lead-car absolute velocity into about five categories. However, in car-following simulator tests, the drivers transmitted little information of relative velocity. At low frequencies of variation in velocity of the lead car (< .05 Hz) the driver of the following car appeared to use a velocity response to detected changes in headway; at higher frequencies, velocity response was used to detected changes in relative velocity. In general, drivers appeared to make little use of relative velocity in the car-following, and therefore based their response upon the perceived headway.

PERCEPTION OF RELATIVE VELOCITY

OBJECTIVE

The objective of the work reported in this section was to determine the cues to the detection of spacing changes in car following situations and measure the capability of drivers to detect such changes.

INTRODUCTION

There are two important situations in the flow of traffic in which a driver must be able to perceive and use information about the velocity of one car relative to his own. These are:

(A) In overtaking and passing - This is probably the most complex and dangerous maneuver performed by a driver. It requires the driver to make estimates of the speed and distance of the oncoming vehicle, the speed of the vehicle he is overtaking and the performance of his own vehicle.

(B) In car-following within a traffic lane - The models of car-following generally assume an equation of the form

$$(1)\quad \ddot{x}_2(t+T) = \lambda(\dot{x}_1[t] - \dot{x}_2\,[t])$$

where the coefficient λ may be dependent on vehicle speed $\dot{x}_2$ and the intervehicle spacing (x_1-x_2). The basic model assumes that the following driver's response (in the form of the time-delayed acceleration $\ddot{x}_2$) is dependent on the magnitude of the relative velocity, that is, it is assumed that the following driver can perceive and scale the relative velocity.

There has been very little research directed specifically at the problem of the perception and use made of relative velocity information. Most published work has concentrated on either empirical studies of the two cases mentioned with little analysis of the underlying human factors, or on the perception of headway changes and relative velocity changes. (For example, Evans and Rothery, 1972; Janssen, 1972; Rockwell and Snider, 1969). These studies are relevant to determining the magnitude of the delay time T in equation 1, but not to the use actually made by the driver of the magnitude of the relative velocity.*

In this report consideration is given to problems of relative velocity scaling and the use that the driver is able to make of relative velocity information. The example of car-following shall be used extensively as this is the traffic situation most readily studied. Most conclusions should, however, also be applicable to the passing situation. The next section reviews and analyzes some of the results of research relevant to this study.

REVIEW AND ANALYSIS OF THE LITERATURE

Olson, et al. (1961) investigated the ability of drivers to make judgments of relative car velocities. At headways of 0.1 and 0.2 mile, they presented to their subjects seven different relative speeds ranging from -30 mph to +30 mph in steps of 10 mph. Subjects viewed the lead vehicle for a period of 7 secs and then made a judgment of the relative velocity.

The important conclusions were:

(1) Subjects were accurate in their judgment of whether the headway between vehicles was increasing or decreasing.

(2) The accuracy of judgments increases as headway is decreased.

(3) Judgments are more accurate when the gap is closing than when it is opening.

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*Discussion of a criterion for detection of spacing changes included as Appendix C.

(4) Subjects tended to underestimate the relative speeds.

These authors carried out an information analysis of their results and found that 1.05 bits* were transmitted at the 0.2 mile headway and 1.38 bits at 0.1 mile headway. If performance had been perfect, 2.81 bits of information would have been transmitted.

As perception of direction of relative velocity was near perfect with their subjects, in each case one bit of information may be associated with the sense of the relative velocity. This then leaves 0.05 and 0.38 bits, for the 0.2 and 0.1 mile headway respectively, for the subject to place the particular relative velocity into one of the three categories. On average, then, these figures tell us that drivers could, once having perceived the direction of the relative velocity, only place this velocity into 1.04 and 1.30 categories, that is, they were unable to discriminate between the various velocity magnitudes.

This is a rather poor performance but is probably easily accounted for by the insensitive perceptual cues available to the driver in carrying out this task. This shall be discussed further in a later section of the report.

Häkkinen (1963) used filmed stimuli of a vehicle approaching at speeds of 30 to 130 km/hr, in steps of 10 km/hr, to construct a scale of approach velocity. The film was used in the laboratory in two ways:

(a) Subjects viewing the film of the vehicle approaching from 300 m to 0 metre.

(b) The film was shown in segments of 300 m to 200 m, 200 m to 100 m and 100 m to 0 m, with the subject making estimates at each distance.

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*The "bit" is the unit of measure of information. It is the natural logarithm of the number of available choices. For example, given 2 choices, 1 bit of information is required to make a choice ($\log_e 2 = 1$).

The results of (a) are summarized by the equation - Estimated Velocity = 1.14 + (actual velocity) 0.91, i.e., there was a tendency to underestimate all velocities).

Of greater importance are the results of (b) as the effects of distance on the perception of approach velocity are seen. Häkkinen's data are regraphed in Figure 18 where it is seen that estimation accuracy is significantly poorer at the larger viewing distance. Häkkinen states:

> "At longer distances . . . . estimates are likely to be independent of actual speeds and quite unreliable."

For each of the test conditions shown in Figure 18, angular velocities, based on the mean distance for each viewing distance have been calculated. These are presented in Table 17. From this table it is seen that the angular velocities for the largest viewing distance are sub-threshold if a threshold value is taken to be 4×10^{-3} rad/sec (Hoffmann, 1968)*. Hence, it is likely that, for accurate estimations angular velocities must be above threshold.

TABLE 17. Angular Velocities (rad/sec) of the Approaching Vehicle for the Test Conditions of Häkkinen (1963). (Based on Average Distance During Exposure.)

Distance Range (Metre)	Vehicle Approach Speed (km/hr)			
	30	50	70	90
300-200	8.16×10^{-4}	1.36×10^{-3}	1.90×10^{-3}	2.45×10^{-3}
200-100	2.27×10^{-3}	3.78×10^{-3}	5.29×10^{-3}	6.80×10^{-3}
100-0	2.04×10^{-2}	3.40×10^{-2}	4.76×10^{-2}	6.12×10^{-2}

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*This value is derived from car-following data. The commonly used value of 6×10^{-4} rad/sec quoted by Michaels (1963) appears to be in error. Michaels apparently derived this value from the range of values of 4 to 40 min of arc/sec determined by Michaels and Cozan (1963). This range corresponds to 1.163×10^{-4} to 11.63×10^{-4} rad/sec, with a mean value of 6.4×10^{-4} rad/sec.

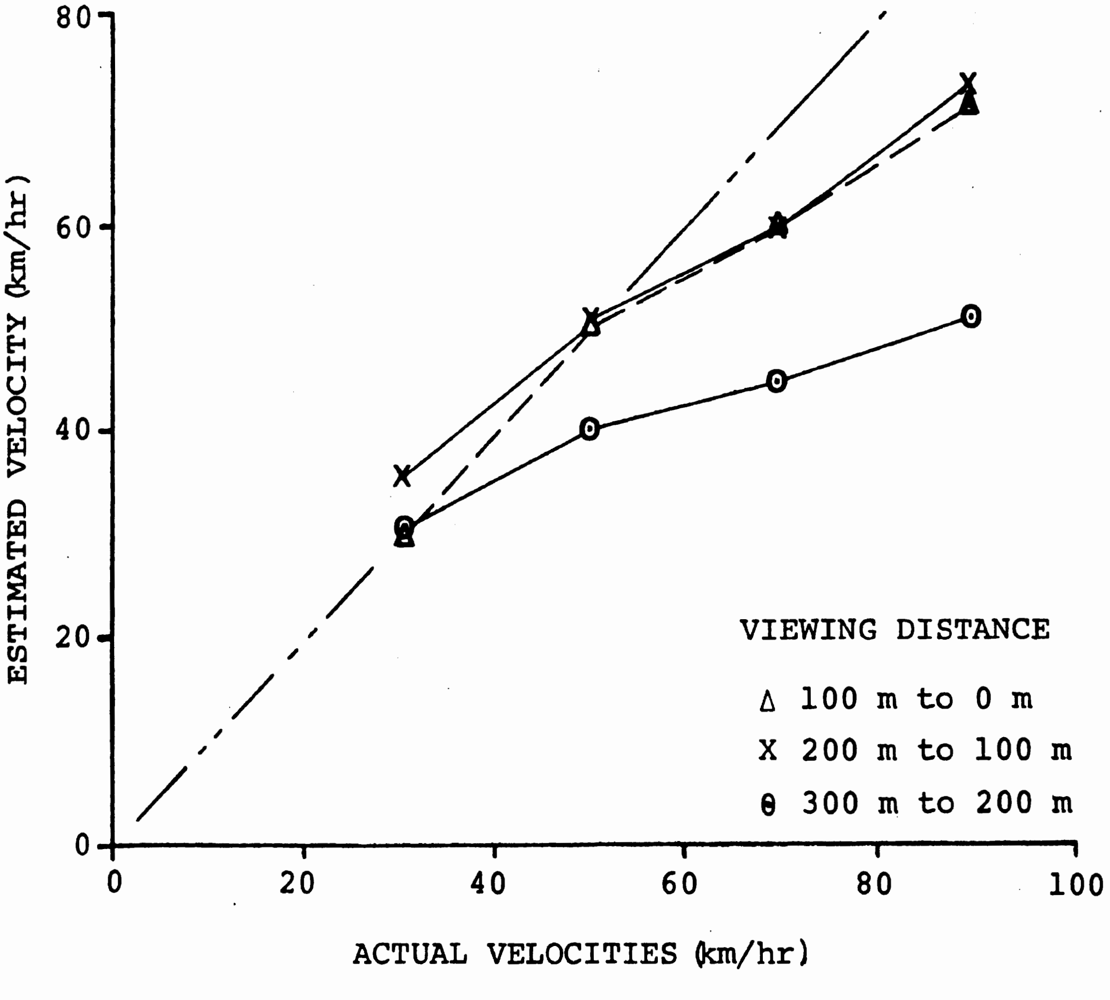


Figure 18. Velocity of approach data from Häkkinen (1963). Estimated velocity at three distances at which estimates were made.

A further experiment on scaling of automobile speed was reported by Semb (1969). Subjects were stationed at distances of 200, 400, 1000 and 2500 ft and observed the oncoming vehicle for a period of 5 sec. The speed range at each distance is given in Table 18. The method of magnitude estimation was used, resulting in the curves of Figure 19. Performance for the 200, 400 and 1000 ft distances was reasonably good, yielding a geometric mean power law exponent of 1.34. (See Table 38 for exponents at various distances.) The estimates at 2500 ft were very irregular. Calculation of the angular velocities shows that only for the 200 ft distance are these likely to be greater than threshold (assuming a threshold value of 4×10^{-3} rad/sec). It could be, however, that the angular velocity threshold is much lower than this figure when the observer is stationary, as in these experiments. Table 18 also presents approximate values for the minimum speed required to produce a just-noticeable-difference in the subtended visual angle at the eye of the observer. All these speeds are within the experimental range and hence it would have been apparent to the observer that the vehicle was in motion. However, only at the highest speeds at 2500 ft distance would motion be detected.

TABLE 18 . Analysis of Angular Cues in Experiment of Semb (1969).

Distance (ft)	Speed Range (mph)	Angular Velocity Range (rad/sec)	Min. Speed For $\frac{\Delta\theta}{\theta}$ = 0.13 in 5 Sec View Time (mph)	Power Law Exponent
200	3-74	$6.6\text{x}10^{-4}$-$1.63\text{x}10^{-2}$	3.33	1.39, 1.32
400	3-74	$1.65\text{x}10^{-4}$-$4.07\text{x}10^{-3}$	6.66	1.31, 1.37
1000	1-65	$8.8\text{x}10^{-6}$-$5.72\text{x}10^{-4}$	16.64	1.31
2500	1-64	$1.41\text{x}10^{-6}$-$9.01\text{x}10^{-5}$	41.6	0.73

From the magnitudes of the angular cues available, it is apparent that the observers were probably basing their judgments on changes in subtended angle rather than on angular velocity directly. Another possibility is that information was obtained from motion of the vehicle relative to the environment, that is, comparing the vehicle position with stationary objects along the road side.

In these experiments the vehicle was not viewed directly from ahead, but from a distance of 8 ft laterally from the road centerline. Calculations show that this lateral displacement has a negligible effect on the angular variable at the distances of the experiment.

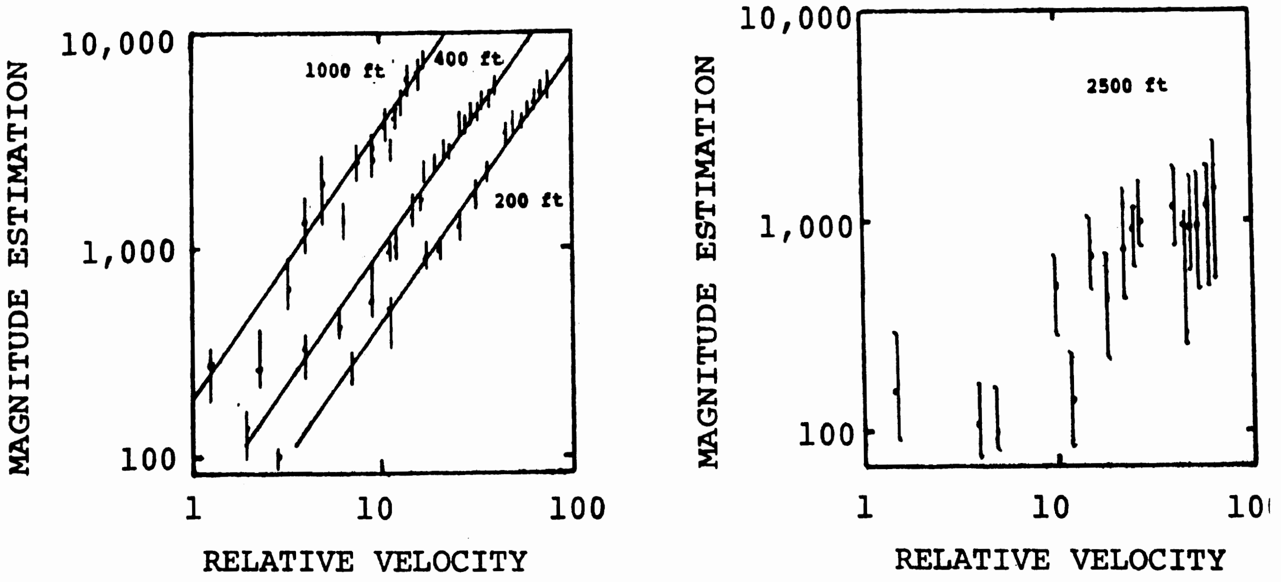


Figure 19. Magnitude estimates of apparent approach speed. From Semb (1969).

Janssen, Michon and Buist (1971) carried out experiments with a device which simulated the motion of the rear taillights under conditions of increasing and decreasing headway. The authors developed scales for the relationship between subjective and physical relative velocities at headways of 53.5, 80.2 and 107 meters (corresponding to 90, 60 and 45 min of subtended visual angle) with relative speeds of 120, 140, 160, 200 and 240 km/hr. Their results are shown in Figure 20.

The data of Janssen et al., are likely to be applicable in such cases as night driving where the cues to the following driver are reduced to the light from the taillights, with no other information coming from the vehicle body size or shape. Under these circumstances, the only information that the driver can obtain about the lead vehicle is via the angular separation and angular velocity of the taillights. It is suggested that these variables are more relevant in the reduced-cue situation than are headway and relative velocity. Janssen's data have been reanalyzed in terms of angular velocity in the following way.

(a) Angular velocities corresponding to the various combinations of relative velocity and headway have been calculated (See Table 19).

TABLE 19. Angular Velocities (rad/sec) Corresponding to the Values of Relative Speed and Headways Used by Janssen et al. (1971).

	Relative Speed Km/Hr						
Headway M	40	80	120	140	160	200	240
53.5	.00544	.0109	.0163	.0191	.0218	.0272	.0327
80.2	.00242	.00484	.00725	.00846	.00967	.0121	.0145
107	.00136	.00272	.00408	.00476	.00544	.0068	.00816

(b) The subjective scale values reported by Janssen et al., were rescaled so that they had a value of 100 at an angular velocity of 5.44×10^{-3} rad/sec. This reference

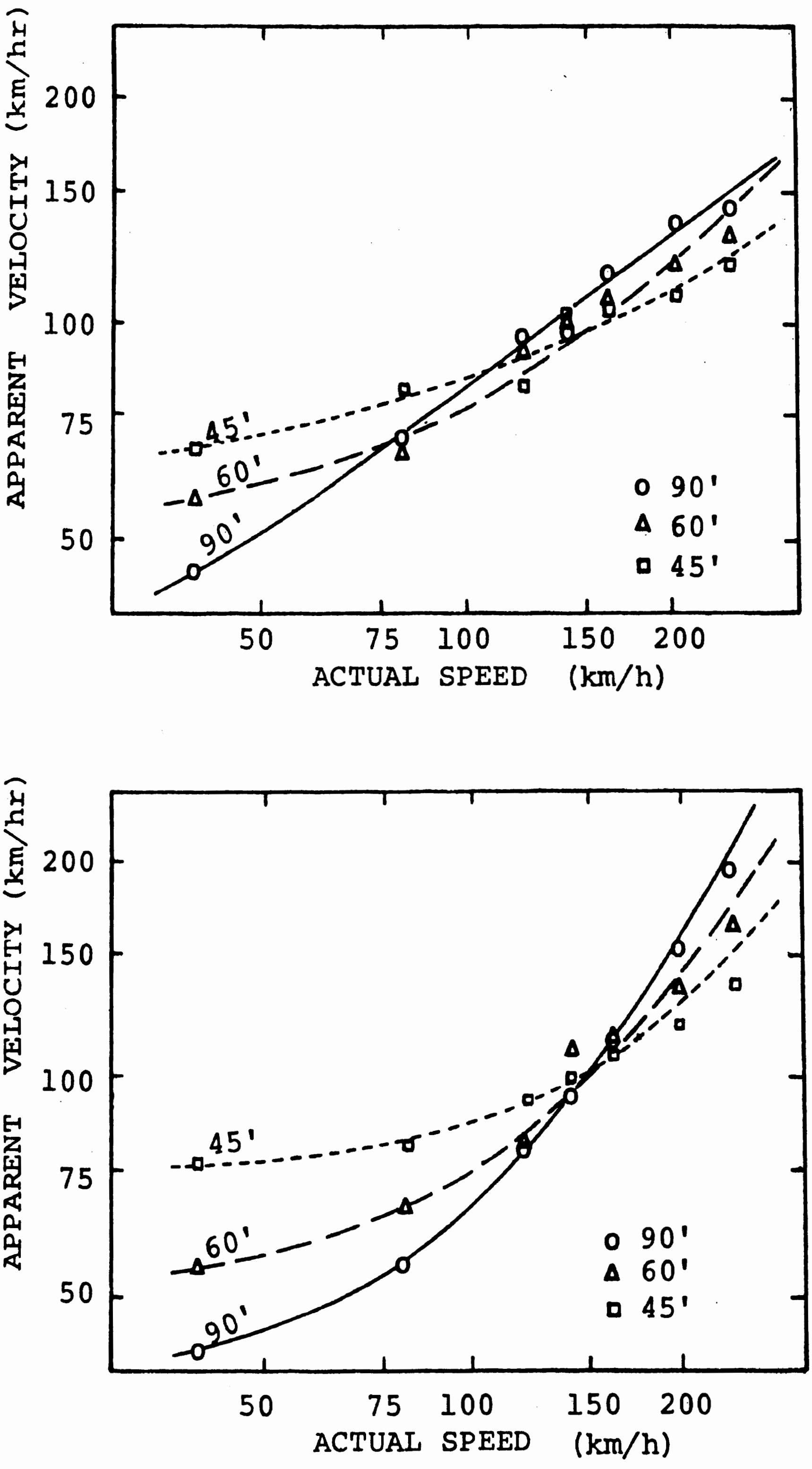


Figure 20. Scales of apparent velocity for approaching and receding lights at 3 simulated headways as determined by Janssen, Michon & Buist (1971).

value of angular velocity was chosen on the basis that it appears in two of the headway conditions and it is also above the threshold value of 4 x 10^{-3} rad/sec determined by Hoffmann (1968). The rescaled values for subjective angular velocity are given in Table 20.

TABLE 20. Rescaled Values of Angular Velocity Obtained From the Data of Janssen et al. (1971). The Subjective Angular Velocities are Scaled to Have a Value of 100 Units at a Reference Physical Angular Velocity of 0.00544 Rad/Sec. The Upper Value in Each Square of the Matrix is For decreasing headway, the Lower Value is For Increasing Headway.

	Relative Velocities Km/Hr						
Headway M	40	80	120	140	160	200	240
53.5	100 100	132 154	190.0 212	226 215	271 258	355 301	460 316
80.2	69.3 71.6	83.4 82.8	102 115	137 124	144 136	167 150	206 164
107	70.0 62.4	73.2 75.4	84.9 77.6	92.5 93.7	100 100	108 102	122 111

The rescaled values are graphed in Figure 21. This figure shows that:

(a) There is no significant difference for the increasing and decreasing headway scales.

(b) Instead of six different scales as obtained by Janssen et al., all the data are collapsed to a single scale.

Two equations have been fitted to the data (except for data points which have an angular velocity lower than a threshold value of 4 x 10^{-3} rad/sec, as these could not be expected to fit

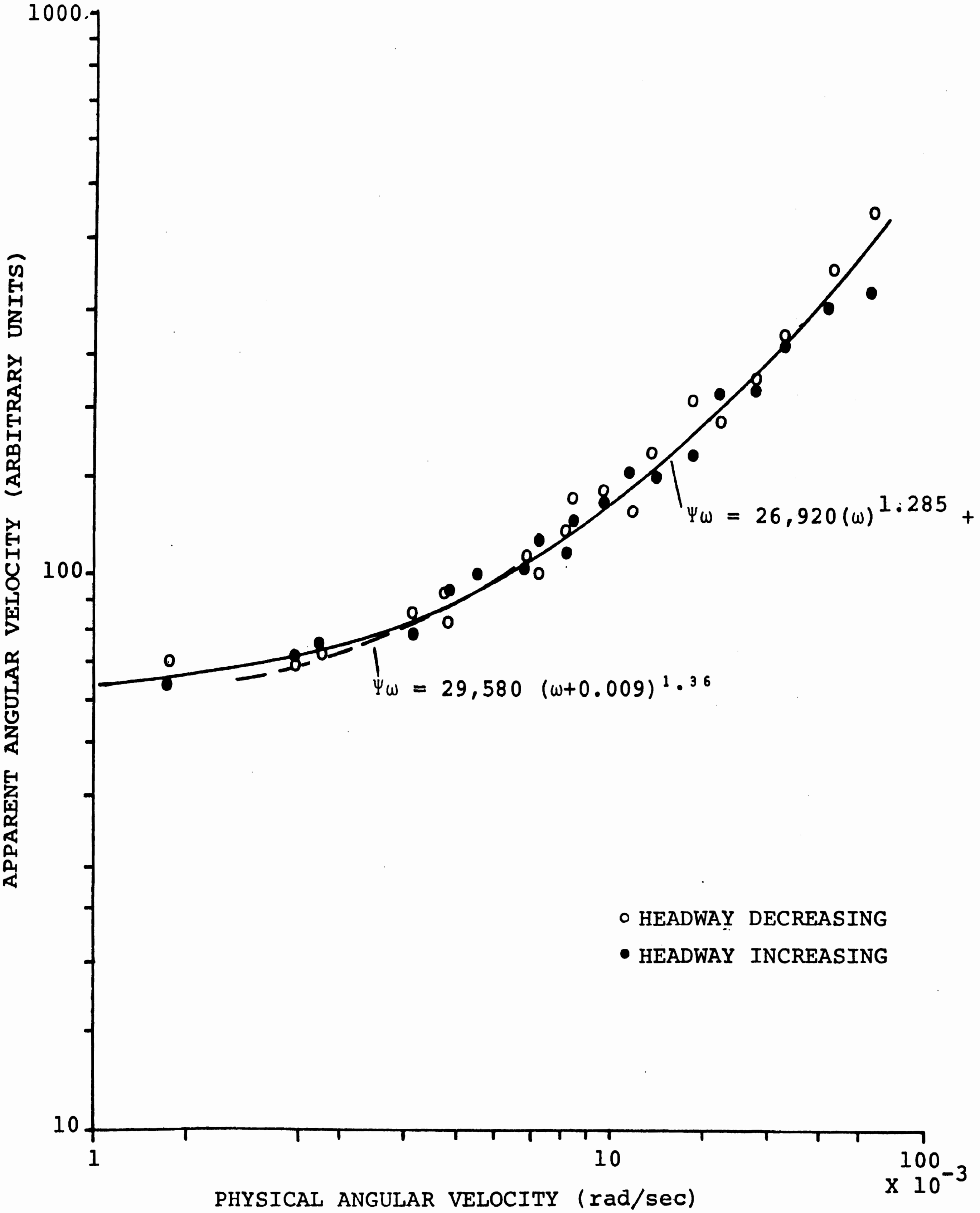


Figure 21. A reanalysis of the data of Janssen, Michon & Buist (1971) i terms of apparent and physical angular velocities.

such a scale). The approximate best-fit lines are given by:

$$\Psi_{\omega} - 60 = 26{,}920\ (\omega)^{1.296}$$

and,

$$\Psi_{\omega} = 29{,}580\ (\omega + 0.009)^{1.36}$$

where ω is the angular velocity in rad/sec and Ψ_{ω} is the corresponding psychological value.

In terms of relative velocity V_r, the corresponding subjective values could be given by:

$$\Psi_{Vr} = \frac{H^2}{W}\ (\Psi_{\omega})$$

or

$$\Psi_{Vr} = \frac{H^2}{W}\ [60 + 26.920\ (\omega)^{1.29}]$$

and

$$\Psi_{Vr} = 29{,}580\ \frac{H^2}{W}\ (\omega + 0.009)^{1.36}$$

where H is the vehicle headway and W the relevant vehicle dimension perceived by the driver (taillight spacing in this case). Above $\omega = 3 \times 10^{-3}$ rad/sec, the fit of these two equations is indistinguishable.

It is noted that the extremely high relative velocities considered by Janssen et al.,do not produce impractical values of angular velocities as they have large headways associated with them. For example, the largest value of angular velocity used (.0327 rad/sec) can be achieved by a relative velocity of 9.3 mph at a headway of 50 ft.

Note that in the studies of Janssen et al. (1971) and of Semb (1969) the observers were stationary. The two experiments yielded power-law exponents of approximately 1.3 yet, in a number of ways, the experiments were very different. In Janssen et al., the only stimulus was a pair of simulated taillights and most of the angular velocities were above threshold; in Semb the stationary environment was included in the stimulus film, but the angular velocities at viewing distances greater than about 400 ft were likely to be below threshold. With these differences the similarity of results is rather surprising. It is possibly worthwhile repeating these scaling experiments but with both absolute and relative velocities of the two vehicles so that the effect of stationary cues is eliminated.

Farber and Silver (1967) report a series of eight empirical studies on driver overtaking and passing under various conditions of overtaking sight distance, subject car speed and oncoming car speed. The major conclusions relevant to this work are:

1. In passing situations limited by available sight distance drivers can judge distance to an oncoming car to within 200 feet, and in passing situations limited by the oncoming car they can judge distance to within 20 percent.

2. Drivers cannot judge and take into account the speed of oncoming traffic in making a passing decision; this is the major source of passing decision errors in passing situations that are limited by the oncoming vehicle.

3. If drivers are given information concerning the speed of oncoming traffic in passing situations, they use this information effectively, together with their own judgment of distance, to make more accurate passing decisions.

The effects of knowledge of oncoming car speed, presented to a driver either as speed directly or as the closing rate, is shown in Figure 22. Farber and Silver summarize the driver's performance as follows:

> ". . . . the threshold passing distance adopted by drivers tends to remain constant regardless of oncoming car speed; this distance is appropriate only for oncoming car speeds close to or slightly above speed limits. . . . . providing closing rate information is technically complex; however, oncoming car speed information appears to be equally effective and is much easier to provide." (p.57)

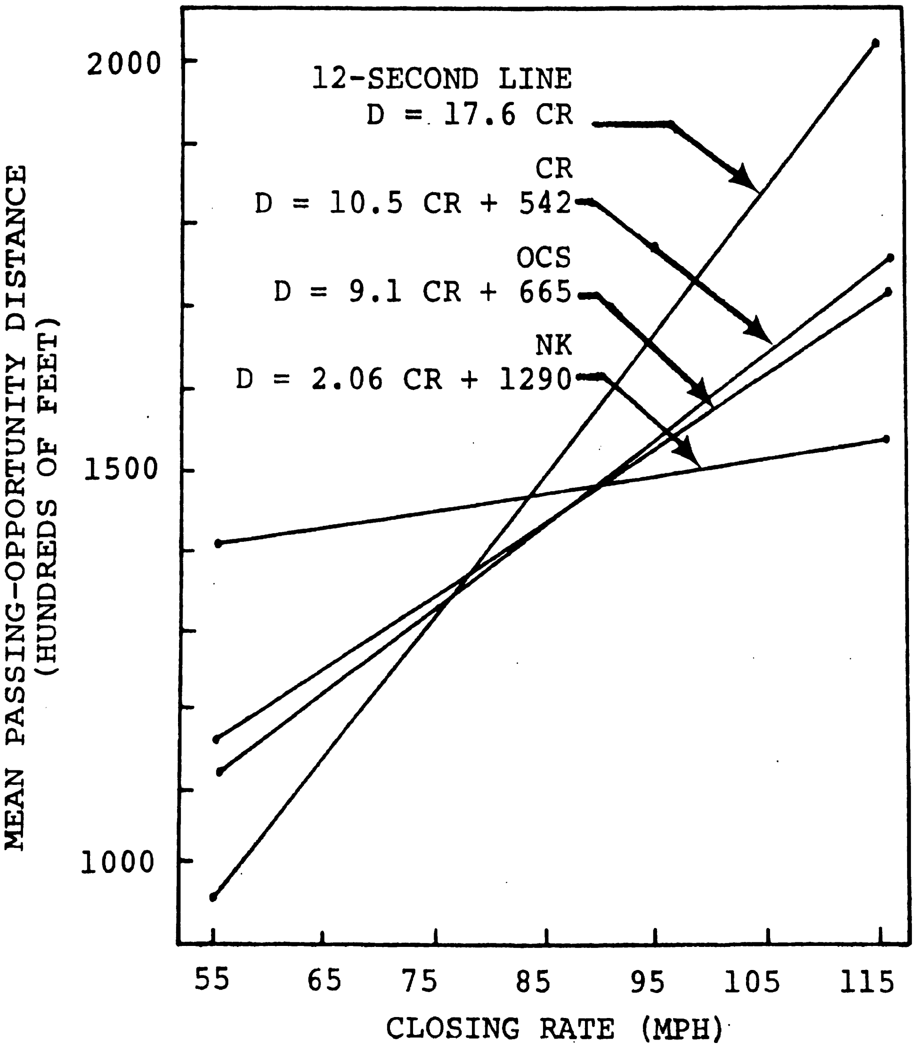


Figure 22. Effects of drivers' knowledge of oncoming car speed or distance at which passing decision is made (Farber & Silver, 1967). NK = no knowledge, OCS = oncoming car speed given, CR = closing rate.

In their experiment "7" subjects, in an overtaking situation, were required to make judgments of 5- and 10-second time headways with constant and variable closing rates in each block of tests. Judgments with the constant closing rates were more accurate than with the variable closing rate (Figure 23). In these tests, subjects were obviously sensitive to the closing rate and to a large extent were able to take it into account in making their judgments. However, Farber and Silver conclude that the "poor judgment of overtaking rate is an important source of decision error in passing opportunities that result from overtaking situations."

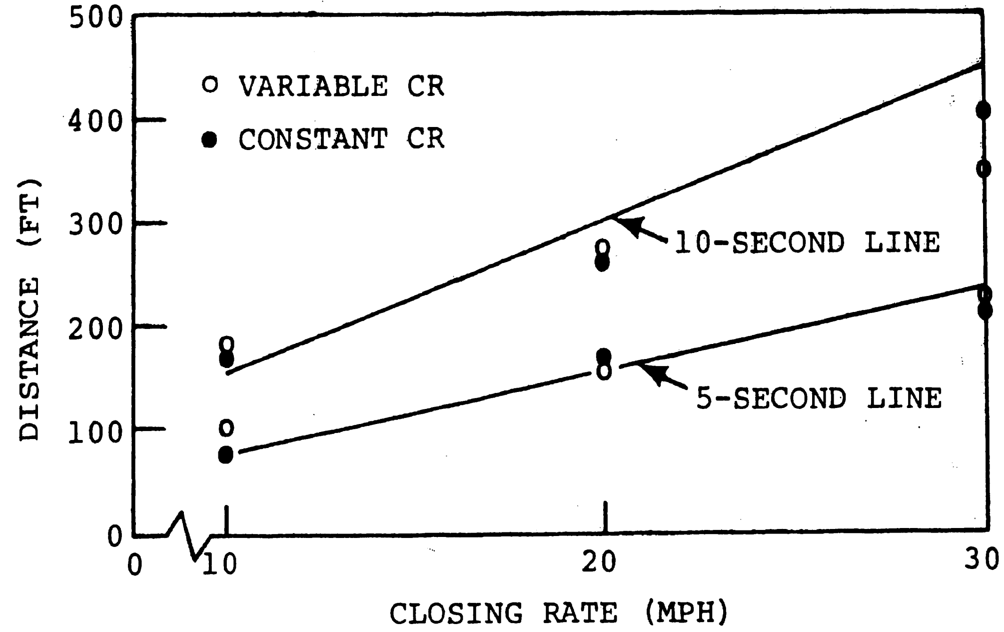


Figure 23. Drivers' judgments of 5 and 10 sec time intervals to closure in an overtaking situation (Farber & Silver, 1967). The two conditions are for constant and variable closing rates.

It is noted that the 5-second estimates are more accurate than those for 10-second headway. Calculation of the angular velocities shows that at the estimated 5-second headway, all angular velocities are above threshold whereas at the estimated 10-second headway, the angular velocities are likely to be below threshold (Table 21). From the data of Farber and Silver values of estimated closing rate (based on the time headway estimations) and the corresponding angular velocity have been calculated. This "apparent" angular velocity is found to be approximately linearly related to the physical angular velocity

TABLE 21. Estimated Time Headway, Equivalent Estimated Closing Rate and the Corresponding Angular Velocity (rad/sec) in the Data of Farber and Silver (1967), Experiment 7 with Variable Closing Rate.

Time Headway Estimate (sec)	Functions	Closing Rate (ft/sec)		
		14.67	29.33	44.00
5	Estimated Time Headway	6.26	5.10	5.83
	Equivalent Estimated Closing Rate	11.72	28.76	37.74
	Corresponding Angular Velocity	1.04×10^{-2}	7.87×10^{-3}	4.01×10^{-3}
10	Estimated Time Headway	11.02	8.92	7.77
	Equivalent Estimated Closing Rate	13.30	32.88	56.63
	Corresponding Angular Velocity	3.37×10^{-3}	2.57×10^{-3}	2.26×10^{-3}

$$\Psi_{\omega} = 0.88\ \omega \text{ rad/sec}$$

A threshold of approximately 3×10^{-3} rad/sec, below which the apparent angular velocity is independent of the physical angular velocity, is shown by this data (Figure 24).

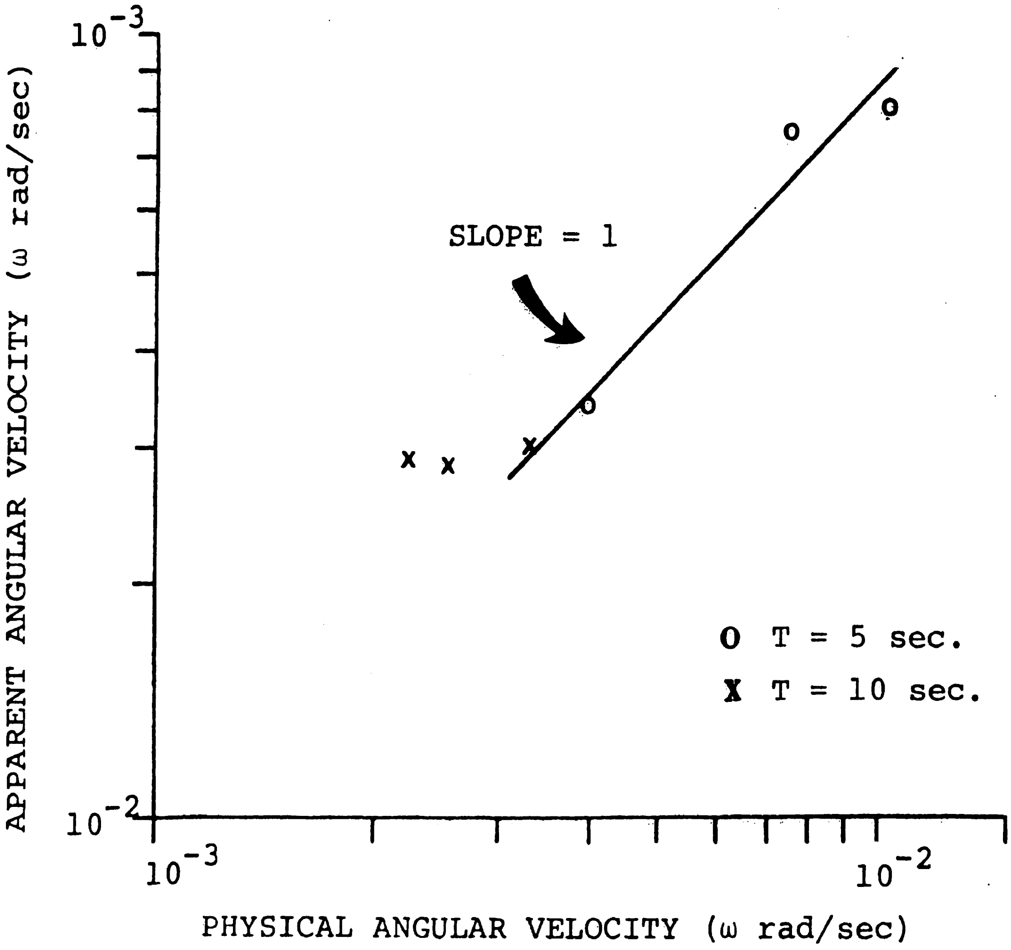


Figure 24. Recalculation of data of Farber and Silver (1967) in terms of apparent and physical angular velocities.

Björkman (1963) carried out an experiment in which observers were required to predict where they would meet an oncoming car. The speed of the subject and oncoming car varied between 20 and 60 km/hr in the combinations shown in Table 22. Björkman found that the meeting point predictions were systematically biased in the direction of the midpoint between cars.

TABLE 22. Analysis of Data of Björkman (1963). Each Cell Contains (1) Estimated Oncoming Vehicle Speed (Km/Hr), (2) Angular Velocity (Rad/Sec) (Mult. x 10^{-4}), and (3) Change in Visual Angle Over 3-Second Viewing Time Divided by Initial Visual Angle.

Own Car Speed (Km/Hr)	Oncoming Car Speed (Km/Hr)				
	20	30	40	50	60
20	21.5 1.09 .08	20.7 1.82 .12	23.4 2.95 .16	18.5 4.89 .22	15.3 7.53 .30
30	33.2 1.22 .09	28.5 1.77 .13	38.6 2.47 .16	29.3 3.43 .20	36.6 4.34 .24
40	39.8 1.43 .11	37.2 1.96 .14	40.2 2.58 .17	43.8 3.39 .21	43.4 3.90 .24
50	45.9 1.67 .13	47.7 2.18 .16	48.5 2.77 .19	50.8 3.51 .23	52.3 4.05 .26
60	51.3 1.99 .15	49.7 2.58 .18	52.1 3.22 .22	50.4 4.12 .26	53.5 4.62 .29

From the data presented by Björkman, the implied subject's estimate of the oncoming car speed has been calculated and is given as the upper number in each cell of Table 22. These figures show that the estimated speed is independent of true oncoming car speed and is approximately equal to the subject's car speed.

The subjects, on average, were able to transmit zero information about the oncoming vehicle speed. The reason for this can be seen from the figures in Table 22. During the 3-second viewing time, nearly all conditions showed a difference in subtended visual angle so that the subject would be aware that relative motion was occurring. However, in all cases the angular velocities are below threshold. Hence, the subject could not scale the relative velocity or make reasonable predictions of the meeting point.

The results of Björkman are in agreement with recent data gathered in England and Sweden and reported by Rumar and Berggrund (1973). These authors state: "Drivers cannot estimate the speed of the oncoming car. . . . . Being in that vague position they seem to assume that the speed of the oncoming car is the same as their own speed (in real traffic secondary cues like the oncoming car being a truck or a sports car certainly has influence on this simple assumption) and consequently base their decision mainly on the estimated distance to the oncoming car, or maybe half that distance where they assume they are going to meet the oncoming car."

An evaluation of a rear-mounted vehicle speed indicator is reported by Jolliffe, Graf and Alden (1971). Their two test conditions were with the lead vehicle having either:

(a) Normal pair taillights.

(b) Normal taillights plus a horizontal light display indicating vehicle speed. The display showed an additional two lights in the speed range 0-10 mph; four between 10 and 20 mph; six between 20 and 30 mph and eight lights between 30 and 40 mph.

Four test speeds were used (10, 20, 30 and 40 mph) with the subject car maintaining a constant speed of 40 mph. Headways varied from 100 feet to 1000 ft. The subject's task was to judge the lead vehicle's speed as one of 10, 20, 30 or 40 mph. Viewing time was 2 seconds. The results of these experiments are presented in Table 23.

TABLE 23. Data of Jolliffe, Graf and Alden (1971) for Errors in Speed Estimation of a Lead Vehicle.

System	Number of Underestimates	Number of Overestimates	Total No. of Responses
Two Taillights	22	17	72
Velocity System	1	22	72

From these data it is possible to calculate an approximate value for the maximum amount of information transmitted with each system. The method was as follows:

(1) As there was no significant speed effect on the number of errors, the numbers along the leading diagonal of the stimulus (actual speed)/response (estimated speed) matrix, should be approximately equal.

(2) The type of error indicates the number of entries in cells above and below the leading diagonal in the S/R matrix.

(3) Each column (stimulus) of the matrix must sum to 18, since each speed was presented an equal number of times.

With these constraints, trial and error methods may be used to determine the approximate maximum information that could have been transmitted by these subjects. Results obtained are:

(1) Two taillights H_T = 0.7 bits = 1.63 categories
(2) Velocity system H_T = 1.15 bits = 2.22 categories

With the normal taillight system subjects could not reliably discriminate more than one speed, once again indicating the poor sensitivity of humans to perception of relative speed.

Performance with the velocity system was somewhat improved. On average, subjects could reliably discriminate two levels of lead vehicle speed over a distance range of 100 to 1000 feet. Hence, the subjects were unable to make full use of the lead vehicle speed information with which they were presented. (Perfect performance would yield H_T = 2 bits = 4 categories).

Salvatore (1972) studied the ability of elementary and secondary school children to sense oncoming car velocity. The children were asked to place the oncoming vehicle speed into one of three categories, slow, medium or fast, corresponding to speed ranges of < 31 mph, 31-40 mph and > 40 mph respectively. It was found that age and sex as well as observation distance, size, noisiness and speed of the oncoming car influence the judgment of velocity.

In particular, Salvatore presents four stimulus-response matrices from which it is possible to calculate information transmitted. The results are:

(a) 5 year old male at 250 ft H_T = 0 bits = 1 catetory
(b) 12 year old male at 250 ft H_T = 0.83 bits = 1.78 categori
(c) 9 year old male at 500 ft H_T = 0.09 bits = 1.06 categori
(d) 14 year old female at 500 ft H_T = 0.20 bits = 1.15 categori

It is seen that, for the sample cases given by Salvatore, the children were not able to reliably discriminate more than one category in the velocity range presented to them, that is, they could say that the vehicle was approaching, but not how fast it was approaching.

Hurst, Perchonok and Seguin (1968) filmed vehicles accepting and rejecting gaps in a traffic stream when vehicles were forced to change from a blocked lane to a freely-flowing lane. They defined 28 measures to determine which best described the criteria used by drivers in accepting or rejecting gaps. In general the highest correlations were obtained with expressions involving time or speed relationship between the subject and following vehicles. More specifically:

- Physical gap size was a poor predictor. All the best predictors had time involved, implying the relative velocities were being estimated.
- The four measures with the highest correlations involved the headway and velocity of the following vehicle.
- Six of the eight best predictors involved the time to closure between the subject and the following vehicle.

CONCLUSIONS OF REVIEW

1. Perception of relative velocity appears to be carried out via the angular velocity of the vehicle ahead. It is necessary for the angular velocity to be above threshold for useful decisions, which involve estimation of time headways or relative velocities, to be made.

2. Analysis shows that, in many conditions under which it is necessary to make decisions involving vehicle maneuvers such as passing or braking to match speeds with a lead vehicle, the angular velocities are below threshold so that direct scaling of rate of closure is not possible.

3. Even when angular velocities are above threshold and capable of being scaled, the human may not be able to readily distinguish between many categories of angular velocity. That is, the absolute amount of information (bits) that can be transmitted is small.

4. If a driver has knowledge of closing rates, he is able to use this information in a way which produces more stable traffic flow. This had implications for vehicle lighting and communication systems.

AIM OF STUDY

The present study is aimed at providing further information on perception of relative velocity; in particular on the aspects of:

1. Cues used by drivers in decision making in car-following (also in overtaking and passing maneuvers).

2. Information transmission in car-following and the ability of drivers to make judgments on relative velocity.

3. Scaling of relative velocity, that is, the relationship between apparent and physical relative velocities.

4. Estimation of closure times.

5. Application of the above data to devise ways in which higher grade information may be communicated to the following driver.

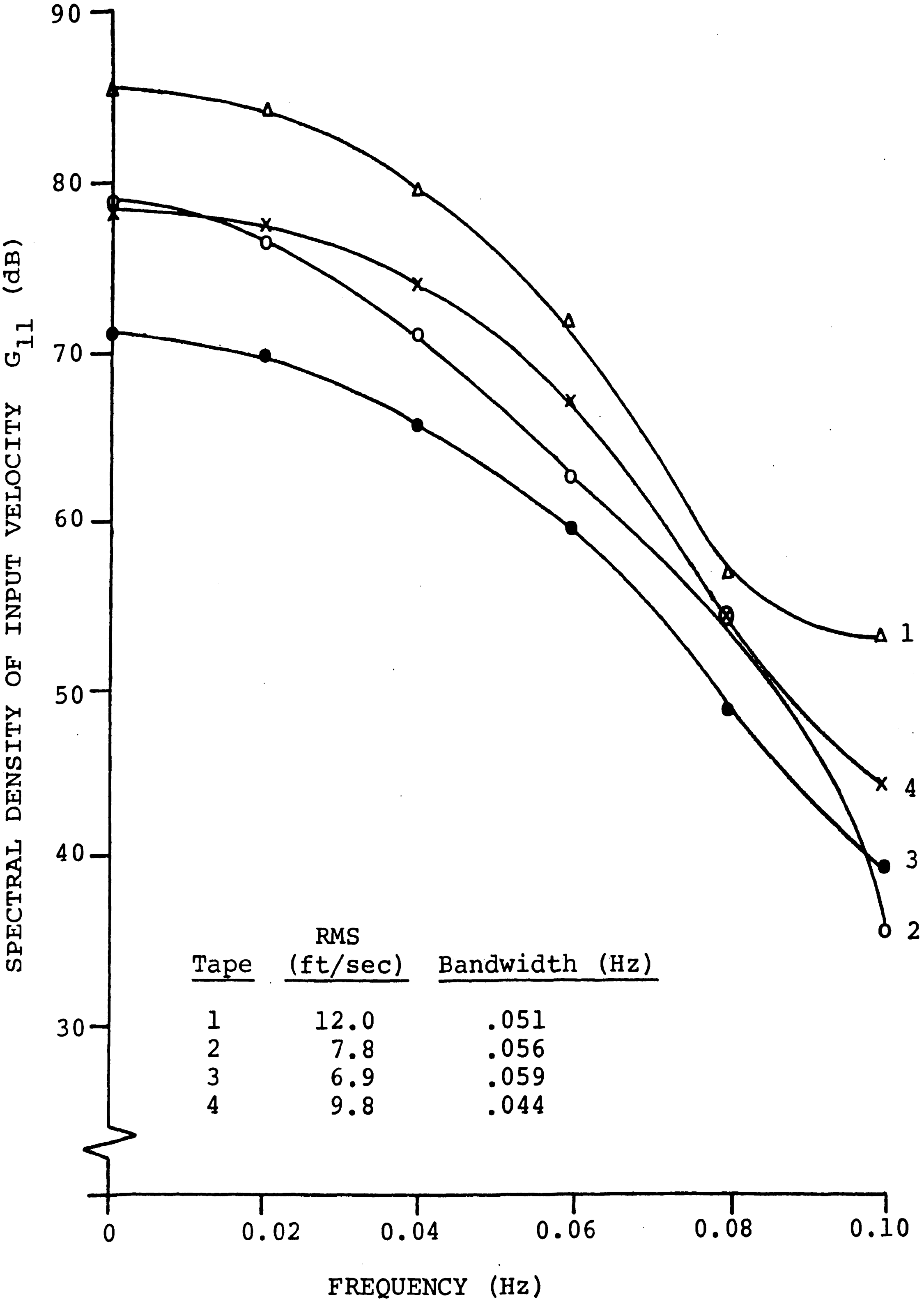
EXPERIMENTS

Three experiments involving perception of relative velocity have been carried out. These are:

1. Car-following in the vehicle rear lighting research driving simulator.
2. Scaling of relative velocity using filmed stimuli of real vehicles.
3. Estimation of closure times using filmed stimuli.

EXPERIMENT 1: CAR-FOLLOWING

OBJECTIVES. The experiment was carried out in the HSRI Part-Task Driving Simulator, which is described by Campbell and Mortimer (1972). The experiment was designed to test whether a side-task could significantly affect performance on a car-following task. The major results of this experiment are reported by Mortimer and Sturgis (1974). The data of this experiment have been used to calculate various parameters related to car-following and the perception of relative velocity.



Tape	RMS (ft/sec)	Bandwidth (Hz)
1	12.0	.051
2	7.8	.056
3	6.9	.059
4	9.8	.044

Figure 25. Spectral densities of lead car velocity input.

METHOD.

Subjects. Four male subjects took part.

The Experiment. Four subjects were used and were presented with two rear signaling systems (System 1: two red lamps, and System 8: blue-green presence, yellow turn and red stop) and three conditions of the side-task (no side-task, side-task at low intensity and side-task at high intensity). Each subject was used on two separate days, on one of which the side-task was operated at low intensity and on the other day at high intensity, in addition to trials without the side-task on each day. A total of eight 10-minute trials was performed by each subject.

The data. The data relevant to this study were recorded directly in digitized form (30/sec) for digital analysis. Measures of lead-car velocity, following-car velocity, relative velocity and headway are available. Although following-car acceleration was recorded, the signal did not appear usable due to a system fault.

Lead Car Velocity Input. Four input tapes were used in this experiment, these being recorded in highway driving (see Mortimer and Sturgis, 1974). The spectra and bandwidth of these input velocities are shown in Figure 25. In each of the four tapes the bandwidth was about 0.05 Hz*. (Note that the ordinate of Figure 25 is plotted in dB and hence does not show the very rapid decrease of spectral density with frequency.) However, the RMS values differ markedly and this variation needs to be taken into consideration in calculations of driver performance in terms of his RMS output of, for instance, velocity or relative velocity.

Data analysis. Darroch and Rothery (1971) investigated the possibility of using time-series analysis in car-following problems. Their paper is largely a description of the digital

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*This designates the region within which the dominant input frequencies were found.

methods used for computation of the driver describing function, various spectral densities and the coherence function.

The data they present for one trial of one subject indicates that time-series analysis may be a very fruitful approach to the study of car-following. The approach they use is essentially that of Bendat and Piersol (1966). From their spectral density functions, it is apparent that car-following involves very low frequencies, with dominant frequencies of around 0.03 Hz and with very little energy above 0.10 Hz following car acceleration and relative velocity. This is in reasonable agreement with the longitudinal acceleration data of Torres (1970), who finds peaks at frequencies of 0.03 - 0.06 Hz and little energy above about 0.2 Hz. From these results it is apparent that bandwidths are very small and standard errors in computations may be large, due to the low frequencies and the limited trial time.

Bendat and Piersol (1966) give an expression for the normalized standard error (E) of the spectral estimate as:

$$E = \frac{1}{\sqrt{Be.T}}$$

where Be is the resolution bandwidth (Hz) and T is the record length (sec). This equation shows that it is necessary to make a compromise between standard error and resolution bandwidth. In this case we require Be to be a maximum of 0.01 Hz and, as T = 600 sec, the standard error will be 41%. The data were sampled at 1-second intervals, giving a cut-off frequency of 2 Hz, well above the range of interest in this experiment. Fifty lags were used in forming the auto- and cross-correlation functions.

Using the equations given in Bendat and Piersol (1966) for digitized data, the following quantities were computed: (1) input spectral density, G_{ii}, (2) output spectral density, G_{oo}, (3) describing function relating output to input, H (magnitude and phase components), (4) coherence function, being a measure of the linear relationship existing between the input and output $\gamma_{io}^2(f)$.

Choice of input and output variables. The car-following task has usually been considered in terms of an acceleration response of the following driver to a relative velocity difference between his own and the leading vehicle. (There are some variations on this model, with sensitivity varying with speed, headway or in a non-linear manner).

Physically, the driver does not respond with an acceleration - at least not directly - but with a movement of the brake or accelerator. Analysis in terms of brake or accelerator position is complex since control in these variables is usually discrete, intermittent and quite often non-existent (as in coasting). This is the reason for using a continuous vehicle measure as the following driver output or response to lead vehicle changes. Rockwell and Snider (1969) discuss this problem and state, "Thus, it may be argued that the driver is controlling the output acceleration of the vehicle and that the functional relationship between his direct physical output, force, and the response of the vehicle controls has little to do with his overall control of the vehicle's acceleration, provided that the relationship is within reasonable limits." This view is accepted in the report and a vehicle response quantity is used as a measure of the driver's response.

There are alternatives to the usual formulation of the stimulus/response pair being relative velocity and acceleration. For example, the following driver may simply consider the task as one of matching velocities, in which the input may be thought of as either the lead car velocity, or the relative velocity, and the response may be the following car velocity. Describing functions for these alternatives may be readily computed from the data available.

If X_1 is the position of the lead car and X_2 that of the following car, the data will allow us to compute the following describing functions:

(1) $\dot{X}_2/\dot{X}_1$ - velocity matching task

(2) $\dot{X}_2/(X_1-X_2)$ - velocity response to headway

(3) $\ddot{X}_2/(X_1-X_2)$ - acceleration response to headway

(4) $\dot{X}_2/(\dot{X}_1-\dot{X}_2)$ - velocity response to relative velocity

(5) $\ddot{X}_2/(\dot{X}_1-\dot{X}_2)$ - acceleration response to relative velocity.

Because of the relationships existing between these describing functions, computation of (1) and (4) will allow ready conversion to the remaining (as well as a number of others). It is hoped that comparison of the obtained form of these describing functions with those known to be readily achieved by human operators may give further information on the stimulus/response pair being used by drivers in car-following. Computation of information transmission (see next section) may also assist in this choice. If these stimulus and response relationships can be determined, better intervehicle communication systems may be devised.

Transinformation rate. Shannon (1948) showed that the transinformation rate for a normally distributed continuous signal is given by

$$I = \frac{dH_T}{dt} = \int \log_2 \left[\frac{P(f) + N(f)}{N(f)}\right] df \qquad (1)$$

where P = signal power and N = noise power

If we assume that the signal is that portion of the output which is linearly related to the input (via a constant parameter linear differential equation), then the noise is that part of the output remaining when $|H|^2 G_{ii}$ (i.e., the input power spectrum times the magnitude square of the input to output transfer function) is subtracted from the output power spectral density G_{oo}

$$G_{oo} = |H|^2 G_{ii} + G_{nn} \tag{2}$$

With this definition of "signal" and "noise", equation (1) becomes

$$I = \log_2 \int \frac{G_{oo}}{G_{oo} - |H|^2 G_{ii}} df$$

and since $|H| = \frac{|G_{io}|}{G_{ii}}$, where G_{io} is the cross-spectral density, then

$$I = \int \log_2 \left[\frac{1}{1 - \gamma_{io}^2(f)} \right] df \tag{3}$$

where γ_{io}^2 is the coherence function between input and output (Bendat and Piersol, 1966),

$$\gamma_{io}^2 = \frac{|G_{io}|^2}{G_{ii}\, G_{oo}} \tag{4}$$

The coherence gives a measure of the extent of the linear relationship between the input and output and is analogous to the linear correlation coefficient.

The form of transinformation, as derived in equation 3, is that used in studies of tracking (Wempe and Baty, 1966, 1968) and vehicle control (Shaw, 1973). It should be noted, from equation 3 that if the driver can exactly follow the lead vehicle, N is equal to zero and the driver is transmitting infinite information.

Effective bandwidth. Effective bandwidth ω_{eff} is defined as the bandwidth of a rectangular power spectral density distribution that has the same average power (area under the curve) and variance as the power spectral density being described (Blackman and Tukey, 1958).

$$\omega_{eff} = \frac{\left[\int_{o}^{\infty} G_{ii}(f)\ df\right]^2}{\int_{o}^{\infty}\left[G_{ii}^{2}(f)\right] df} \qquad (5)$$

If we now consider equation (1) in terms of a signal having a rectangular power spectral density of bandwidth ω_{eff} in which the signal power P and the noise power N are constant over frequency, we can write

$$I = \omega_{eff} \log_2 \frac{\text{(Mean square of received signal)}}{\text{Mean square of noise, } \sigma n^2} \qquad (6)$$

Using these equations Shaw (1973) developed a method of determining an estimate of the quantum step size that can be discriminated for a particular variable.

From equation (6), having computed I from equation (3), ω_{eff} from equation (5) and the mean square of the output, σ_n^2 may be obtained. A range of $\pm 2\sigma_n = 4\sigma_n$ may then be taken as an estimate of the quantum step size, since with probability = 0.955, the achieved level is within 4 x (RMS noise) range about the desired level (i.e., the measure $4\sigma_n$ gives a measure of the drivers' ability to discriminate between different levels of a variable when he is doing so in a perceptually "noisy" background).

The number of quantum steps that he is able to discriminate is then given by

$$N = \frac{\text{Range of Variable}}{4\sigma_n} \qquad (7)$$

or

$$H_T = \log_2 N \text{ (bits of information)} \qquad (8)$$

It is necessary for the $4\sigma_n$ to be greater than the threshold for the particular variable; this in fact provides some check on the validity of this approach. Shaw (1973) uses a different approach in estimating the number of quantum steps. This is based on the independence of sample points at time intervals of $(\frac{1}{2\omega_{eff}})$. In this case, an estimate of N is obtained from

$$I = 2\omega_{eff} \log_2 N \tag{9}$$

A non-flat power spectrum indicates the existence of intersample influence between sample points $(\frac{1}{2\omega_{eff}})$ apart. Which of (7) or (9) is the better measure is unknown; in general (7) will yield a lower number of steps than equation (9). If there is a strongly dominant frequency in the variable, the estimates of equations (7) and (9) are not likely to be greatly different (within 1 bit of information).

RESULTS.

General Performance Measures. Table 24 gives values of RMS lead car velocity, following car velocity, relative velocity and headway. Also included are the mean headway and range of relative velocity. Bandwidths of lead car velocity, following car velocity, relative velocity, headway and following car acceleration are given in Table 25.

Spectra. Some typical spectra of following car acceleration, relative velocity and headway are shown in Figures 26, 27, 28 and 29. The spectral density (ordinate) in each of these figures is plotted on a linear scale and the small bandwidths listed in Table 25 are apparent. Means and standard deviations of the bandwidths are:

Following car acceleration,	Mean = .092 Hz,	S.D. = .016 Hz
Relative velocity,	Mean = .096 Hz,	S.D. = .017 Hz
Headway changes,	Mean = .060 Hz,	S.D. = .019 Hz

TABLE 24. Mean and RMS Measures of Velocity and Headway in the Car-Following Experiment.

File No. & Condition Code	RMS Lead Car Velocity (Ft/Sec)	RMS Following Car Velocity (Ft/Sec)	RMS Relative Velocity (Ft/Sec)	RMS Following Car Velocity (Ft/Sec)	Range of Relative Velocity (Ft/Sec)	Mean Headway (Ft)	RMS Headway (Ft)
1 11YH	12.02	15.94	9.55	6.34	53.7	226	66
2 11NH	7.82	11.43	7.56	4.75	39.1	245	58
3 18NH	6.93	8.86	6.69	3.45	38.1	240	65
4 18YH	9.90	12.11	7.45	4.65	42.4	264	67
5 28NL	11.98	13.06	4.84	5.23	33.9	145	35
6 28YL	7.81	9.55	6.99	3.74	34.2	257	88
7 21YL	6.93	9.32	7.15	3.95	39.3	253	73
8 21NL	9.53	9.92	6.92	3.87	40.1	234	70
9 31NL	12.02	17.00	5.52	6.75	39.3	198	46
10 31YL	7.77	9.84	4.91	3.58	27.7	247	100
11 38YL	6.96	9.16	3.94	2.96	18.7	234	41
12 38NL	9.82	10.69	3.82	3.96	21.6	193	45
13 18NL	12.02	17.43	6.27	7.11	39.3	164	34
14 18YL	7.76	10.89	7.15	4.38	41.4	205	46
15 11YL	6.88	9.78	6.70	4.31	35.2	208	49
16 11NL	9.87	11.66	5.50	4.58	20.2	189	36
17 21YH	12.01	14.03	6.58	5.71	41.0	167	52
18 28NH	6.91	8.89	5.45	4.36	29.8	140	29
19 28YH	9.76	11.64	7.21	4.48	39.2	177	54
20 38YH	11.97	13.27	4.36	5.08	27.1	155	40
21 38NH	7.78	5.53	3.27	3.58	19.7	174	42
22 31NH	6.97	7.27	3.32	3.41	18.3	215	58
23 31YH	9.80	10.83	3.48	3.77	20.4	201	50
24 48YH	11.94	14.59	6.44	6.34	38.4	141	32
25 48NH	7.75	9.86	5.89	4.77	35.9	145	23
26 41NH	6.87	10.34	6.77	5.27	49.8	156	34
27 41YH	9.67	11.73	6.41	5.15	40.5	152	32
28 21NH	7.71	9.27	5.70	4.48	35.0	132	24
29 41NL	11.90	14.48	7.12	6.78	42.5	136	33
30 41YL	7.71	9.80	5.82	4.72	24.7	170	32
31 48YL	6.83	10.11	6.78	5.37	38.2	155	29
32 48NL	9.71	11.56	5.96	5.05	37.5	166	25

TABLE 25. Bandwidths of Velocities and Headway for Experiment 1.

File Number & Condition Code	Bandwidth of Lead Car Velocity (Hz)	Bandwidth of Following Car Velocity (Hz)	Bandwidth of Relative Velocity (Hz)	Bandwidth of Following Car Acceleration	Bandwidth of Headway
1 11YH	.051	.055	.077	.068	.051
2 11N	.056	.064	.078	.071	.056
3 18N	.059	.056	.080	.076	.040
4 18YH	.044	.055	.071	.066	.044
5 28N	.051	.036	.109	.081	.055
6 28YL	.056	.052	.091	.090	.042
7 21YL	.059	.064	.073	.094	.037
8 21N	.044	.051	.086	.102	.049
9 31N	.051	.083	.100	.100	.063
10 31YL	.056	.049	.079	.072	.030
11 33YL	.059	.060	.105	.096	.048
12 38N	.044	.046	.101	.092	.033
13 18N	.051	.060	.076	.097	.067
14 18YL	.056	.062	.072	.071	.060
15 11YL	.059	.070	.097	.089	.049
16 11N	.044	.056	.081	.083	.069
17 21YH	.051	.059	.089	.075	.064
18 28N	.059	.087	.110	.115	.078
19 28YH	.044	.083	.095	.085	.051
20 38YH	.051	.053	.102	.071	.043
21 38N	.056	.064	.142	.089	.052
22 31N	.059	.066	.107	.107	.036
23 31YH	.044	.042	.114	.078	.038
24 48YH	.051	.065	.106	.093	.080
25 48N	.056	.086	.111	.114	.096
26 41N	.059	.090	.093	.098	.077
27 41YH	.044	.064	.076	.101	.075
28 21N	.056	.082	.129	.129	.076
29 41N	.051	.077	.117	.118	.100
30 41YL	.056	.086	.100	.105	.088
31 48YL	.059	.101	.100	.113	.088
32 48N	.044	.066	.090	.105	.084

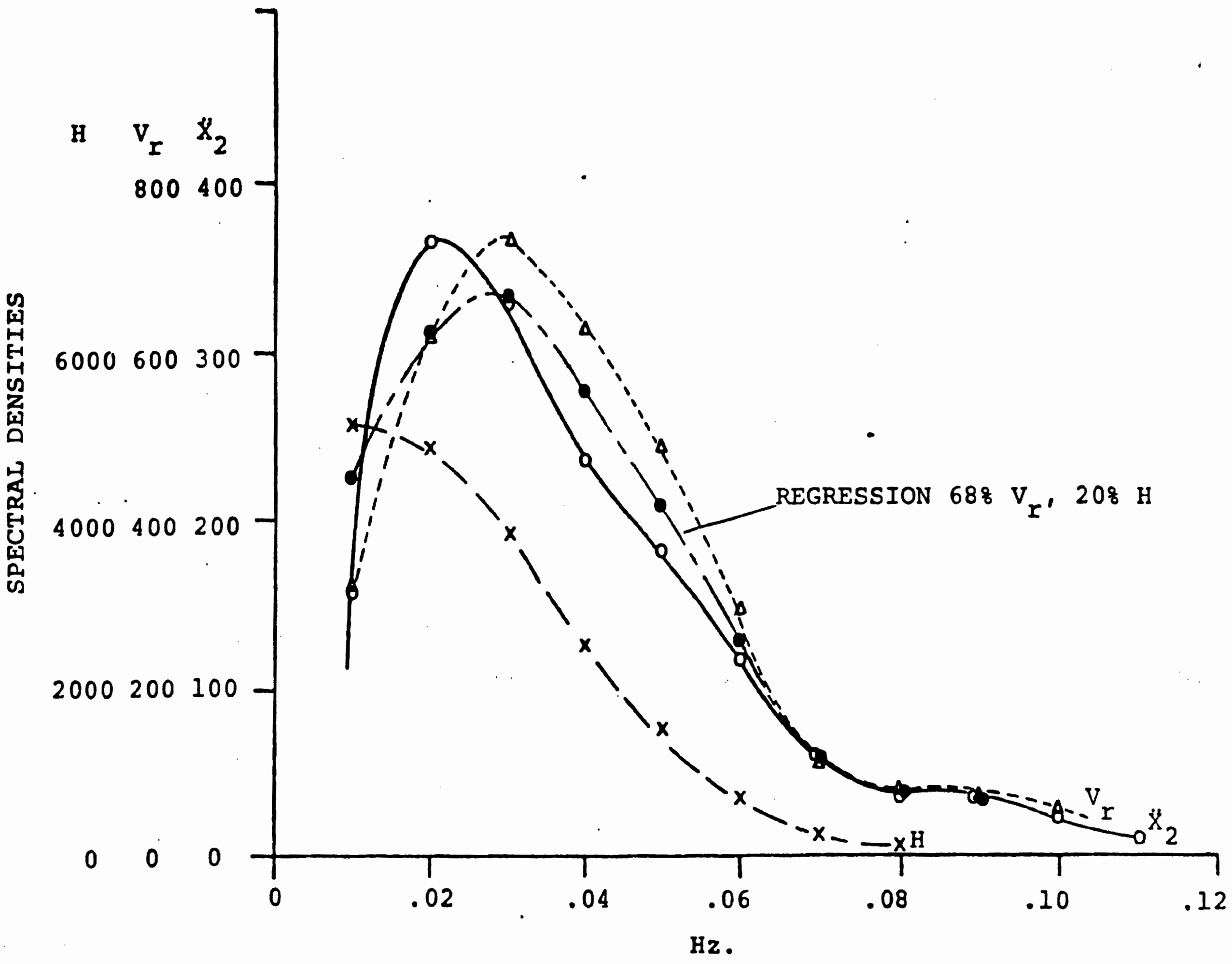


Figure 26. Spectral densities of following car acceleration, relative velocity and headway for file 1. The regression of $\ddot{X}_2$ with H and V_r is also included.

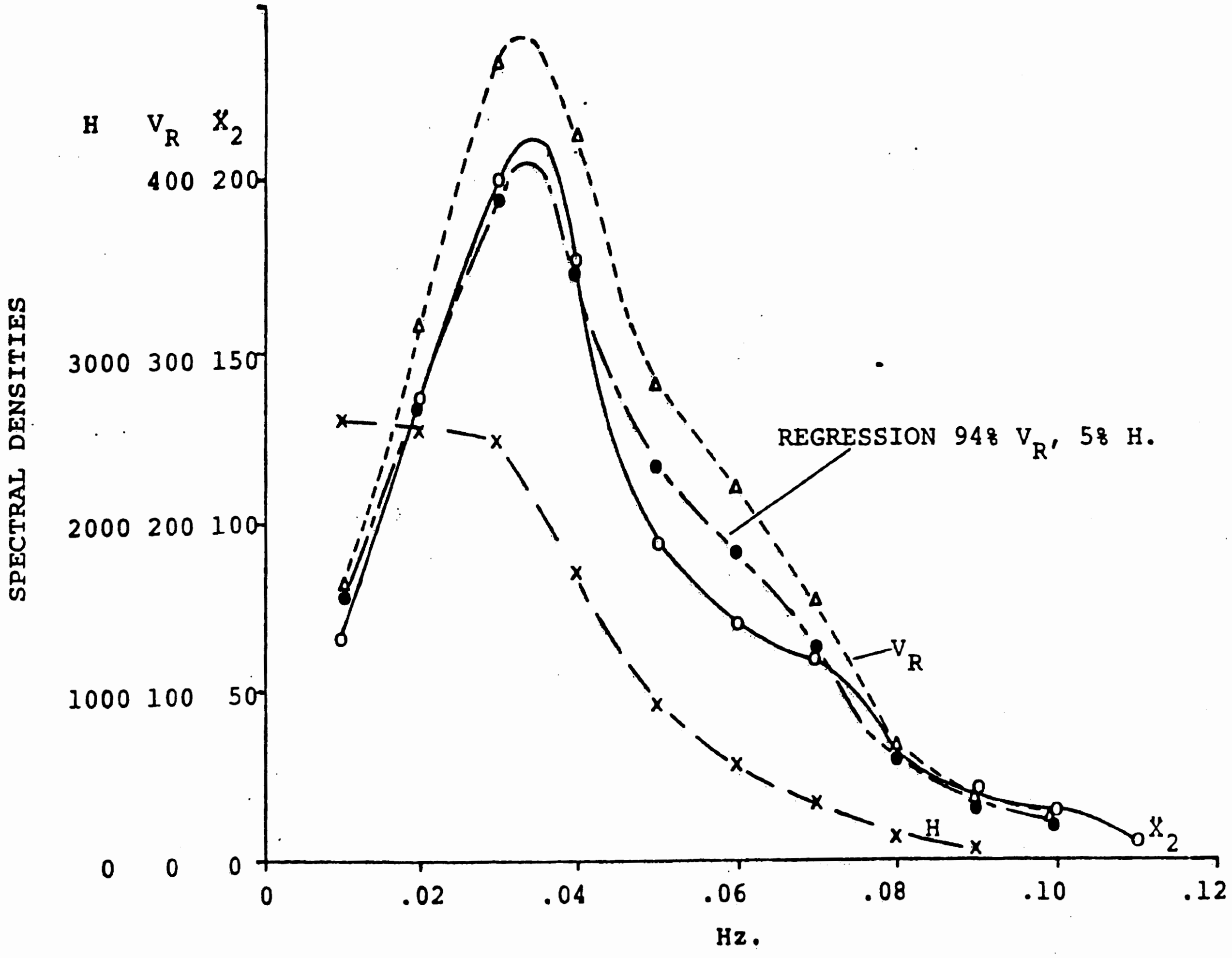


Figure 27. Spectral densities of following car acceleration, relative velocity and headway for file 2. The regression of $\ddot{X}_2$ with H and V_r is also included.

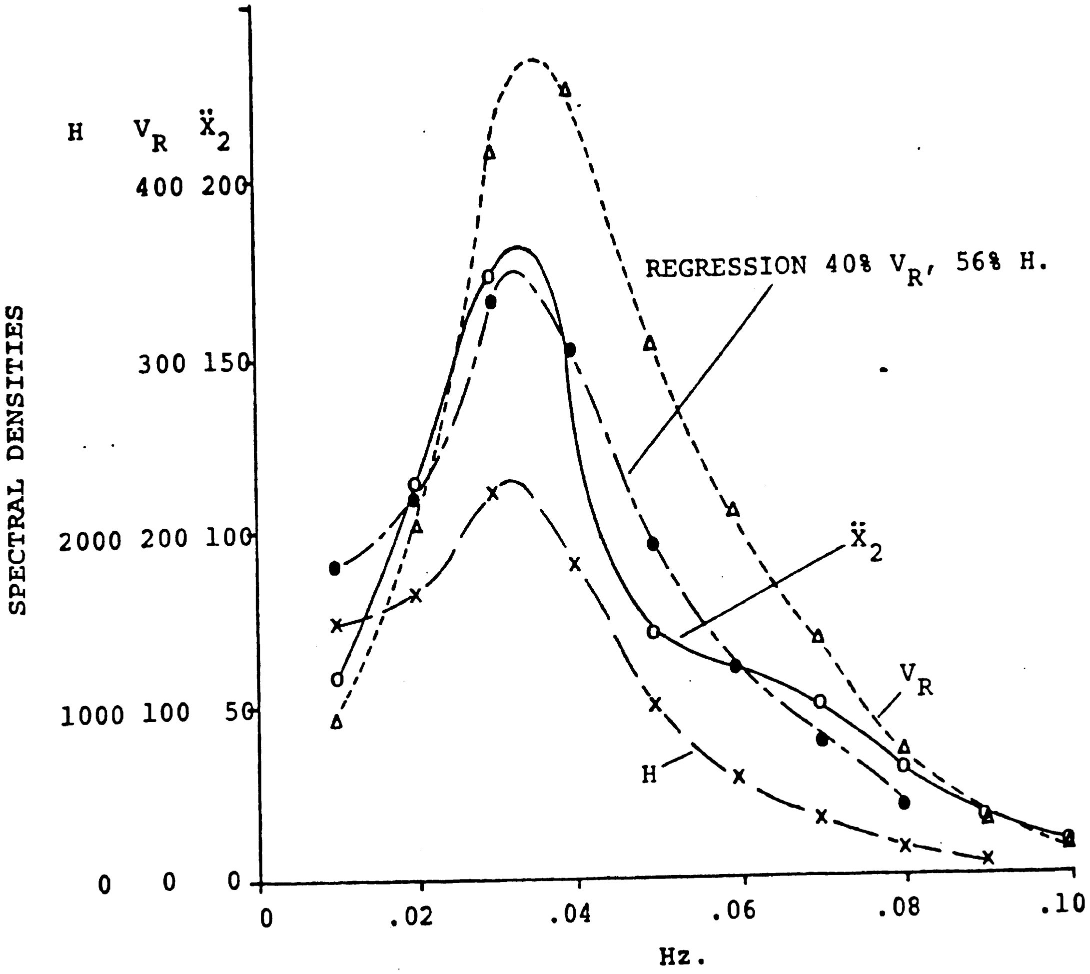


Figure 28. Spectral densities of following car acceleration, relative velocity and headway for file 14. The regression of $\ddot{X}_2$ with H and V_r is also included.

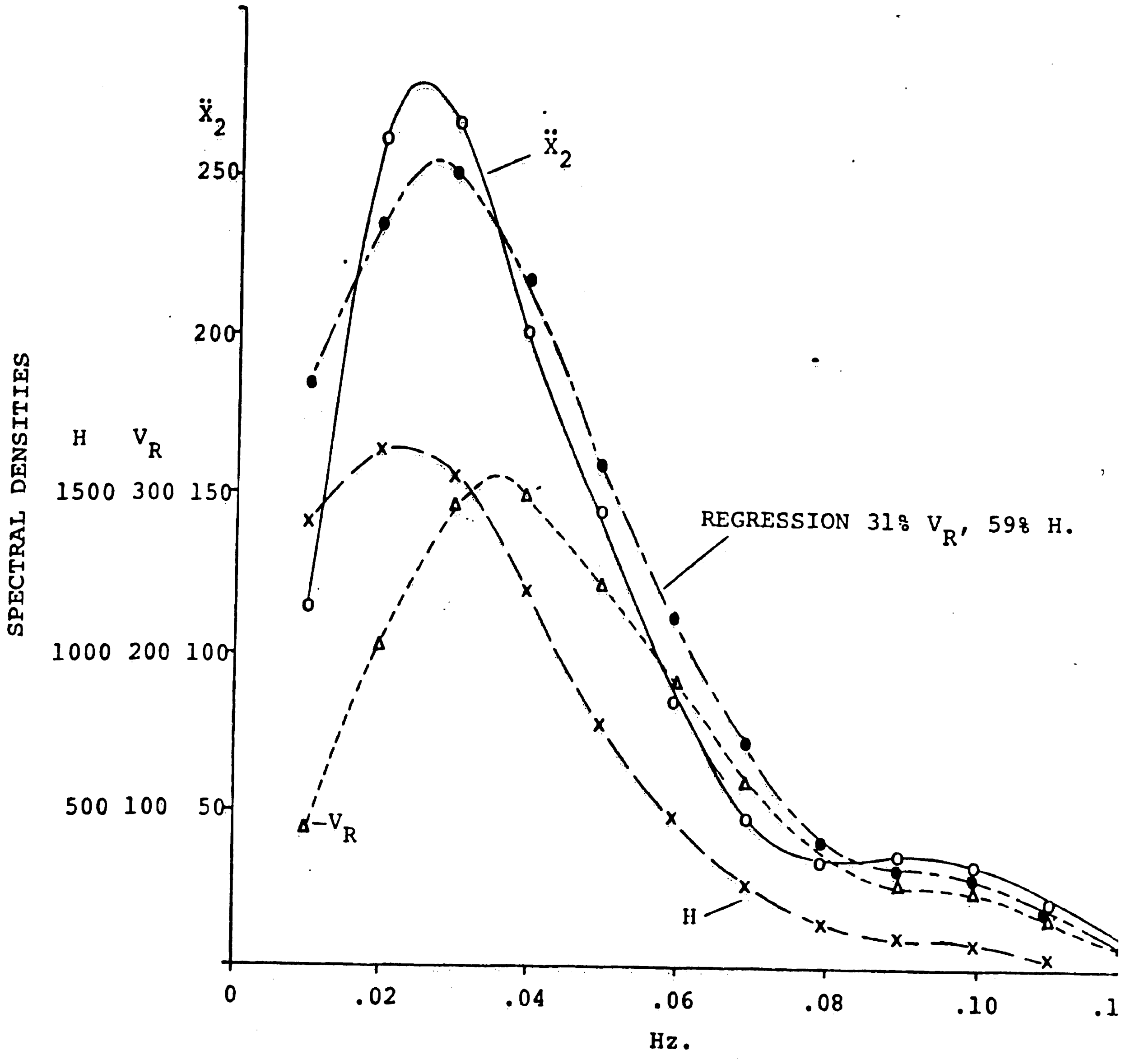


Figure 29. Spectral densities of following car acceleration, relative velocity and headway for file 17. The regression of $\ddot{X}_2$ with H and V_r is also included.

Transinformation Rates. Two values of transinformation rate (bits/sec) have been computed:

(a) Between relative velocity and following car velocity. This is based on the assumption that the driver is using relative velocity information as an input and responding with a change of his own vehicle velocity.

(b) Between lead and following vehicle velocities. This analysis is based on the assumption that the driver considers the task as one of velocity watching. Values of transinformation rate, number of categories and bits of information for relative velocity and lead car velocity are given in Table 26. The means and standard deviations are:

- Relative Velocity - following car velocity:

Transinformation rate Mean = 0.172, S.D. = .052
No. categories = 2.78, S.D. = 0.59
Bits of information = 1.45, S.D. = 0.27

- Lead Car - following car velocity:

Transinformation rate Mean = 0.184, S.D. = .062
No. categories = 5.24, S.D. = 2.64
Bits of information = 2.16, S.D. = 0.71

There is no significant difference between the transinformation rates ($p > 0.2$). However, the number of categories and bits of information in the two cases are significantly different at $p < .001$, that is, the driver is able to absolutely identify more categories of velocity of the lead vehicle than he can of the relative velocity.

Describing Functions. Using the method previously described, two describing functions have been computed:

(a) Lead car - following car velocities. In this case all 32 trials showed a gain close to unity - as would be expected if the driver is attempting to match velocities - along

TABLE 26. Measures of Transmitted Information in Car-Following.

	File No. & Condition Code	Relative Velocity - Following Car Velocity Transinformation (Bits/Sec)	No. of Categories of Relative Velocity	Bits of Relative Velocity Information	Lead and Following Car Velocity Transinformation (Bits/Sec)	No. of Categories of Lead Car Velocity	Bits of Lead Car Velocity Information
1	11YH	.117	2.38	1.25	.121	3.38	1.76
2	11N	.144	2.45	1.29	.115	2.84	1.51
3	18N	.111	2.30	1.20	.076	2.07	1.05
4	18YH	.105	2.38	1.25	.122	3.03	1.60
5	28N	.144	2.76	1.47	.263	8.96	3.16
6	28YL	.131	2.17	1.12	.091	2.45	1.29
7	21YL	.095	2.16	1.11	.069	1.93	.95
8	21N	.116	2.31	1.21	.096	2.48	1.31
9	31N	.178	3.30	1.72	.269	10.50	3.39
10	31YL	.111	2.30	1.20	.168	3.99	2.00
11	38YL	.129	1.52	0.86	.174	3.63	1.86
12	38N	.172	2.55	1.35	.193	5.83	2.41
13	18N	.134	2.88	1.53	.246	9.53	3.25
14	18YL	.130	2.70	1.43	.131	3.18	1.67
15	11YL	.209	2.76	1.47	.091	2.26	1.18
16	11N	.157	2.68	1.42	.205	5.75	2.52
17	21YH	.150	2.50	1.48	.260	7.08	2.52
18	28N	.244	2.95	1.56	.170	3.55	1.83
19	28YH	.143	2.64	1.40	.105	2.71	1.44
20	38YH	.193	2.95	1.55	.281	10.09	3.33
21	38N	.181	2.34	1.23	.223	5.58	2.48
22	31N	.179	2.46	1.30	.212	4.53	2.18
23	31YH	.213	2.80	1.49	.218	6.40	2.68
24	48YH	.254	3.41	1.77	.272	9.47	3.24
25	48N	.276	3.61	1.85	.221	5.39	2.45
26	41N	.279	5.20	2.38	.171	3.55	1.83
27	41YH	.153	3.18	1.67	.222	6.72	2.75
28	21N	.258	3.03	1.63	.199	4.78	3.26
29	41N	.255	3.18	1.67	.255	8.54	3.09
30	41YL	.200	2.98	1.57	.197	4.76	2.25
31	48YL	.199	2.81	1.49	.191	4.01	2.00
32	48N	.139	2.69	1.42	.263	9.05	3.18

with an approximately constant time delay. The describing function is of the form,

$$\frac{\dot{X}_2(j\omega)}{\dot{X}_1(j\omega)} = Ke^{-j\omega\tau}$$

where $K \approx 1$ and τ is the delay time (sec). Phase lags for eight trials of one subject are shown in Figure 30, where it is seen that the phase lag (degrees) increases approximately linearly with frequency, implying a constant lag time. (This statement is generally true up to the bandwidth of control of the driver, i.e., approximately 0.06 Hz.) Phase lags for all four subjects were approximately 2 sec when averaged over the 8 trials.

(b) Relative velocity - following car velocity. Typical magnitude and phase plots are shown in Figures 31 to 36 and Figures 37 and 38. All data points are included and those having coherence greater than 0.5 are indicated with an X. (This means that at least 70% of variance is accounted for, at the particular frequency, by the linear describing function analysis.)

Comparison of Describing Functions Derived From Relative Velocity and Headway as Input. In the experiment, both relative velocity and headway were recorded. It should be possible to obtain the describing function using either of these as input and the resulting describing functions should be simply related by

$$\frac{\dot{X}_2(j\omega)}{V_r(j\omega)} = \frac{1}{j\omega}\left[\frac{\dot{X}_2(j\omega)}{H(j\omega)}\right]$$

Empirically, it is not easy to obtain accurate describing functions with H as input, since the bandwidth of H is generally smaller than that for V_r and hence, for a given record length, the coherences will be lower with H than V_r. Generally then, relative velocity should be used as the input in determining

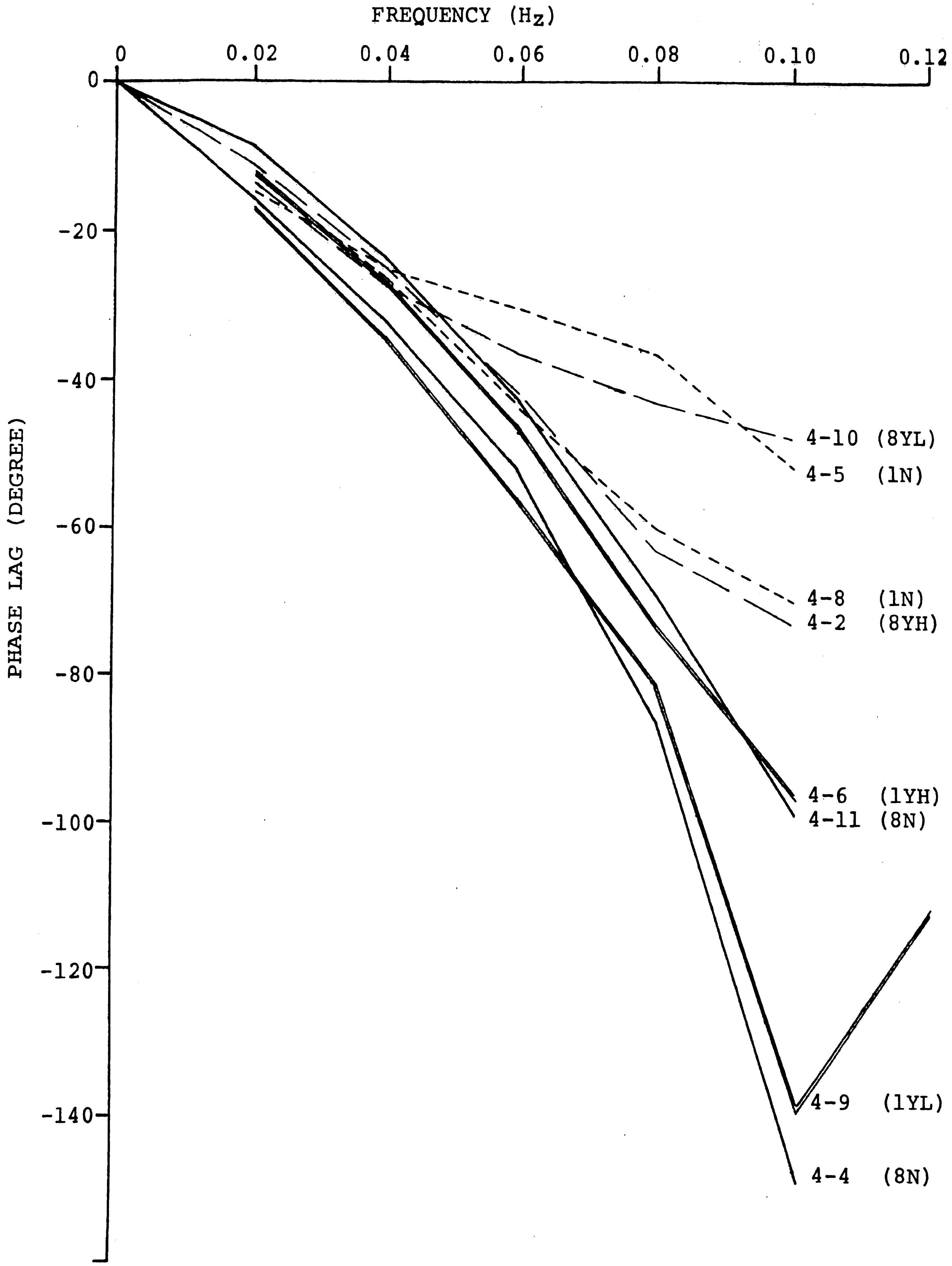


Figure 30. Phase lags for the lead car/following car velocity describing function. Subject 4.

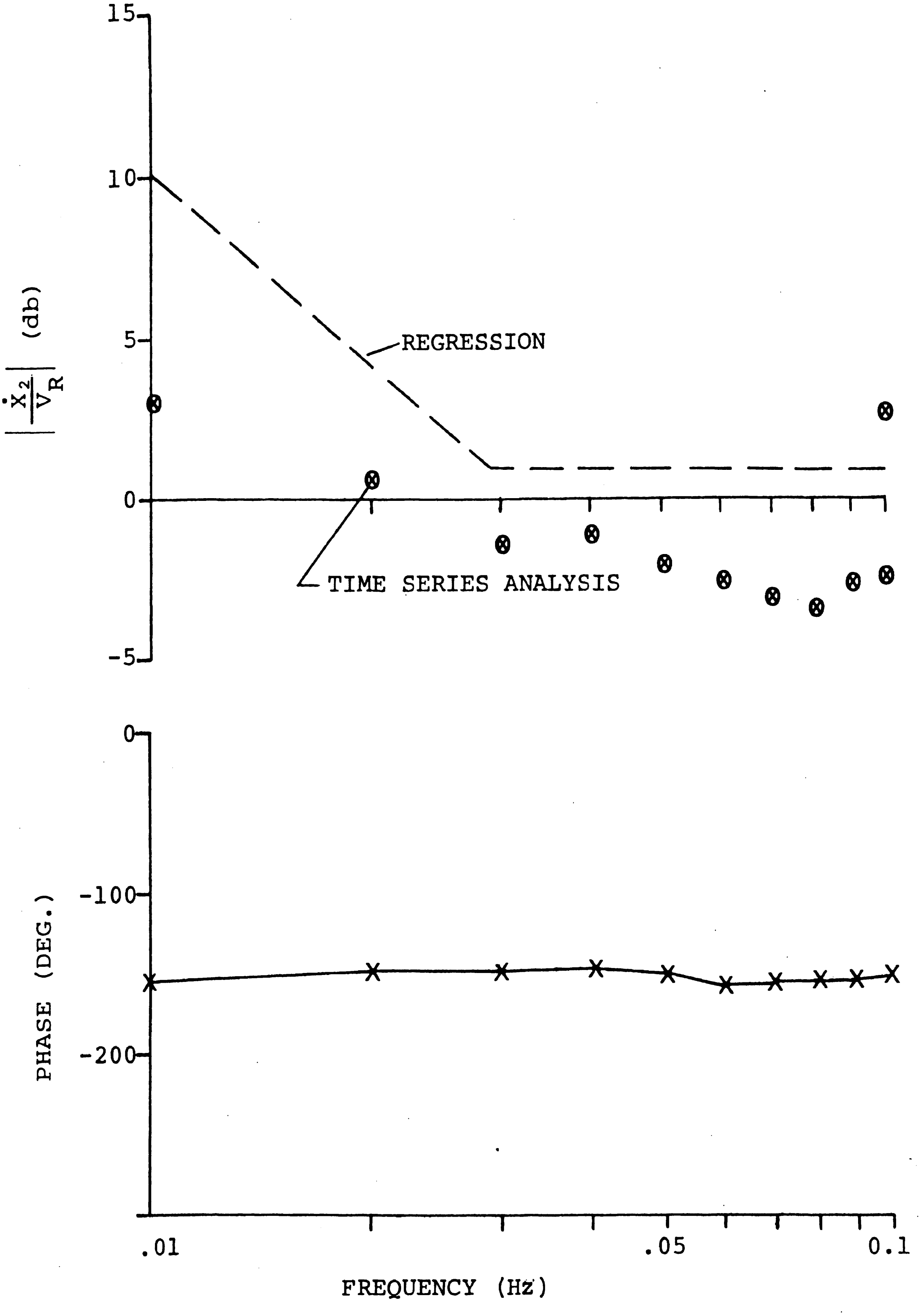


Figure 31. Following car velocity/relative velocity describing functions showing drivers gain and phase as a function of frequency (File 3).

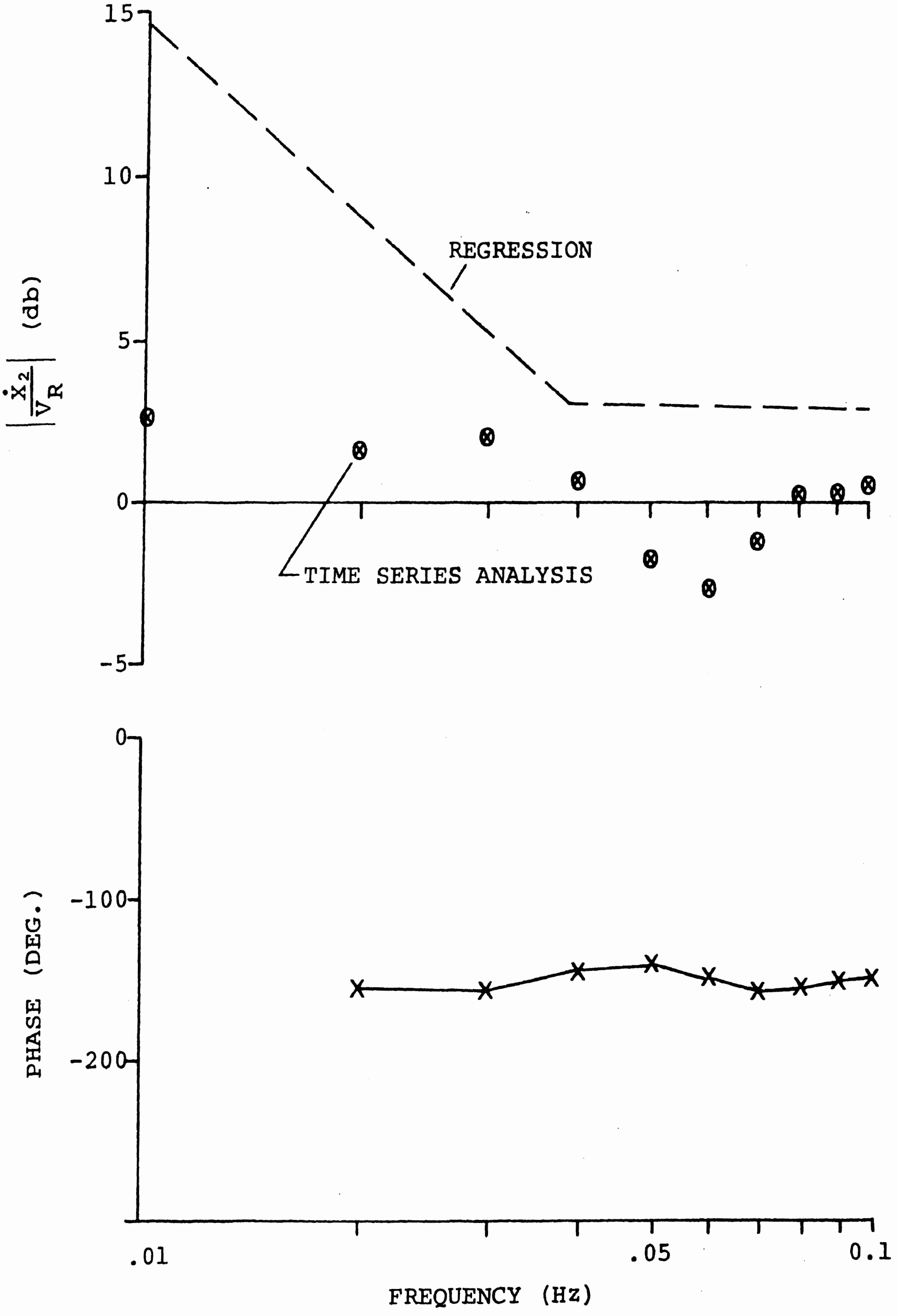


Figure 32. Following car velocity/relative velocity describing functions showing drivers gain and phase as a function of frequency (File 4).

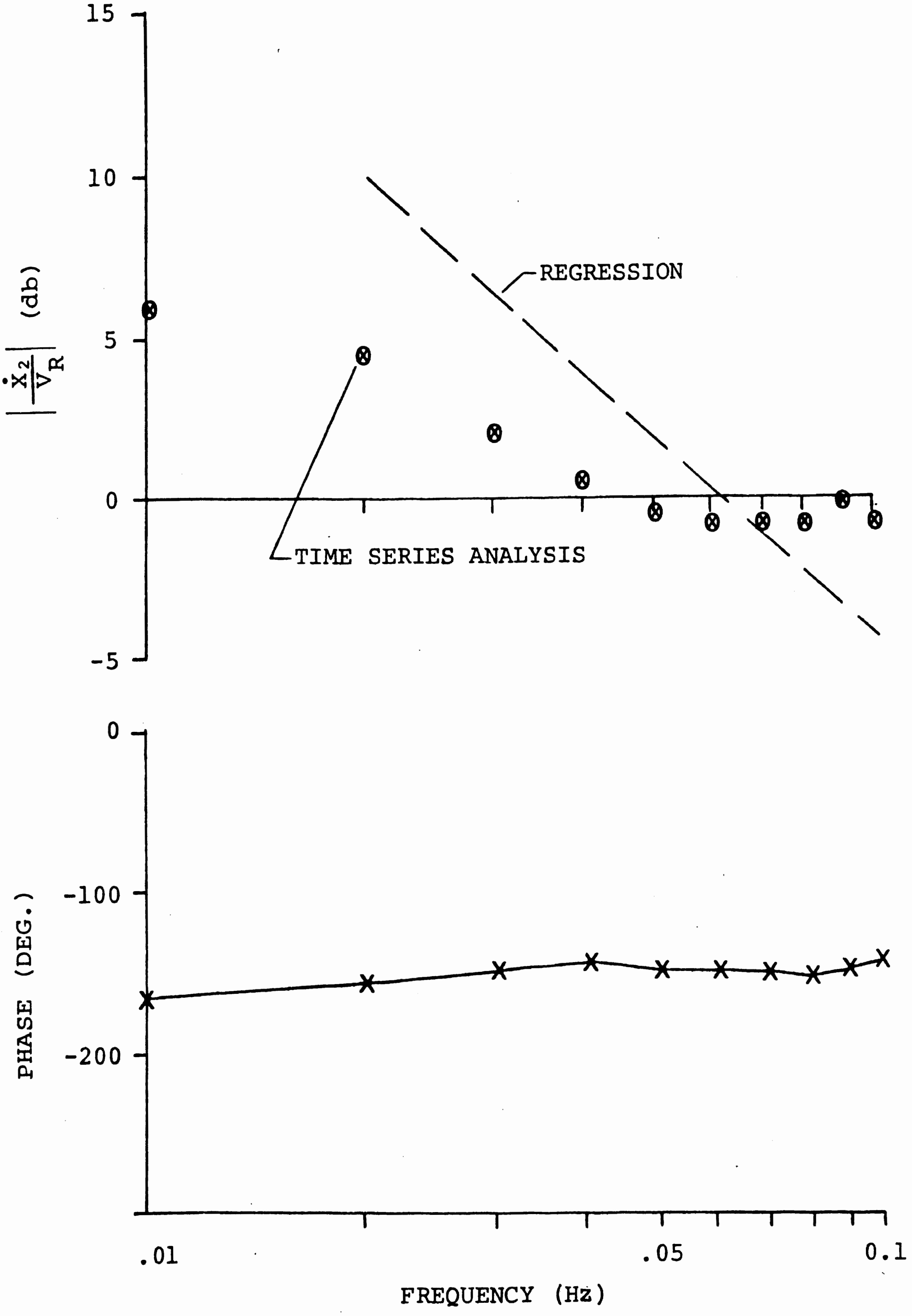


Figure 33. Following car velocity/relative velocity describing functions showing drivers gain and phase as a function of frequency (File 1).

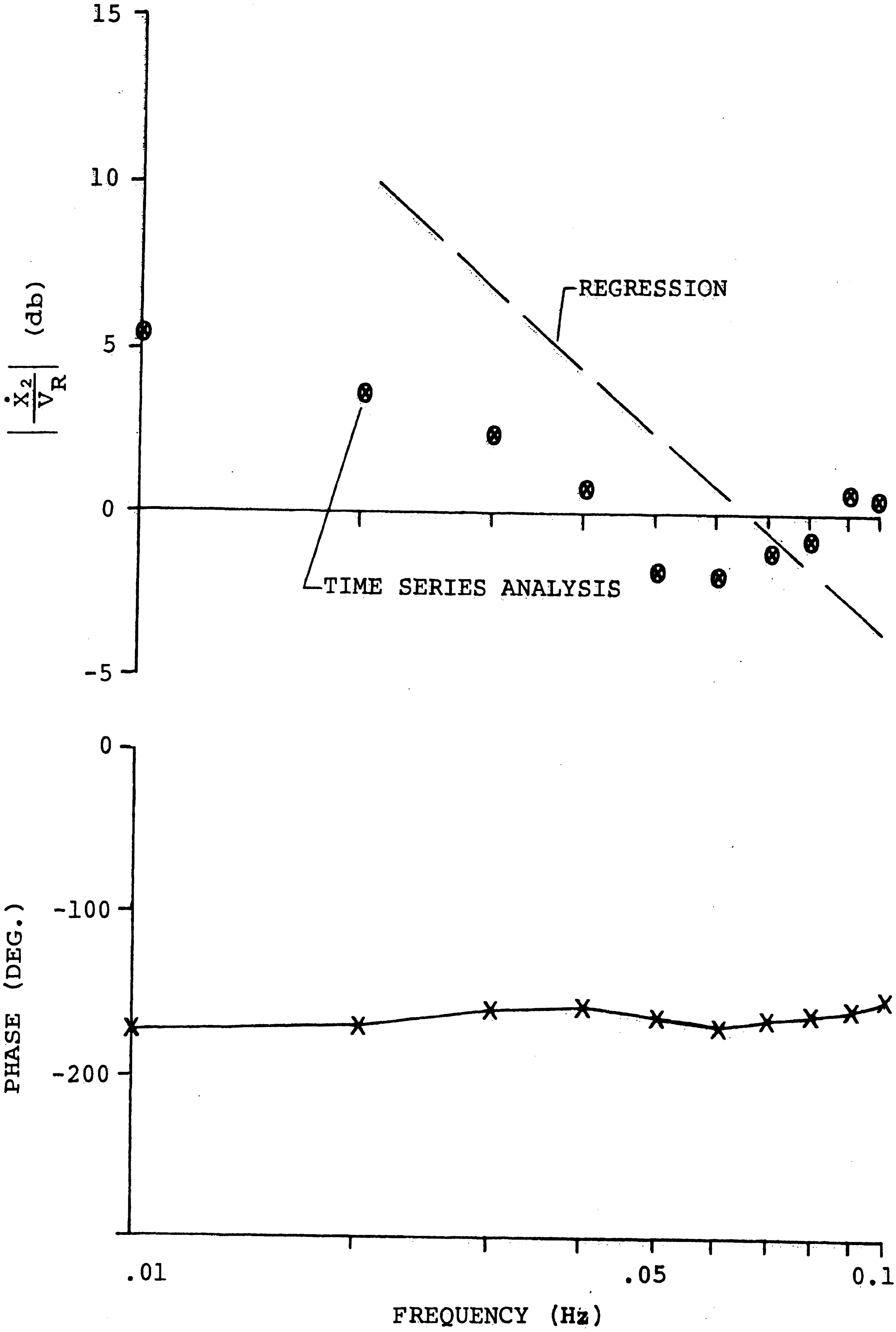


Figure 34. Following car velocity/relative velocity describing functions showing drivers gain and phase as a function of frequency (File 2).

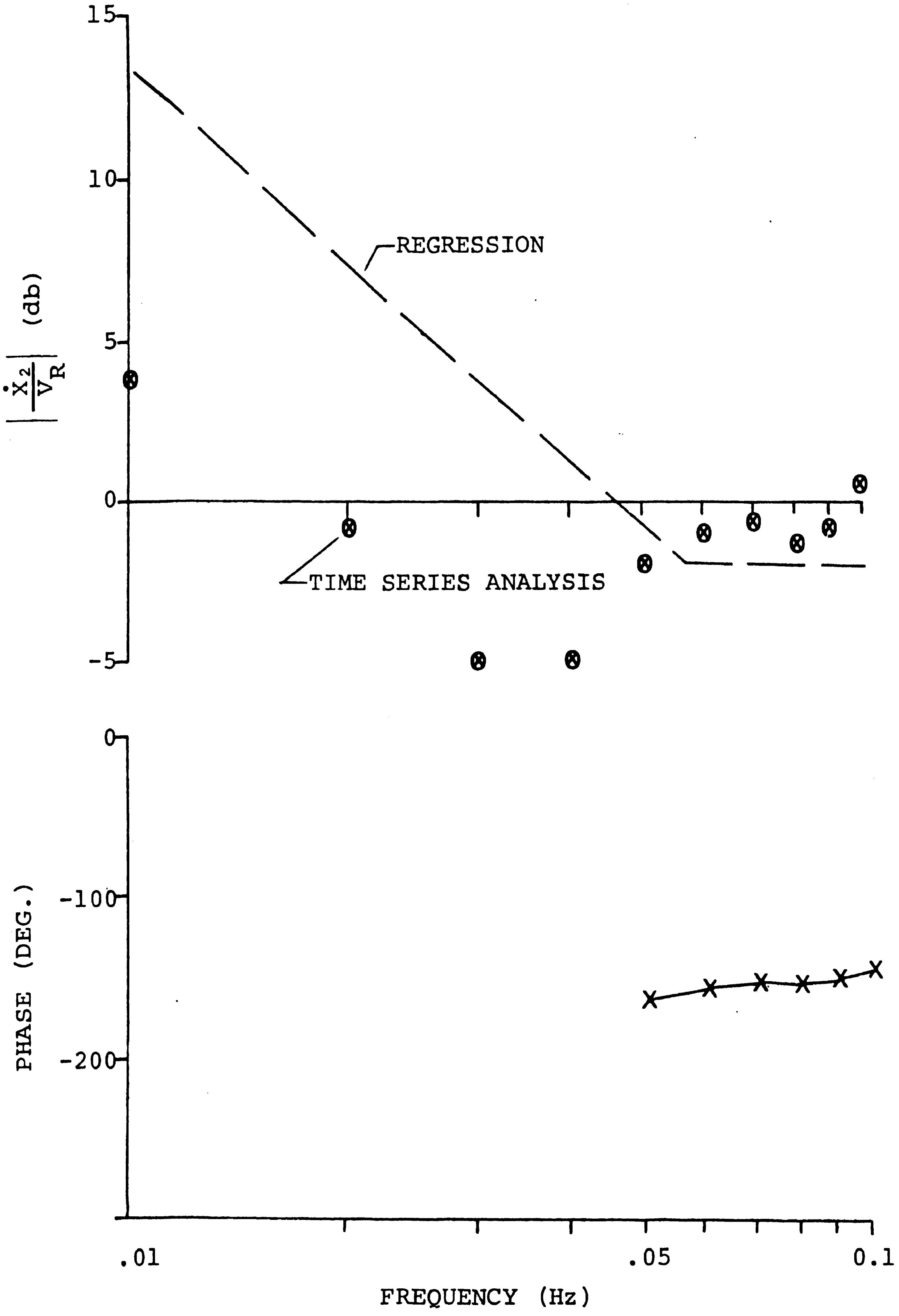


Figure 35. Following car velocity/relative velocity describing functions showing drivers gain and phase as a function of frequency (File 6).

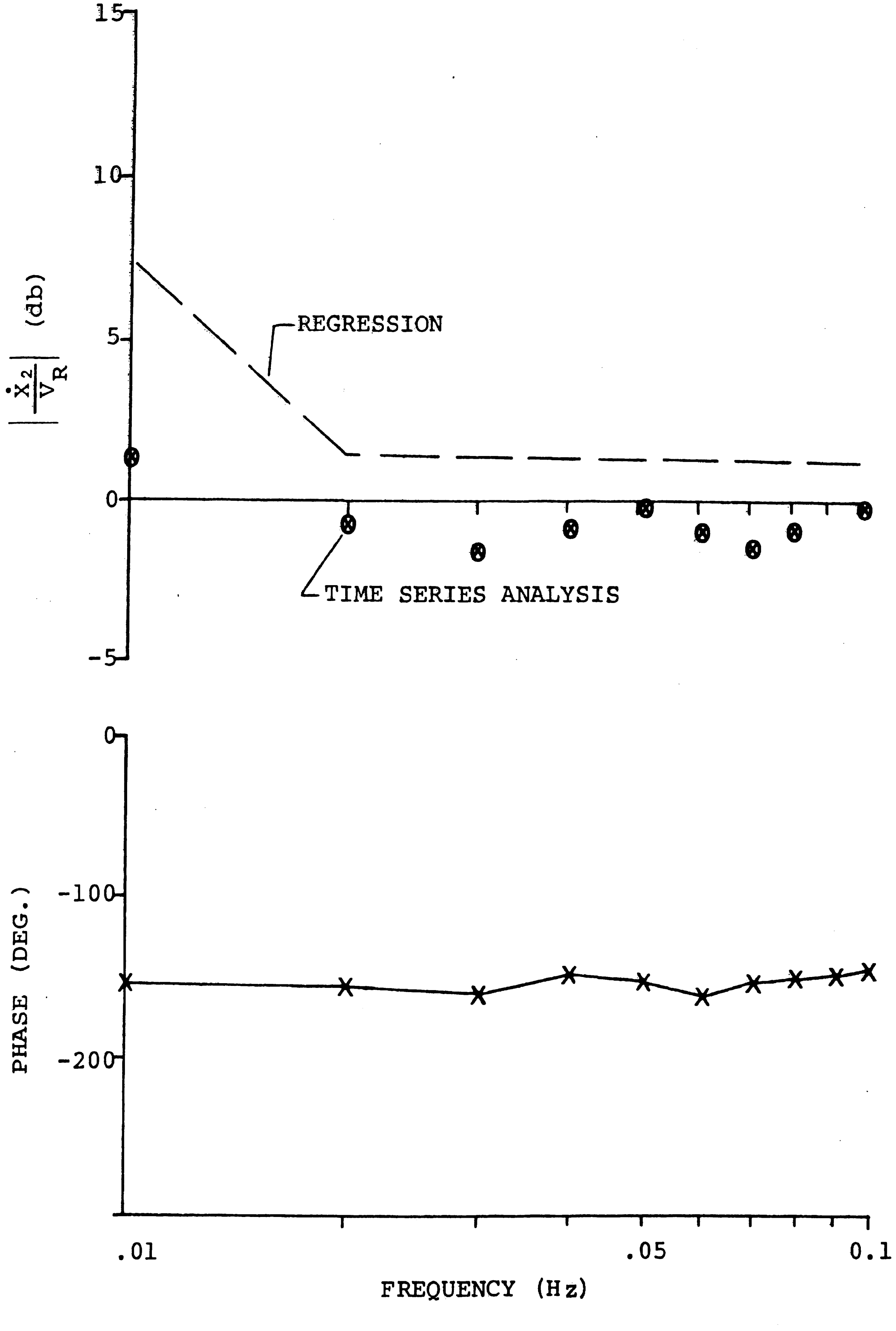


Figure 36. Following car velocity/relative velocity describing functions showing drivers gain and phase as a function of frequency (File 7).

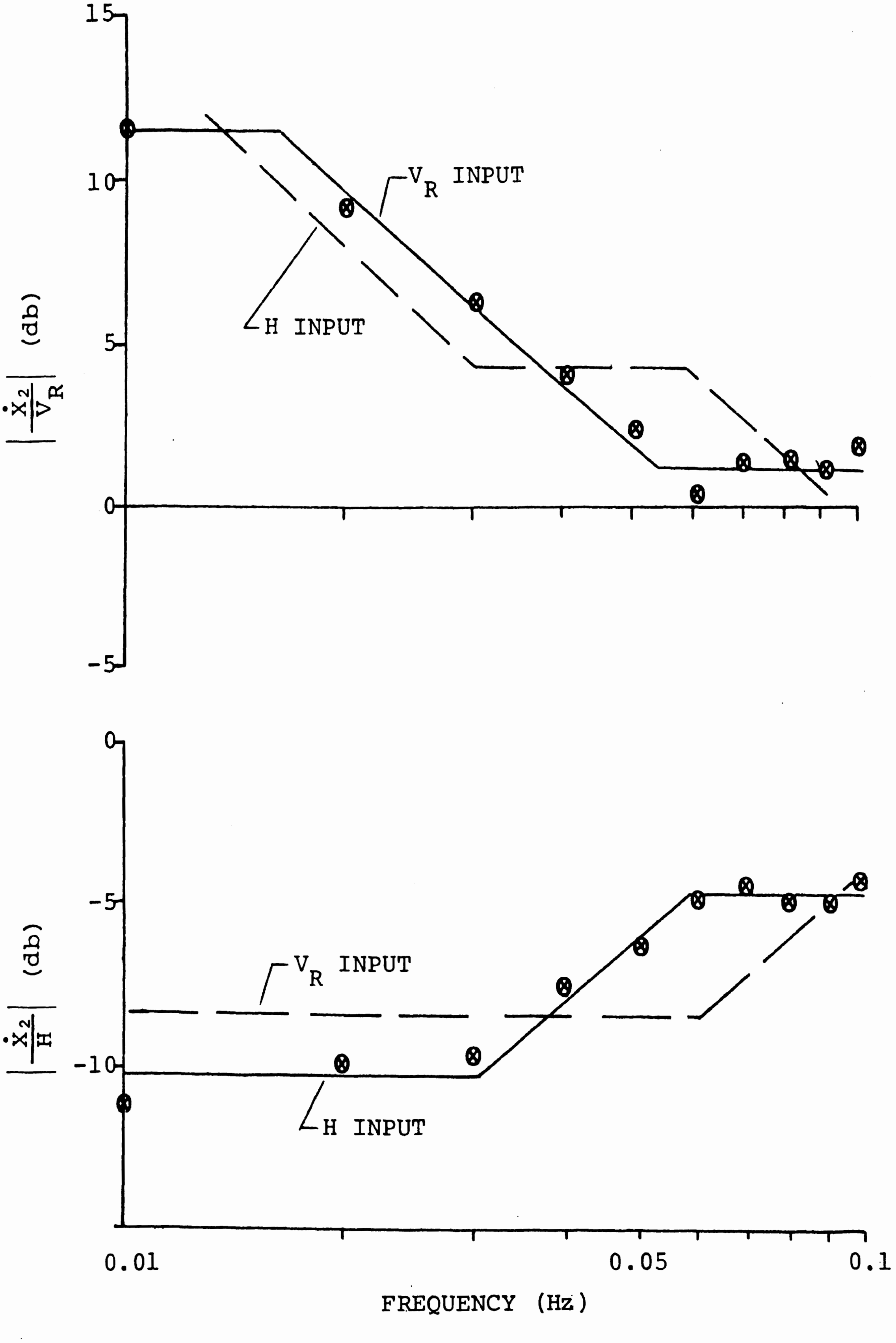


Figure 37. Describing functions derived using H and V_R as inputs and a comparison between these (File 5).

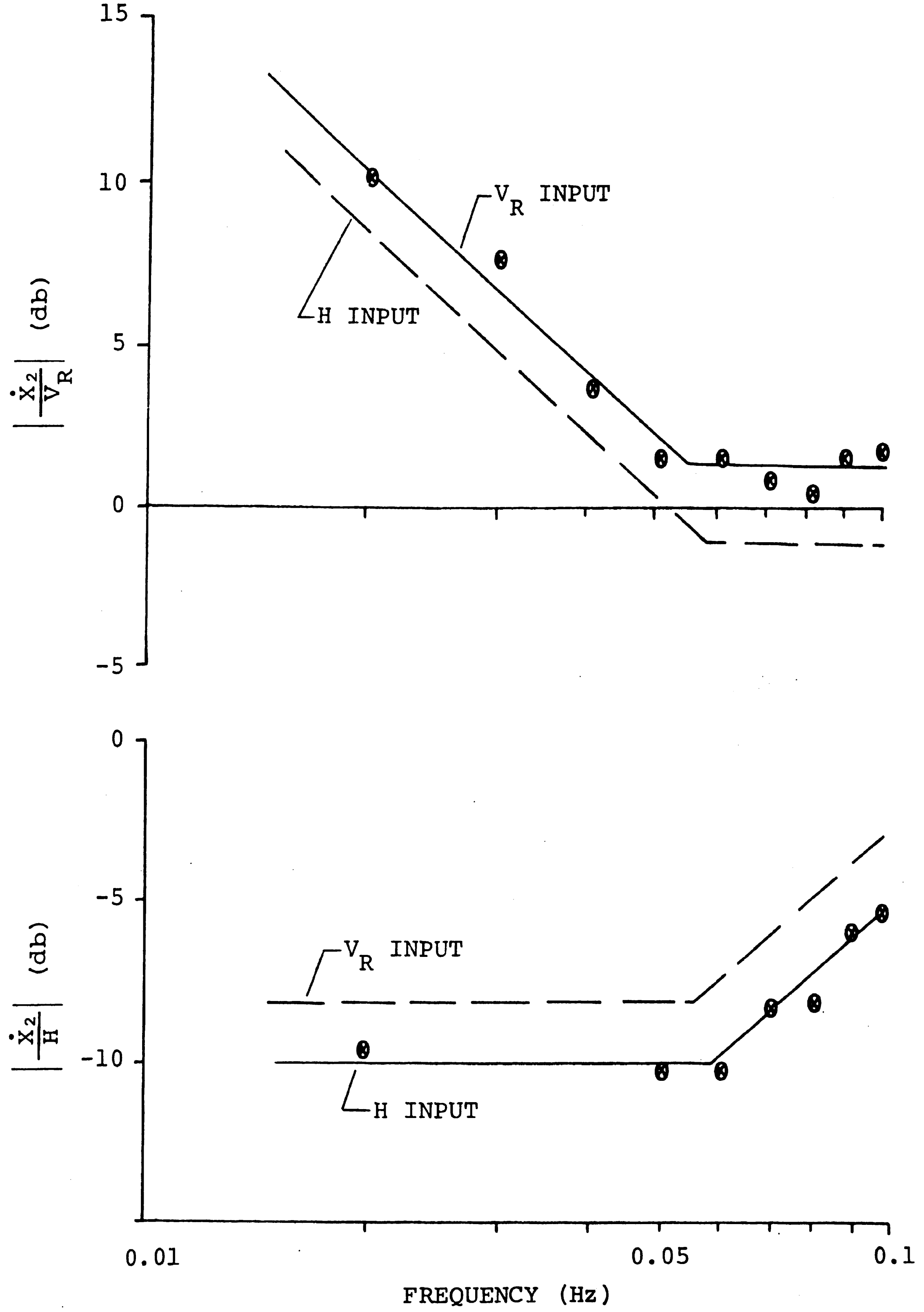


Figure 38. Describing functions derived using H and V_R as inputs and a comparison between these (File 24).

the describing function.

A comparison is given here for Files 5 and 24, which produced coherences > 0.5 for both V_r and H as inputs. The experimentally obtained gain plots are shown in Figures 37 and 38, for the two inputs. The corresponding approximate describing functions are:

File 5 (i) with V_r as input;

$$\left|\frac{\dot{X}_2(j\omega)}{V_r(j\omega)}\right| = \frac{3.76(1+3.0j\omega)}{(1+9.95j\omega)} \simeq \frac{0.38}{j\omega}(1+3.0j\omega)$$

which gives

$$\left|\frac{\dot{X}_2(j\omega)}{H(j\omega)}\right| = 0.38(1+3.0j\omega)$$

(ii) with H as input,

$$\left|\frac{\dot{X}_2(j\omega)}{H(j\omega)}\right| = \frac{0.31(1+5.31j\omega)}{(1+2.74j\omega)}$$

or

$$\left|\frac{\dot{X}_2(j\omega)}{V_r(j\omega)}\right| = \frac{0.31(1+5.3j\omega)}{j\omega(1+2.74j\omega)}$$

A similar analysis for file 24 gives the equations

(i) V_r as input; $\left|\frac{\dot{X}_2(j\omega)}{V_r(j\omega)}\right| = \frac{0.4}{j\omega}(1+2.89j\omega)$

(ii) H as input; $\left|\frac{\dot{X}_2(j\omega)}{H(j\omega)}\right| = 0.32(1+2.74j\omega)$

The asymptotes of these describing functions are included in Figures 37 and 38, and it is seen that differences do exist which might lead to different interpretations of the data. In the report only data with V_r as input has been used since only in several runs were the coherences sufficiently large, with H as input, to validly determine a describing function. A possible reason for the discrepancy between the results obtained by the two inputs is that the system is not linear - in this case probably due to the large thresholds involved in detecting changes in the input variables. Graphs plotted in the relative velocity-headway space support this contention (see discussion).

Regression Analysis. Two approaches have been taken to determine the describing function.

(i) The usual method as just described wherein magnitude and phase relationships between input and output are determined,

(ii) by means of a regression analysis in which the approximate magnitude relationship was determined. This method was used so that some indication of the magnitudes of the contributions of headway and relative velocity variations, to the vehicle response, could be obtained.

It was hoped that there would be reasonable agreement between the results of the two methods; this was, in fact, not achieved in many of the trials.

The describing functions have been analyzed with $\dot{X}_2$ (following car velocity) as the drivers' response and V_r (relative velocity) as the input.

It is possible, from the digitized data, to perform a regression of the form

$$\dot{X}_2 = aH+bV_r$$

This form has been used by Rockwell and Snider (1969) (but in terms of following car acceleration, $\ddot{X}_2$). However, if comparisons are to be made with the describing function, the above form is inadequate, as there is a $\frac{\pi}{2}$ phase shift between headway and relative velocity.* Hence, a better form for regression is

$$(\dot{X}_2)^2 = a(H)^2 + b(V_r)^2 \tag{10}$$

Performing the linear operation of autocorrelation and Fourier Transformation on these quantities yields a relationship between spectral densities.

$$(G_{\dot{X}2})^2 = a(G_H)^2 + b(G_{VR})^2 \tag{11}$$

Now as $G_H = \frac{G_{VR}}{\omega}$, the above equation becomes,

$$\left|\frac{G_{\dot{X}2}}{G_{VR}}\right| = a^{\frac{1}{2}} \left[\frac{1}{\omega^2} + \frac{b}{a}\right]^{\frac{1}{2}} = \left|\frac{\dot{X}_2}{V_r}\right| \tag{12}$$

Regressions of the form

$$(\ddot{X}_2)^2 = a(H)^2 + b(V_r)^2$$

or

$$\left|\frac{G_{\ddot{X}2}}{G_{VR}}\right| = a^{\frac{1}{2}} \left[\frac{1}{\omega^2} + \frac{b}{a}\right]^{\frac{1}{2}} = \left|\frac{\ddot{X}_2}{VR}\right| \tag{13}$$

were also included in the analysis.

Now consider a describing function of the form

$$\frac{\dot{X}_2}{V_R} = \frac{K}{j\omega}(1+Tj\omega) \tag{14}$$

---

*Note that H and V_r are here assumed to be independent inputs to the driver. Also phase shifts due to the drivers' response lag are ignored. These are included in the describing function analysis.

giving

$$\left|\frac{\dot{X}_2}{V_r}\right| = K\sqrt{\frac{1}{\omega^2} + T^2} \qquad (15)$$

we see that, comparing equations (13) and (15) we have

$$K = \sqrt{a} \; ; \; T = \sqrt{\frac{b}{a}} \qquad (16)$$

Also, equation (16) applies if we have a describing function of the form

$$\frac{X_2}{V_r} = \frac{K}{j}\,(1+Tj\omega) \qquad (17)$$

or

$$\frac{\ddot{X}_2}{V_r} = \frac{K}{(j\omega)^2}\,(+Tj\omega) \qquad (18)$$

The appropriate regression to use, of equations (11) and (13), is readily chosen as the coefficients a, b must be positive. In 27 of the 32 cases studied, this condition was satisfied by only one of the two regressions; 1 case had both regressions with positive coefficients and 4 had both regressions with one negative coefficient (see Table 27).

In cases where both coefficients were positive, the percent variance accounted for by H and V_r in the regression, were calculated by the method given in Guilford (1965). These percentages, the coefficient of correlation and the coefficients of the regressions, are presented in Table 27. (The method fails if the coefficients a, b are not both positive.)

A comparison between the describing functions and the regression magnitude function is given in Figures 31-36.

DISCUSSION

Spectra. Bandwidths of following car acceleration and of

TABLE 27. Summary of Regression Data, Including Percent of Variance Accounted for by Headway and Relative Velocity, the Correlation Coefficient and the Regression Coefficients. Response Variables are Following Car Acceleration ($\ddot{x}$) and Velocity ($\dot{x}$).

	Following Car Acceleration					Following Car Velocity				
File	%VR	%H	Rc	a(H)	b(VR)	%VR	%H	Rc	a(H)	b(VR)
1. 11YH	.680	.204	.93	.00125	.17255	-.022	.951	.96	.281	-.820
2. 11N	.939	.045	.99	.00025	.165	.016	.979	.997	.173	.108
3. 18N	.999	-.086	.945	-.00012	.077	.156	.805	.976	.041	1.232
4. 18YH	1.060	-.085	.985	-.00038	.180	.153	.844	.998	.108	1.809
5. 28N	.734	.204	.961	.0095	1.615	-.027	1.018	.994	2.589	-10.246
6. 28YL	1.035	-.083	.970	-.00015	.116	.030	.969	.999	.079	.626
7. 21YL	.974	-.134	.897	-.00016	.0625	.367	.610	.985	.021	1.461
8. 21N	.724	.166	.930	.00025	.061	-.025	1.023	.999	.115	-.861
9. 31N	.075	.519	.710	.050	.525	-.007	.987	.988	7.372	-84.81
10. 31YL	1.340	-.443	.935	-.0021	.663	.709	.258	.980	.054	21.868
11. 38YL	.797	.010	.874	.00007	.320	.080	.854	.959	.267	3.281
12. 38N	1.159	-.264	.934	-.0028	1.487	.158	.842	1.00	.687	28.181
13. 18N	-.252	1.054	.870	.091	-.579	.149	.422	.690	7.724	-93.492
14. 18YL	.399	.558	.973	.0035	.060	-.320	1.288	.980	.339	-3.792
15. 11YL	.685	-.020	.769	-.00052	.200	.182	.705	.928	.066	2.763
16. 11N	.122	.685	.874	.0177	.078	.080	.803	.926	2.253	-22.36
17. 21YH	.313	.593	.940	.0160	.277	-.131	1.105	.984	1.769	-20.29
18. 28N	.787	.034	.884	.0020	.300	-.024	.951	.954	.497	-1.911
19. 28YH	.592	.274	.915	.00095	.071	-.087	1.029	.964	.287	-4.760
20. 38YH	1.086	-.093	.996	-.0048	3.128	.250	.727	.986	1.593	62.75
21. 38N	.238	-.007	.245	-.0036	2.337	.050	.583	.743	.890	40.29
22. 31N	.850	-.138	.805	-.004	1.247	.643	.346	.994	.146	39.40
23. 31YH	.870	-.093	.853	-.0014	2.472	.086	.889	.984	1.843	41.57
24. 48YH	-.053	.840	.860	.069	-.146	.059	.874	.938	4.827	-45.5
25. 48N	.312	.364	.777	.019	.199	.164	.643	.874	1.197	-5.493
26. 41N	1.017	-.068	.969	-.00115	.332	-.114	1.011	.935	.398	-.977
27. 41YH	.398	.491	.930	.0166	.0722	.192	.547	.825	2.550	-19.29
28. 21N	.935	.038	.983	.00083	.347	-.036	1.033	.998	.452	-1.463
29. 41N	-.085	.865	.855	.087	-.143	.407	.153	.680	4.42	-29.48
30. 41YL	.402	.264	.770	.0155	.191	.051	.912	.978	.953	-3.952
31. 48YL	.791	.057	.903	.0035	.282	-.073	.784	.804	.498	-1.551
32. 48N	.071	.531	.717	.029	.067	.194	-.019	.094	1.716	-10.99

relative velocity are similar (mean values of 0.092 and 0.096 Hz respectively) possibly indicating the major effect of relative velocity on response acceleration (or alternatively the effect of headway chnages on response velocity, depending on which output/input pair is being used by the driver). Bandwidth of headway changes is lower at 0.06 Hz, a result which is expected as headway change is the time integral of relative velocity.

The spectra show close to zero variance in each of the variables above a frequency of 0.1 Hz. (The spectral density is essentially an analysis of variance by frequency and the area under the curve is equal to the mean-square value.) Longitudinal control of the vehicle is of a much lower frequency nature than lateral control in which bandwidths may be up to 1 Hz (Shaw, 1973). The low bandwidths are probably due to a combination of:

1. The longitudinal dynamics of the vehicle do not allow higher frequency control.
2. There are long delay times due to detection of changes in headway and relative velocity (Hoffmann, 1968).

The data of Torres (1970) on freeway driving shows a peak in the acceleration spectrum below 0.06 Hz, which is comparable with the value obtained in this experiment, but also a second smaller peak at about 0.2 Hz. This dual peak spectrum may indicate a dual mode form of control (maybe on headway and relative velocity) as has been found by McLean and Hoffmann (1972) in the lateral control of a vehicle.

<u>Information Measures</u>. As mentioned in the results, there is no significant difference between the rate of transmission of information whether the input is considered as the lead vehicle velocity or the relative velocity. The highly significant difference occurs in the number of categories of these variables that can be absolutely identified in this car-following situation. Part of this may be due to the range of lead

vehicle velocity being greater than that for relative velocity, (approximately 48 ft/sec) but this cannot account for all the observed difference in sensitivity. It is apparent that even under the dim lighting conditions of the simulator, the driver could obtain more information about the lead car velocity than he could about the relative velocity. This may not necessarily be true of real driving, but may be worth further investigation as it does have implications for the feasibility and design of inter-vehicle velocity communication displays.

Previous work on the perception of relative velocity shows reasonable agreement with results obtained here. Olson et al. (1961) obtained 1.05 and 1.38 bits of information at 0.2 and 0.1 mile headway respectively. For the 7-second viewing time used, these correspond to transinformation rates of 0.15 and 0.2 bits/sec. Darroch and Rothery (1971) present the coherence function for one subject. The transinformation rate has been calculated from this figure and is found to be approximately 0.17 bits/sec. Approximately three categories of relative velocity could be discriminated, i.e., about 1.6 bits of information. The headway in this case was about 60 feet. Figure 39 includes the data from the present experiment as well as that of Olson et al. (1961) and that calculated from Darroch and Rothery (1971).

The dominant feature of the data presented in Figure 39 is the small number of categories of relative velocity that are identified in this car-following experiment. Two categories are necessary for making the decision of whether the headway is increasing or decreasing, leaving only a single category, at most, in which to place the relative velocity magnitude. This appears rather difficult to accept in view of the fact that drivers can readily scale relative velocity, providing the threshold is exceeded (see Experiments 2 and 3). The simplest explanation in this case is probably that, in a car-following

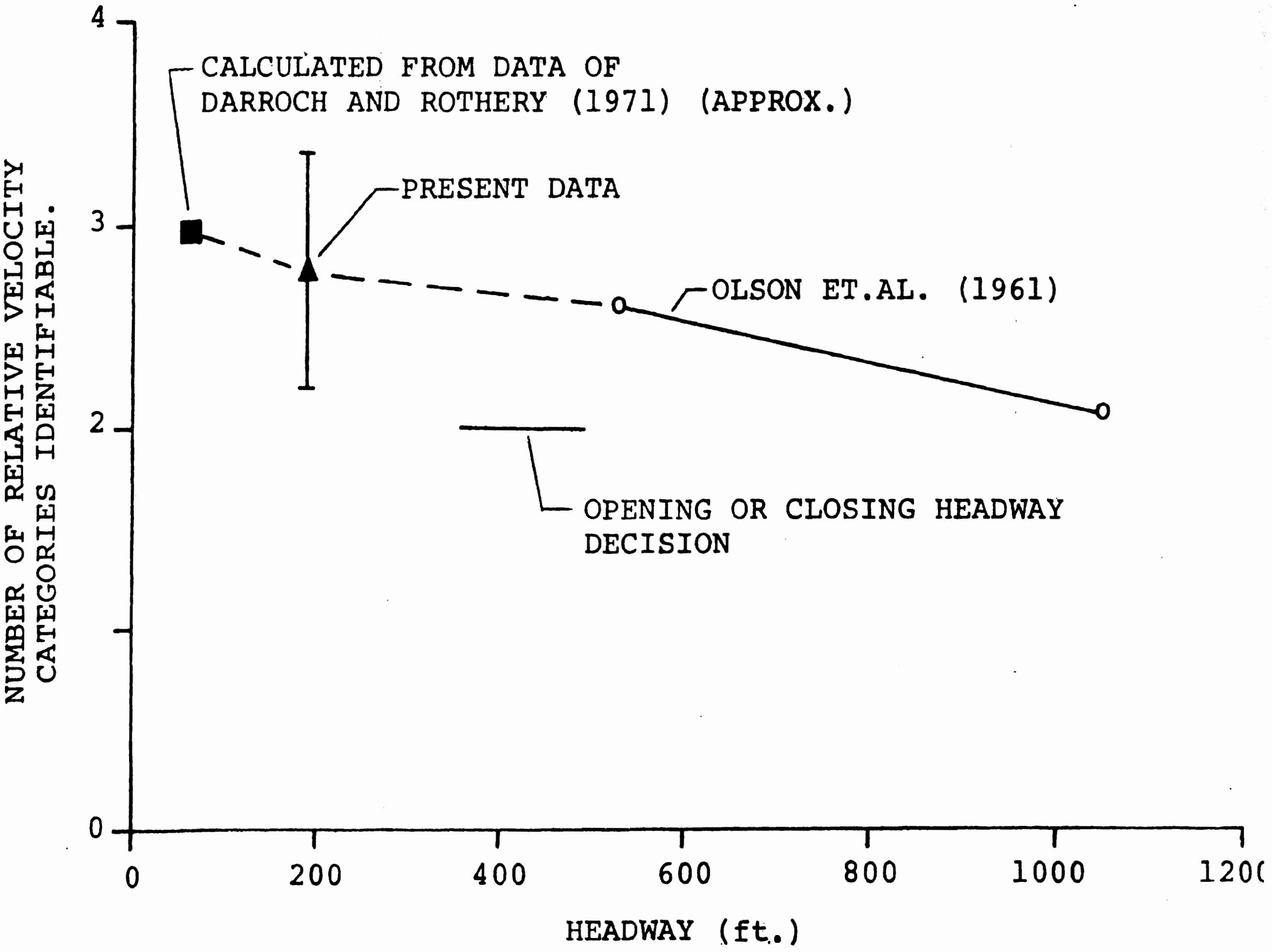


Figure 39. Number of categories into which relative velocity can b(absolutely identified. Results from Experiment I and data of Olson et al. (1961) and Darroch and Rothery (19

situation, the following driver makes little attempt at scaling the relative velocity but responds with braking or accelerator movements upon detection of a change in headway or of a relative velocity. Only when the relative velocity is large will he make a control response which is scaled to the magnitude of the relative velocity.

Describing Functions. Generally, at frequencies greater than 0.05 Hz, the describing function is of the form

$$\left|\frac{\dot{X}_2(j\omega)}{V_r(j\omega)}\right| = K_1 = \text{const} \qquad (17)$$

At frequencies less than 0.05 Hz, the describing functions often show the form (12 of the 32 trials)

$$\left|\frac{\dot{X}_2(j\omega)}{V_r(j\omega)}\right| = \frac{K_2}{j\omega} \qquad (18)$$

which is equivalent to

$$\left|\frac{\ddot{X}_2(j\omega)}{V_r(j\omega)}\right| = K_2 \qquad (19)$$

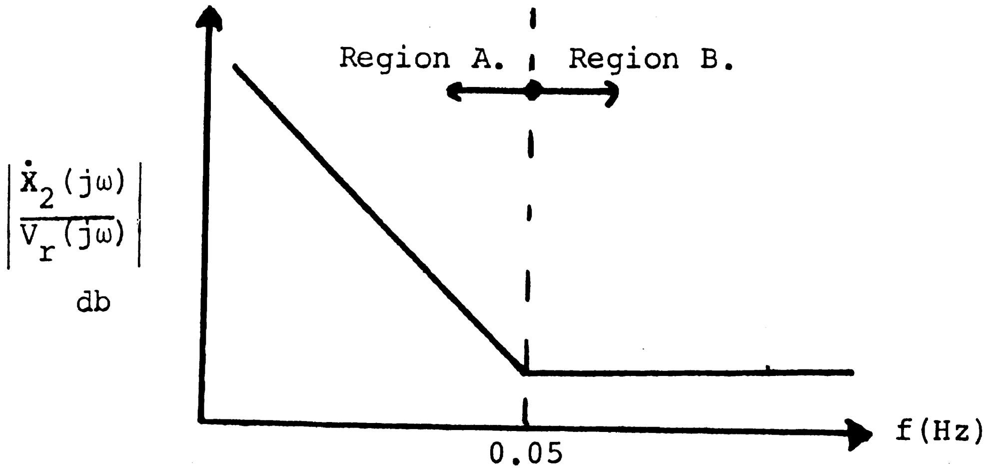
or

$$\left|\frac{\dot{X}_2(j\omega)}{H(j\omega)}\right| = K_2 \qquad (20)$$

In these 12 trials, the describing function over the computed range is given approximately by

$$\left|\frac{\dot{X}_2(j\omega)}{V_r(j\omega)}\right| = \frac{K}{J}(1+Tj\omega) \qquad (21)$$

As a basis for discussion, consider the most commonly occurring form of describing function (see Figures 37 and 38).



Region A. There are three possible input/output pairs represented by equations 18, 19 and 20. The most likely one of these to be used by the driver is equation (20), that is, a velocity response to change in headway. The reasons for this are:

- At low frequencies the relative velocities are likely to be small and, hence, may not be available as a driver input (see also the section on relative velocity-headway space).
- A human can operate more effectively as a simple gain (as in equation 20) than as an integrator, as in equation (10).

Region B. The only possible alternative to equation (17) in this region is that of an acceleration response to a relative acceleration. It is doubtful that a human has the perceptual mechanisms to sense relative acceleration via the visual system. Hence, the likely mechanism of longitudinal control in this frequency range is a velocity response to a relative velocity input.

The conclusion of this analysis is that the driver's response is that of his vehicle's velocity, not acceleration, as has been generally assumed in car-following models. This conclusion must, however, be viewed with some caution at this time since,

- More precise data are required.
- The data were collected in a simulator, which did not provide any following-car acceleration cue to the driver (other than auditory cues).

As mentioned earlier, the interpretation of the data may be dependent on whether the headway or relative velocity was used as an input variable in the computations. If we consider, for example, the data of Figure 37 derived from the headway input, three regions of control may be defined. On the basis of the reasoning used earlier, these are likely to be:

$f \leq .03$ Hz; $\dot{X}_2$ response to H input.
$.03 \leq f \leq .058$ Hz; $\dot{X}_2$ response to V_r input.
$f \geq 0.058$ Hz; $\ddot{X}_2$ response to V_r input.

In this case a region with a stimulus/response pair the same as that of the usual car-following models is found to exist.

A feature common to all 32 trials in Experiment 1 was that the phase lags were close to -150° and varied little with frequency. These phase lags did not correspond to those associated with describing functions of the form of equation (21) and would require the addition of extra phase terms to the describing function to account for them. One of these would be $e^{-j\omega\tau}$ to describe the reaction time which here is about 2 secs.

Regression Analysis. In general, the describing functions derived from the regression analysis were not in particularly good agreement with those obtained by time-series analysis. The reason for this is apparent. In the regression analysis, the describing function magnitude was limited to one of two forms (equations 11 and 13), a restriction which does not exist in the time-series analysis. It is, however, possible in a number of cases to obtain an approximate estimate of the percentage of variance in the driver's output attributable to variations of relative velocity and headway, since the describing function magnitude plots are in "reasonable" agreement. These cases are listed in Table 28 along with the major input and response variables.

These 12 cases may be summarized as:

5 cases of $(V_r, H) \rightarrow \ddot{X}_2$
6 cases of $V_r \rightarrow \ddot{X}_2$ or $H \rightarrow \dot{X}_2$
1 case of $(V_r, H) \rightarrow \dot{X}_2$

TABLE 28. Regressions Which Have Reasonable Agreement With the Corresponding Describing Function.

Subject	File	$\%V_R$	%H	Output	Stimulus-Response Pairs
1	1. 11YH	68	20	Accel.	$(V_R,H) \rightarrow \ddot{x}_2$
	2. 11N	2	98	Vel.	$H \rightarrow \dot{x}_2$ or $V_R \rightarrow \ddot{x}_2$
	3. 18N	16	81	Vel.	$H \rightarrow \dot{x}_2$ or $V_R \rightarrow \ddot{x}_2$
	4. 18YH	15	84	Vel.	$H \rightarrow \dot{x}_2$ or $V_R \rightarrow \ddot{x}_2$
	14. 18YL	40	56	Accel.	$(V_R,H) \rightarrow \ddot{x}_2$
	16. 11N	12	69	Accel.	$(V_r,H) \rightarrow \ddot{x}_2$
2	6. 28YL	3	97	Vel.	$H \rightarrow \dot{x}_2$ or $V_R \rightarrow \ddot{x}_2$
	7. 21YL	37	61	Vel.	$(V_R,H) \rightarrow \dot{x}_2$
	17. 21YH	31	59	Accel.	$(V_R,H) \rightarrow \ddot{x}_2$
3	11. 38YL	80	1	Accel.	$V_R \rightarrow \ddot{x}_2$ or $H \rightarrow \dot{x}_2$
4	25. 48N	31	36	Accel.	$(V_R,H) \rightarrow \ddot{x}_2$
	31. 48YL	79	6	Accel.	$V_R \rightarrow \ddot{x}_2$ or $H \rightarrow \dot{x}_2$

A feature of these regressions is that a given subject will, on different trials, use differing amounts of inputs from headway and relative velocity to control the vehicle (assuming that these regressions are meaningful).

The picture is somewhat simplified if the regression with the largest correlation coefficient is chosen. In this case 26 of the 32 cases are closely approximated by:

$G_{\dot{X}_2} = \sqrt{a}\, G_H$ (i.e., headway accounts for most of the variance).

or

$G_{\ddot{X}_2} = \sqrt{b}\, G_{Vr}$ (i.e., relative velocity accounts for most of the variance).

These regression are equivalent in saying (as noted earlier) that drivers are responding with a velocity to a change in headway.

The remaining 6 regressions have,

3 with both V_r and H affecting $\dot{X}_2$
1 with both V_r and H affecting $\ddot{X}_2$
2 with H dominantly affecting $\ddot{X}_2$

The last of these is a rather surprising -- and highly unlikely -- result, since it is very difficult for a human to control a system of this order.

The Headway - Relative Velocity Space. From the RMS value of relative velocity and the mean and RMS values of headway for a given trial, it is possible to determine the percentage of time over which a given boundary for detection of angular velocity is exceeded. The method assumes that:

(1) the detection value of angular velocity is fixed,
(2) the headway and relative velocity are distributed normally,

and is illustrated in Figure 40 on the data of File 28 (see Table 23). This particular subject showed a threshold of about 2.3×10^{-3} rad/sec on the scaling experiment (Experiment 2). From the line corresponding to the threshold angular velocity, the probabilities of corresponding pairs of H, V_r points are determined from tables of the normal distribution. The joint probabilities, summed over ±3 standard deviations of V_r and H, then gives the probability that the relative-velocity detection boundary is exceeded. In this case, on 22% of the trial time the boundary is exceeded.

The results of such an analysis may be useful in determining the form of control being used by the following driver.

For example, consider the data of Files 28 and 16.

(1) File 28: (93% relative velocity; 4% headway).

The detection boundary for relative velocity is exceeded only 22% of the trial time.

(2) File 16: (12% V_r, 69% H). Separate tests, using the method of Experiment 2, showed that this subject had a detection angular velocity of about 4×10^{-3} rad/sec. Analysis of the joint probabilities shows that the detection boundary for relative velocity is exceeded on only 0.38% of the trial time.

CONCLUSIONS ON DRIVERS' LONGITUDINAL CONTROL. (EXPERIMENT 1).

1. The data suggest that control actions are made when relative velocity or headway changes are detected, with very little scaling of the response to the magnitude of the stimulus input.

2. The data suggest that the driver responds with a change in his vehicle velocity to (a) changes in headway at frequencies below 0.05 Hz and (b) changes in relative velocity above 0.05 Hz.

3. An alternative method of finding the magnitude of the

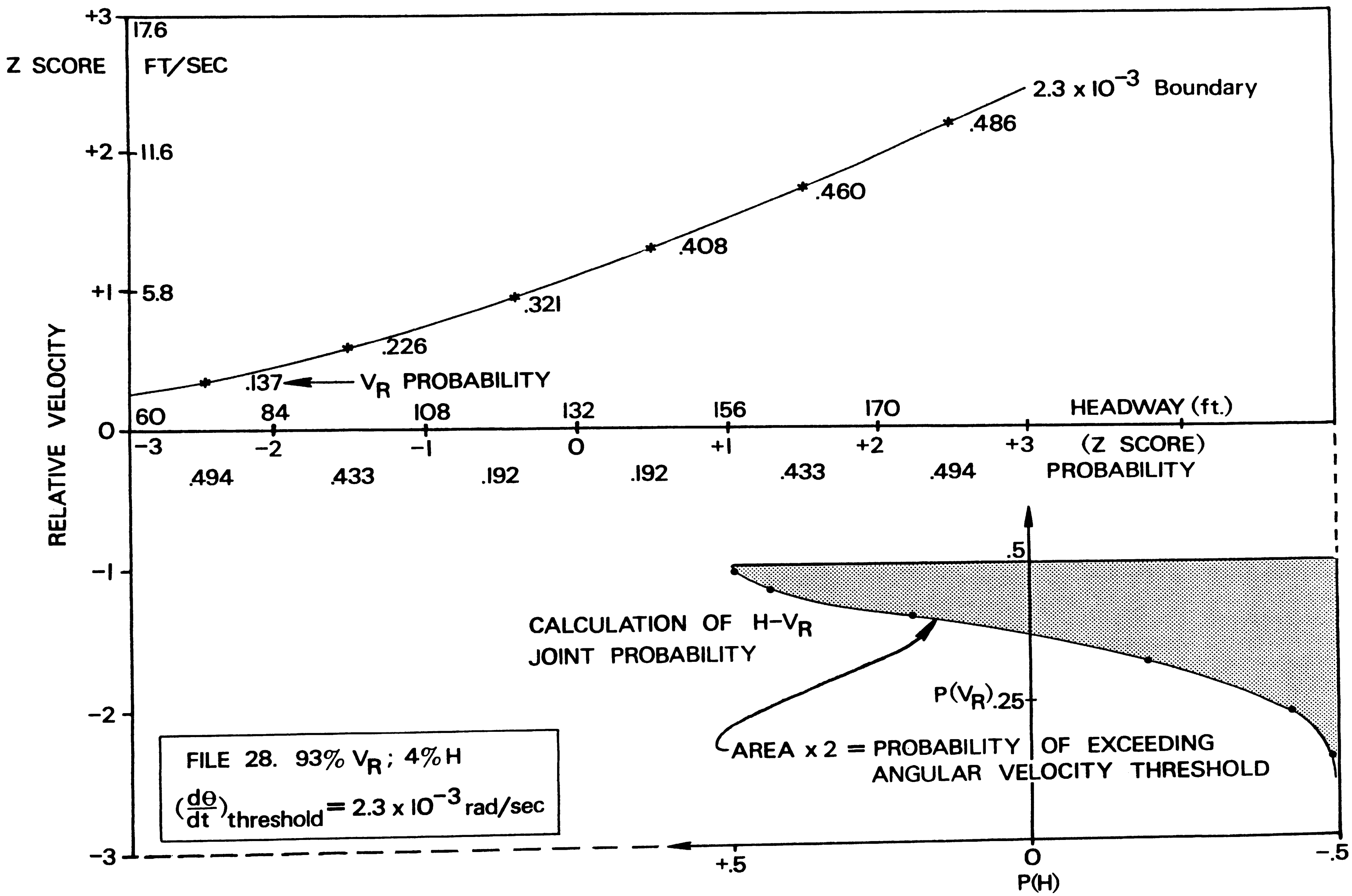


Figure 40. Method for determining probability of the driver's headway-relative velocity trajectory exceeding the threshold for detection of angular velocity.

describing function via a regression analysis provided an estimate of the amount of headway and relative velocity control being used by the driver. It was felt that the severe constraints on the method make these estimates of limited use.

EXPERIMENT 2: SCALING OF RELATIVE VELOCITY

OBJECTIVES. In the analysis of past studies presented in this report it was noted that two studies found power law exponents of approximately 1.3 in the equations relating apparent and physical relative velocity with a vehicle moving towards the observer (Semb, 1969; Hoffman, 1971). In both of these studies the observer was stationary and, hence, may have had extra cues available to him which he would not have if he were in motion, as is the case when a following vehicle is overtaking a lead vehicle. The aim of this experiment was to determine a scale of relative motion (with the observer having both relative and absolute motion) and also to investigate thresholds for relative velocity.

METHOD.

Stimulus Material. Because of the limited time available for these experiments, it was decided to limit the tests to positive relative velocity; that is, with the following vehicle approaching or overtaking the lead vehicle. This case is also of most practical significance.

Eight filmed stimuli were used in the experiment. All had a mean headway of 92 feet during the 4-second exposure and the relative velocity was closely constant during this period. The relative velocities were accurately calibrated from the film by means of a "Vanguard" film reader. The selected film strips had the angular velocities and visual angle changes given in Table 29. The relative velocity range covers the range of below threshold values to the maximum that could

TABLE 29. Mean Angular Velocity (rad/sec) and Weber Ratio of Visual Angle for the Eight Stimuli Used in Experiment 2 (Mean Headway = 22 Ft).

Stimulus Speed (Ft/Sec)	Angular Velocity (Rad/Sec)	$\frac{\Delta\theta}{\theta}$
1.77	1.29×10^{-3}	.040
3.13	2.28×10^{-3}	.073
3.95	2.88×10^{-3}	.094
7.26	5.29×10^{-3}	.187
10.67	7.77×10^{-3}	.302
14.36	10.46×10^{-3}	.454
17.80	12.97×10^{-3}	.631
23.70	17.27×10^{-3}	1.063

safely be produced without impacting the lead vehicle. In presentation to the subjects, the projector speed was accurately matched to the camera speed by use of stroboscopic equipment.

Procedure. A ratio rating method using different stimulus groups was used (Eckman, 1958). The advantage of this technique is its relative economy; both in the costs of film duplication and time taken to test subjects. The stimulus pairs used are shown in Table 30. The stimuli were ordered in this way to achieve a large range in the physical ratios of relative velocities. The sixteen comparisons were presented in random order and presented twice to each subject. There was 2 seconds of blank frame between presentation of the two stimuli being compared. The subject judged which of the two stimuli had the higher relative velocity and also the ratio of the relative velocities. Each stimulus pair was judged twice and the geometric mean ratio was used in constructing the

TABLE 30. Matrix of Comparisons Used in the Ratio-Rating Method of Ekman (1958), Showing the Velocity Ratios in the Stimulus Pairs.

		Stimulus Relative Speed Ft/Sec			
		1.77	3.95	10.67	17.80
Stimulus Relative Speed Ft/Sec	3.13	1.77	0.79	0.29	0.18
	7.26	4.10	1.84	0.68	0.41
	14.36	8.11	3.64	1.35	0.81
	23.70	13.39	6.00	2.22	1.33

velocity scale. Instructions to the subject are included in Appendix D.

RESULTS OF EXPERIMENT 2. A number of the subjects had difficulty in understanding the concepts of "ratio" and "relative speed." It was necessary to explain these concepts in detail and even then, there was some doubt that they were fully understood. The twelve experimental subjects used a very limited range of ratios in making their responses. The maximum used by any subject was 6.0 and the geometric mean maximum over all subjects was 2.9. This is to be compared with the maximum ratio of 13.39 actually presented in the stimulus films (see Table 30).

The stimulus films have since been presented to a group of 5 professional engineers; these gave a mean maximum ratio of 11.8, that is, the group familiar with the use of number and concepts of relative motion were able to more accurately estimate the approach speed ratios.

The data for subjective relative speed have been scaled and, assuming a relationship of the form of Stevens law,

$$\Psi V_r = K(V_r)^{\eta}$$

where V_r = relative speed in ft/sec.

ΨV_r = subjective relative speed in arbitrary units, the magnitude of the power law exponent (η) and the threshold speed have been determined. The threshold relative speeds (the speed at which the subjective relative speed starts to increase with physical relative speed) have been converted to threshold angular velocities by means of the equation:

$$\omega \text{ threshold} = \frac{W(V_r) \text{ threshold}}{H^2}$$

where H had a value of 92 feet in this experiment.

Results of subjective relative speed for several subjects and all subjects combined are shown in Figure 41. The conclusions are combined with those of experiment 3 following.

EXPERIMENT 3: ESTIMATION OF TIMES TO CLOSURE

OBJECTIVES. A very common type of estimation made by drivers, in a number of driving situations, is the time to closure (or the position of closure). Yet little has been reported on the study of such estimations (Farber and Silver, 1967; Björkman, 1963). This experiment is aimed at providing further information on this aspect of driver decision making. In particular, the experiment is designed to:

(1) investigate accuracy of closure time estimations as a function of relative speed, headway and stimulus presentation time.

(2) Derive a scale relating apparent and physical relative velocity from the relationship between the subjective and actual closure times.

(3) To investigate the thresholds for angular velocity, and the time required for perception of angular velocity, via the effect of stimulus presentation time on the angular velocity threshold.

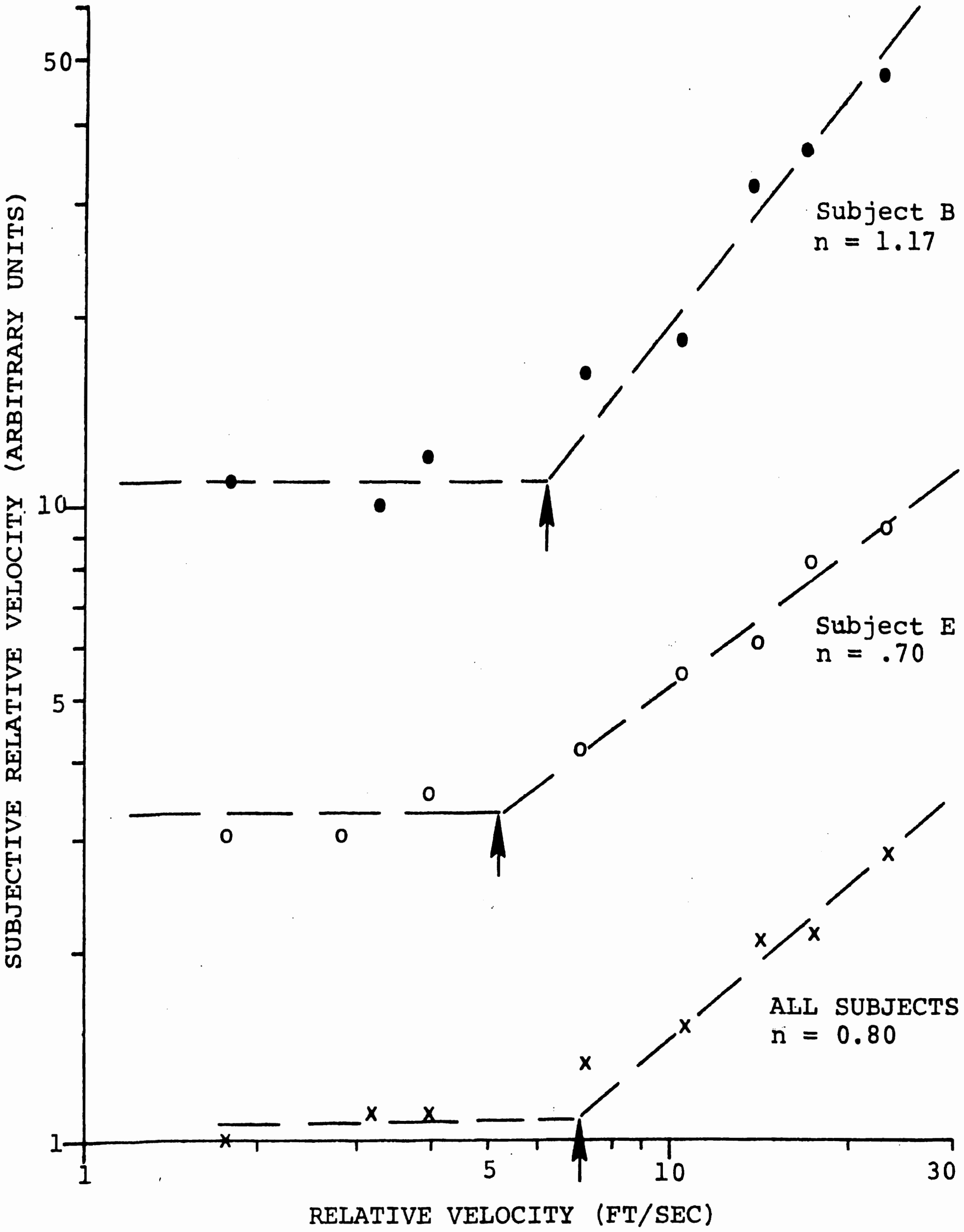


Figure 41. Results of relative velocity scaling for subjects B and E and geometric mean data over 12 subjects. The arrows mark the value taken as the threshold relative velocity.

METHOD.

Stimulus Material. Stimulus films were made, calibrated and projected as in Experiment 2.

Four relative velocities (3.41, 7.46, 9.11, 17.05 ft/sec), three final headways (62, 103, 144 ft) and four stimulus presentation times (0.68, 1.37, 2.05, 2.74 sec) were used in the experiment, making a total of 49 conditions. The angular velocities covered the range from sub-threshold to the maximum likely to be achieved in normal vehicle closure. These values, along with the actual closure times are given in Table 31. The Weber ratio of change of visual angle subtended by the lead vehicle during the stimulus presentation is presented in Table 32. Here again, the Weber ratio ranges from sub-threshold to easily detectable.

Procedure. The 48 conditions were presented in random order, with two replications of each stimulus. An electronic counter automatically started at the end of each exposure. The subject stopped an electronic timer with a response key when he estimated that closure occurred.

During the experiment, the subject heard the noise of a vehicle traveling at 50 mph. This was found necessary to eliminate disturbance through starting and stopping the projector. All trials were carried out in the one experimental session, taking a total time of approximately one hour. Instructions to the subject are included in Appendix E.

Subjects. Twelve subjects, six male and six female, were used in these experiments. They were volunteers and were paid for their participation. All subjects were used in both experiments; half the males and females carried out Experiment 2 first and the other half did Experiment 3 before Experiment 2.

The exponents and threshold angular velocities obtained in this experiment are given in Table 33.

TABLE 31. Angular Velocities (rad/sec) at the End of Exposure (Upper Entry) and Actual Times to Closure (Sec) for Four Relative Speeds and Three Final Headways Used in Experiment 3.

Headway (Ft)	Relative Velocity (Ft/Sec)			
	3.41	7.46	9.11	17.05
62	5.47×10^{-3} 18.18	11.97×10^{-3} 8.31	14.60×10^{-3} 6.81	27.4×10^{-3} 3.64
103	1.98×10^{-3} 30.21	4.34×10^{-3} 13.81	5.30×10^{-3} 11.31	9.91×10^{-3} 6.04
144	1.01×10^{-3} 42.23	2.22×10^{-3} 19.30	2.71×10^{-3} 15.81	5.07×10^{-3} 8.45

TABLE 32. Weber Ratios of Subtended Visual Angle for the Four Relative Velocities, Three Headways and Four Exposure Times Used in Experiment 3. An Asterisk Marks Those Values Likely to be Detectable (>0.12).

Headway (Ft)	Relative Speeds (Ft/Sec)			
	3.41	7.46	9.11	17.05
62	.038	.082	.101	.187*
	.075	.165*	.201*	.377*
	.113	.247*	.301*	.564*
	.151*	.330*	.403*	.754*
103	.023	.050	.060	.113
	.045	.099	.121*	.227*
	.068	.148*	.181*	.329*
	.186*	.198*	.242*	.454*
144	.016	.035	.043	.081
	.032	.071	.087	.162*
	.049	.106	.130*	.243*
	.065	.142*	.173*	.324*

TABLE 33. Power Law Exponents and Angular Velocity Thresholds for 12 Subjects in Experiment 2.

Subject	Power Law Exponent	Angular Velocity Threshold $(\text{Sec})^{-1} \times 10^3$
A	.88	4.5
B	1.17	4.4
C	-	5.3
D	.75	3.9
E	.70	7.5
F	.85	5.8
G	.70	3.9
H	.76	6.2
I	.76	3.4
J	.73	6.2
K	-	6.6
L	.76	6.1

In only 10 of the 12 subjects was it possible to obtain reasonable estimates of the exponent. In the other two cases the scatter was very large. The geometric mean value of the exponent was 0.80 and the arithmetic mean angular velocity threshold was 0.0052 rad/sec.

Data for three professional engineer subjects are shown in Figure 42. It is apparent from this graph that much larger response ratios are being used.

RESULTS OF EXPERIMENT 3. As noted earlier, the task of the subject in this experiment was to attempt to estimate the time at which closure between the lead vehicle and his own vehicle would occur. In performing this task there were two distinct groups of subjects.

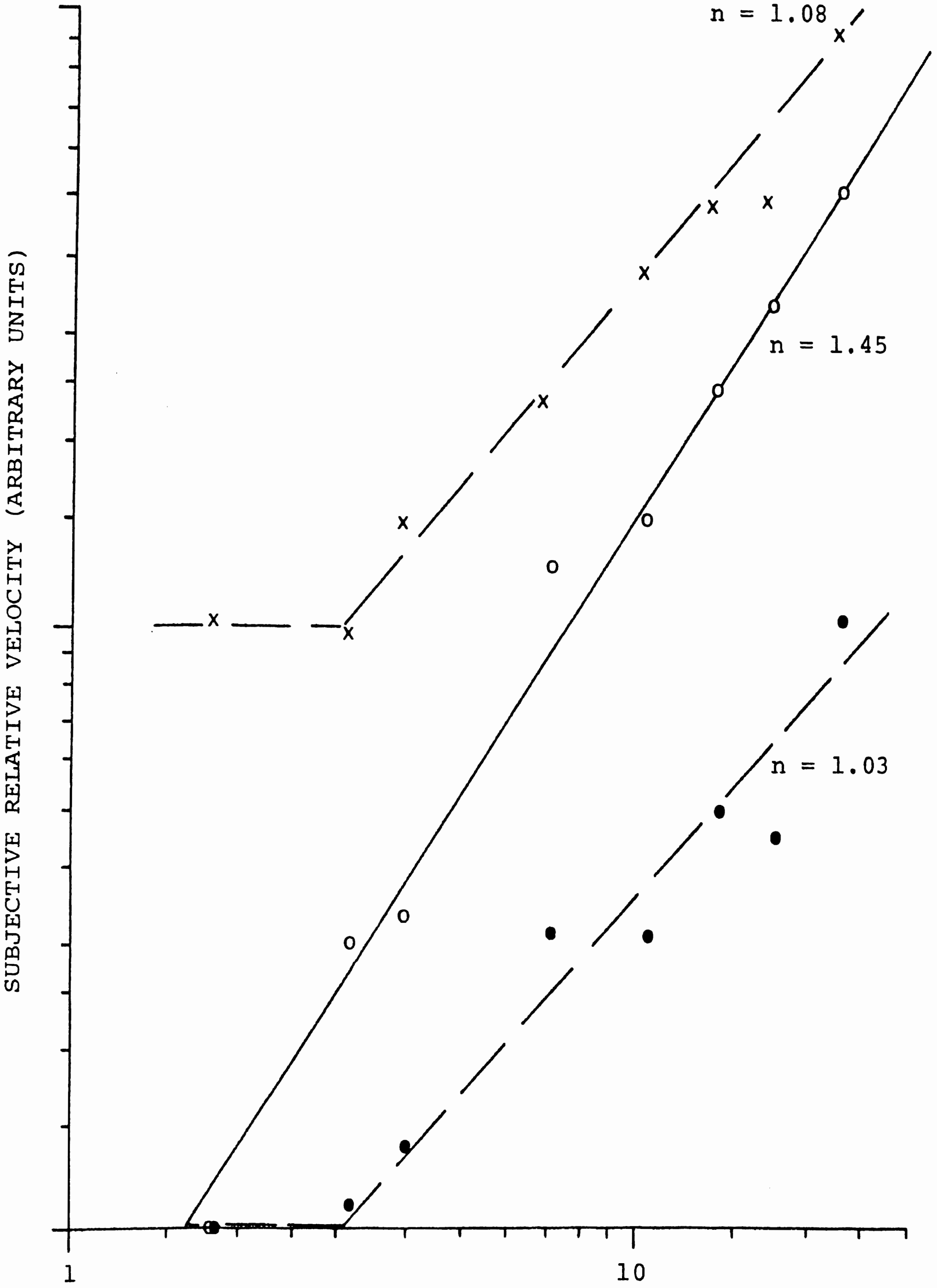


Figure 42. Scales of subjective relative velocity for three professional engineer subjects.

Group A: These were able to make reasonably accurate estimates of the time to closure. Results of subject D are given in Figure 43 for the four stimulus presentation times.

Group B: Subjects in this group greatly underestimated the time to closure, but their time estimates were linearly related to the real time to closure. Results for subject K are shown in Figure 44, in which the gradient of the straight line relating subjective and physical time is approximately 0.26.

It is seen in Figures 43 and 44 that, for closure times greater than about 18 sec the estimated or subjective time deviates greatly from the linear relationship. In the experimental situation, these times correspond to angular velocities being less than 2.2×10^{-3} rad/sec, suggesting that perception of angular velocity is necessary in order to make accurate estimates of closure.

Four of the 5 subjects in group B were female; 5 males were in group A along with 2 females. There is no significant sex effect on group membership ($p = 0.13$ by Fishers exact test).

Relative Velocity Scales. From the time estimation data, scales of subjective angular velocity have been constructed by converting the subjective and physical values via the following equations:

$$\omega_a = \frac{W}{Ht_a}, \quad \omega_s = \frac{W}{Ht_s}$$

where

t_a = actual time to closure.

t_s = subjective time to closure

ω_a = actual angular velocity at the end of the stimulus exposure.

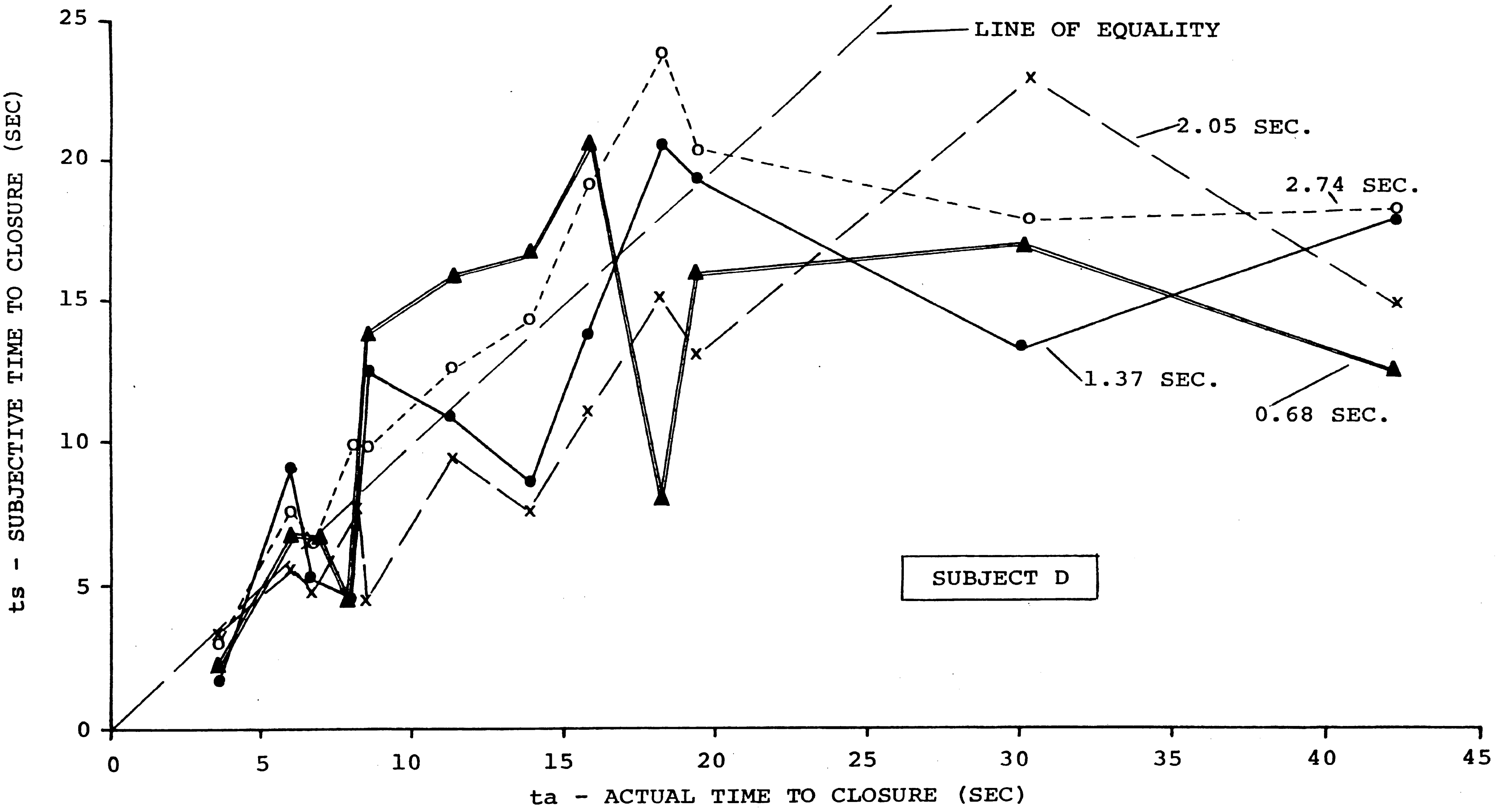


Figure 43. Estimated times to closure for subject D in Experiment 3. (Group A subject).

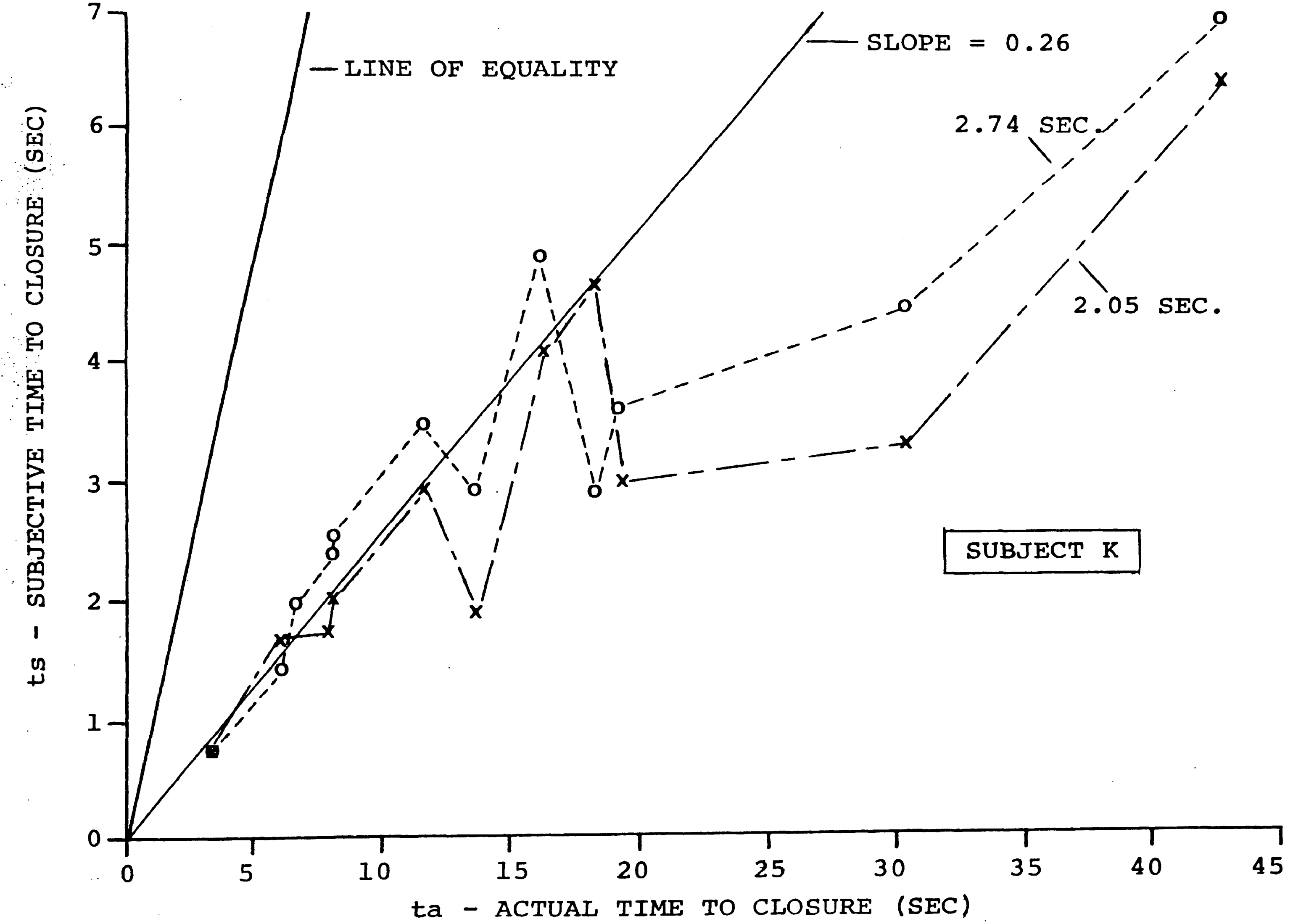


Figure 44. Estimated times to closure for subject K in Experiment 3. (Group A subject).

ω_s = subjective angular velocity.
W = vehicle width in ft.
H = headway in ft.

Typical results from this analysis are presented in Figures 45 and 46 for a group A and group B subject, respectively.

The exponents of the power law-relationship for all subjects are given in Table 34, and the corresponding angular velocity thresholds (where an estimate could be obtained)in Table 35. Means and standard deviations of the exponents and thresholds are given in Tables 36 and 37.

TABLE 34. Power Law Exponents Obtained by Estimation of Time to Closure in Experiment 3.

	Subject	Sex	Stimulus Presentation Time (Sec)			
			2.74	2.05	1.37	0.68
Group A	A	F	.88	.83	.92	1.45
	B	M	1.48	1.44	1.34	1.41
	C	M	1.23	.74	1.0	1.05
	D	M	1.15	1.0	1.48	1.21
	E	M	1.15	1.31	1.48	1.43
	F	M	.85	.89	.81	.87
	G	F	1.03	1.03	1.18	1.18
Group B	H	M	.80	.98	.85	.85
	I	F	.65	.81	.93	.71
	J	F	.76	.95	1.05	1.05
	K	F	.85	.90	1.13	.88
	L	F	.90	.71	.85	1.07

Geometric mean = 1.01

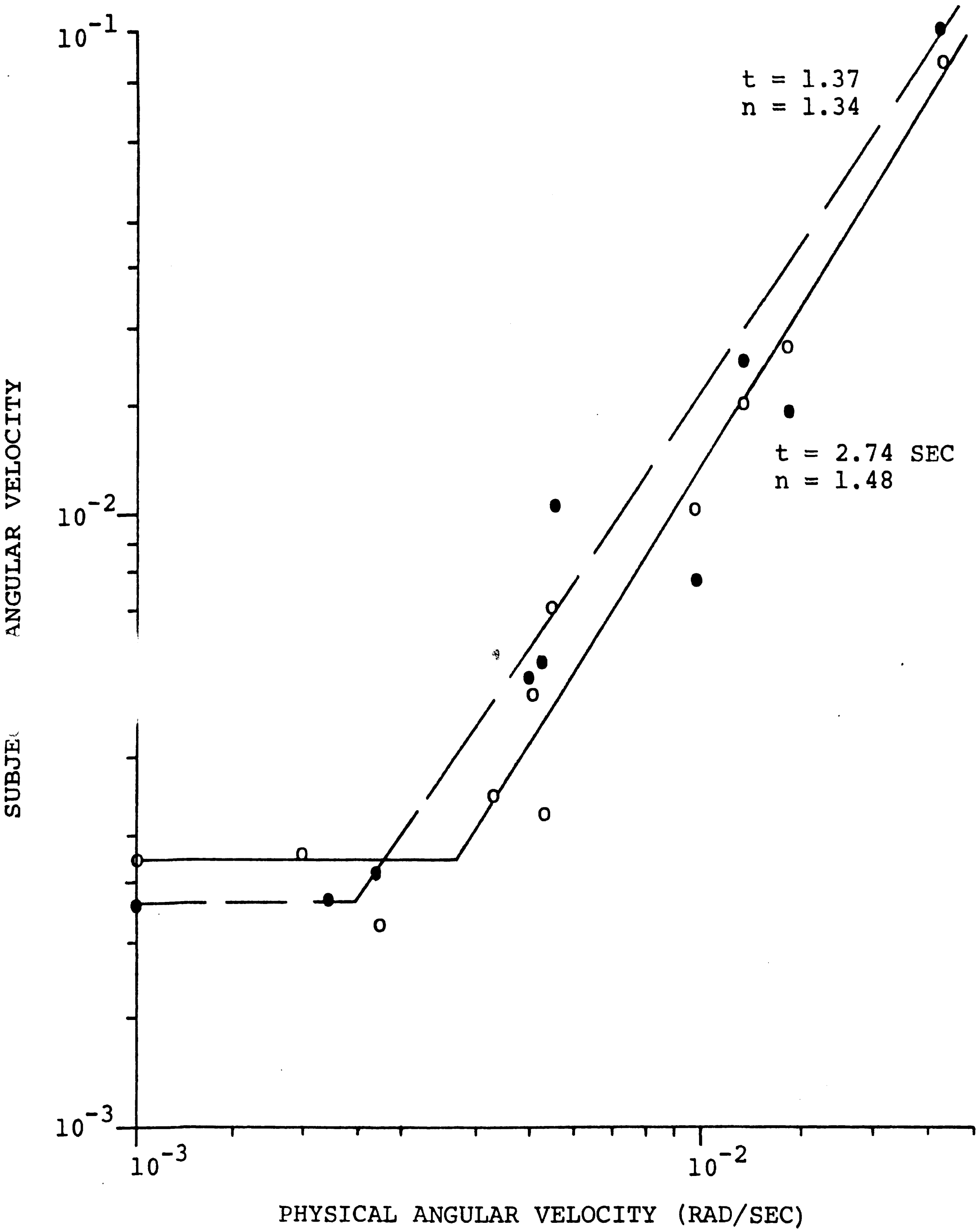


Figure 45. Scales of subjective angular velocity obtained from estimation of time to closure (subject B, group A).

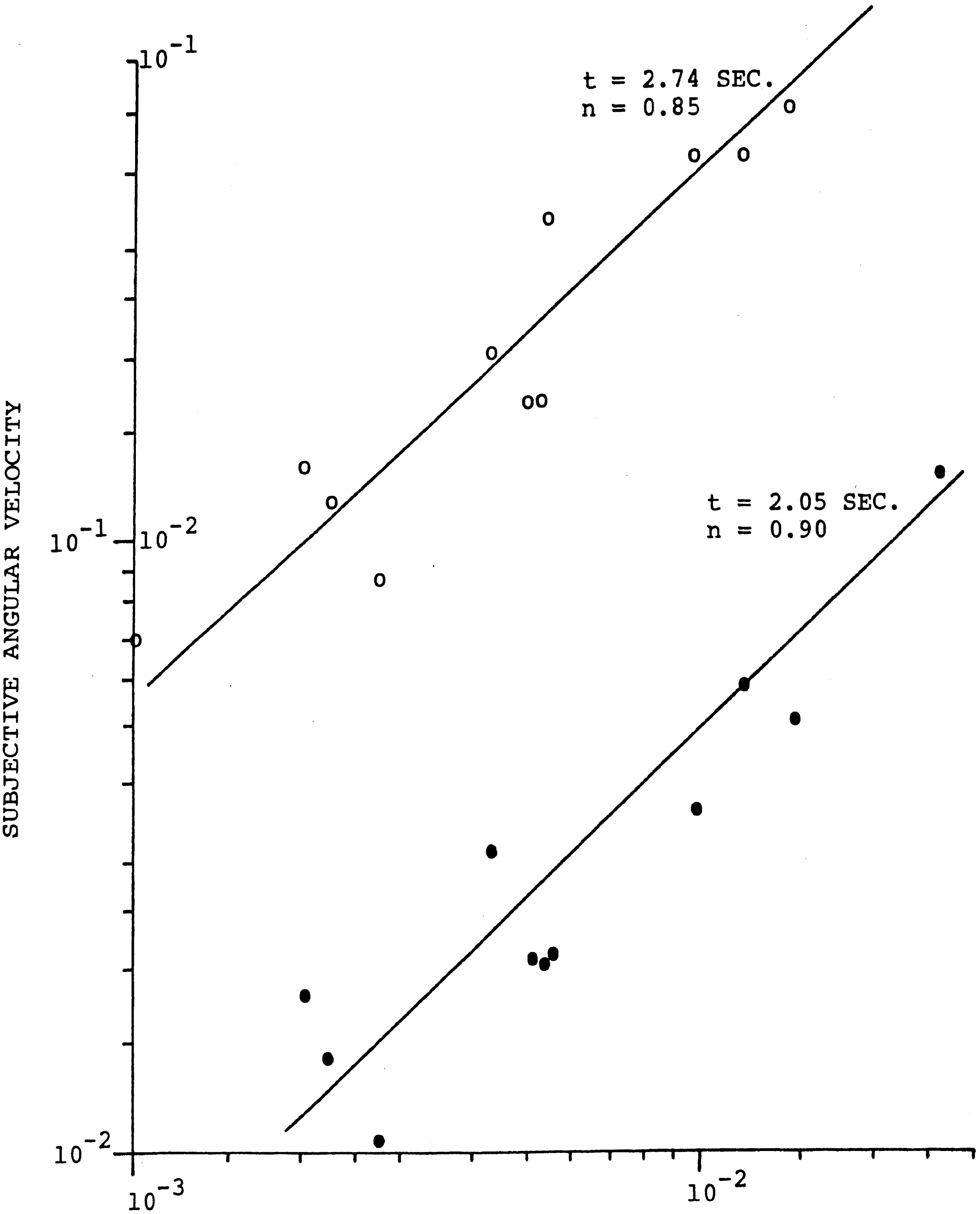


Figure 46. Scales of subjective angular velocity obtained from estimation of time to closure (Subject K, Group B).

TABLE 35. Approximate Angular Velocity Thresholds (Rad/Sec x 10^{-3}) Obtained in Experiment 3.

Subject	Stimulus Presentation Time (Sec)			
	2.74	2.05	1.37	0.68
A	-	-	-	2.6
B	3.7	4.6	2.5	4.6
C	4.3	2.1	2.9	3.0
D	3.0	2.1	3.6	3.0
E	-	-	-	2.0
F	2.5	2.7	2.8	3.3
G	2.5	2.2	2.8	2.5
H	-	-	2.5	3.0
I	-	2.3	2.4	2.7
J	2.5	-	2.5	2.5
K	-	-	-	-
L	2.8	2.7	2.8	2.6

Arithmetic mean threshold angular velocity = 0.0028 rad/sec

TABLE 36. Means and Standard Deviations of the Exponents of Groups A and B and of the Combined Data.

Experiment	Group A			Group B			All Subjects		
	N	$\bar{\eta}$	S.D.	N	$\bar{\eta}$	S.D.	N	$\bar{\eta}$	S.D.
II	6	.84	.18	4	.75	.02	10	.81	.14
III 2.74	7	1.11	.22	5	.79	.10	12	.98	.24
2.05	7	1.03	.26	5	.87	.11	12	.97	.22
1.37	7	1.17	.27	5	.96	.13	12	1.09	.24
0.68	7	1.23	.22	5	.91	.15	12	1.10	.25

TABLE 37. Means and Standard Deviations of the Threshold Angular Velocities in Experiment 3.

Experiment	N	$^{\omega}$Threshold	S.D.
II	12	.0052	.0013
III 2.74	7	.0030	.0007
2.05	7	.0027	.0009
1.37	9	.0028	.0004
0.68	11	.0029	.0007

A number of t-tests have been carried out on these data with the following results:

Exponents.

1. Significant differences exist between groups A and B in two of the stimulus presentation times (t) of Experiment 3 (a) $t = 2.74$ has $p < .01$ and (b) $t = 0.68$ has $p < .02$. Other cases show no significant differences.

2. With groups combined, the Experiment 2 exponents are significantly smaller than those of each presentation time of Experiment 3 ($p < .05$), while there is no significant difference between the four presentation times of Experiment 3.

Angular Velocity Thresholds.

1. No significant differences between groups A and B.
2. No significant differences between the presentation times of Experiment 3.
3. A highly significant difference between the thresholds obtained in Experiments 2 and 3 ($p < .01$).

DISCUSSION OF EXPERIMENTS 2 AND 3.

Exponents. In both experiments some subjects had difficulty in making judgments of the type required. This was demonstrated in the restricted range of numbers or ratios which the subjects were willing to use when estimating relative velocity ratios or time to closure.

In Experiment 2, it has been noted that the geometric mean maximum ratio was 2.9, compared with the maximum stimulus ratio of 13.39. The geometric mean exponent was 0.90. Five professional engineer subjects produced a geometric mean maximum ratio of 11.8 and a geometric mean exponent of 1.17 using the same stimulus material and with similar experimental conditions. For the 10 subjects of Experiment 2, there is a rank-order correlation coefficient of 0.6 between maximum response ratio and the magnitude of the exponent (not quite significant at $p = 0.05$). This intra-model variation of the exponent is in agreement with the model of Teghtsoonian (1973).

This same behavior is seen in the data of Experiment 3. and, when viewed in this context, the results of the group B subjects fit in with the overall scheme. That is, the differences in the magnitude of the exponents of group B compared with group A can be largely accounted for by the subjects' use of numbers. (This might also be explained by the predominance of females in group B.)

In Experiment 3 the rank-order correlation between the magnitude of the exponent and the response ratio (considered in terms of time) is 0.82 and this is significant at $p < .01$ (see Table 38).

The geometric mean response ratio in Experiment 3 is 14.5 compared with 2.9 in Experiment 2. Hence, even though different quantities were being estimated in these experiments, the response ratio effect may be a dominant factor in the highly significant differences ($p < .001$) occurring between the exponents obtained in these two experiments.

The geometric mean exponent over both experiments is 0.97,

TABLE 38. Variation of the Power Law Exponent in Experiment 3 With the Response Magnitude Ratio.

Subject	Min. Time Estimate (Sec)	Max. Time Estimate (Sec)	R= $\frac{t_{Max.}}{t_{Min.}}$	Geometric Mean Exponent	Rank R	Rank $\bar{\eta}$
A	.49	13.65	27.9	.99	3	5.5
B	1.62	24.34	15.0	1.42	4	1
C	1.81	22.61	12.5	.99	7	5.5
D	1.76	24.07	13.7	1.20	6	3
E	1.26	37.8	30.0	1.34	2	2
F	1.10	13.51	12.3	.85	8	11
G	.94	28.72	30.6	1.10	1	4
H	.51	4.61	9.0	.87	11	9.5
I	.66	4.82	7.3	.77	12	12
J	.31	4.58	14.8	.94	5	7
K	.59	6.37	10.8	.93	9	8
L	.28	2.80	10.0	.87	10	9.5

Geometric mean exponent = 1.01

Geometric mean response ratio = 14.5

suggesting that subjects do have veridical perception of relative velocity. This is not in good agreement with the results of Semb (1969) and of Janssen et al. (1971) who obtained values of about 1.3. In both these experiments, however, the subject was "stationary" as compared to the "moving" frame of reference used in the present experiments.

An unexpected finding of Experiment 3 was that the experiment was not affected by stimulus presentation times between 0.68 and 2.74 sec. It is apparent that subjects were able to scale relative speed in very short intervals of time. Experimental scatter of the data was, however, decreased with the longer viewing times.

Threshold of Angular Velocity. Experiment 2 gave a mean threshold value of 5.2×10^{-3} rad/sec. This was significantly different ($p < .001$) to the mean value of 2.8×10^{-3} rad/sec obtained in Experiment 3. The overall mean value was 3.5×10^{-3} rad/sec, which is close to the value of 3.9×10^{-3} obtained by Hoffmann (1968) from an analysis of data from other authors.

The data of Experiment 3 showed no effect of stimulus presentation time on the magnitude of the threshold, once again demonstrating that only very brief exposures are required to perceive and scale relative velocity. The larger threshold in Experiment 2 may be due to the subject's difficulty in using ratios in this method.

CONCLUSIONS (EXPERIMENTS 2 and 3).

1. Response range ratios have a major effect on the magnitude of the power law exponent. The response range ratio is likely to be affected by the type of experiment and the subject's familiarity with the use of numbers.

2. Geometric mean exponents close to unity suggest veridical perception of relative velocity.

3. The thresholds for angular velocity were found to be 5.2×10^{-3} rad/sec in Experiment 2 and 2.8×10^{-3} rad/sec in Experiment 3, with an overall mean of 3.5×10^{-3} rad/sec.

4. Relative velocity can be perceived and scaled in times as short as 0.68 sec when it is above threshold. Increase in viewing time does not significantly affect the magnitude of the threshold or exponent, but does reduce scatter in the results.

DISCUSSION OF CAR-FOLLOWING STUDIES

As noted in the aims of this report, one purpose of the experiments was to attempt to determine ways in which higher grade information regarding the motion of the lead vehicle may be communicated to the following driver. Different authors disagree on the need for this, for example.

Frick (1970) considers that "closing rate and distance information appears to be adequately contained within the pattern of an array of lights suitably displayed on the rear of a vehicle. It does not seem necessary to use special coding such as color changes, changes in number of lights or variable flash rate to develop required data."

Owen (1970) considers that the deceleration signal can be improved by:

(a) A panic stop signal.
(b) Indicate deceleration by green, amber and red lamps.
(c) Actuate the stop lamp when the accelerator is released.
(d) Actuate a separate amber lamp when the accelerator is released.
(e) Flash stop lamps at an increasing rate as the rate of deceleration increases.

An improved estimate of headway distance may also be obtained by:

(a) Having on all vehicles an exact spacing of tail (presence) lamps on each side of the vehicle.
(b) A fusion system of various lighted geometric patterns.

In the following section, previous research on the use of velocity and acceleration displays is briefly reviewed, for both car-following and overtaking situations.

EXPERIMENTS ON SPEED AND DECELERATION DISPLAYS

There are two classes of devices which may be used to impart information about a lead vehicle to the driver of a following car.

These are:

(i) Devices in the following vehicle:
Examples of this type of system are those of Gantzer and Rockwell (1968) and Fenton and Montaro (1968). In these systems relative velocity and headway information (or deviation from a set headway) is displayed to the driver.
Such systems can improve car-following performance but in practice would require complex electronic systems to acquire the necessary information. These devices shall not be further considered in this report.

(ii) Lighting devices on the rear of the lead vehicle:
In this class are included devices ranging from improved rear lighting systems to velocity and acceleration displays.

SPEED DISPLAYS. Farber and Silver (1967) showed that, in overtaking situation, knowledge of the oncoming car speed (given verbally) assisted the overtaking driver in making valid overtaking decisions.

Reilly and Cameron (1969) placed a speed display, consisting of 2 coloured rotating beacons, on the top of a vehicle with the oncoming vehicle speed coded at 20, 30, 40 and 50 mph. They found that, with the display, shorter safety margins were accepted more frequently. They conclude that "although the present results are insufficient to rule out any possible benefits of displaying oncoming vehicle speed, they do suggest that a dramatic improvement in passing judgment is not likely to be easily achieved by this means."

Hoffmann (1974) has experimented with a display to assist in overtaking judgments, in which the number of lights displayed on the roof of the oncoming vehicle is proportional to vehicle speed in increments of 10 mph. This display enabled overtaking driver to place the oncoming vehicle speed into 4 categories at a distance of 1000 feet, with a drop to 2 categories at 1500 feet. Without the velocity display only 2 categories of oncoming vehicle speed could be discriminated between 500 and 1500 feet. No study was made on the effect of the display on overtaking decisions. The information imparted by the display was apparently limited by ability to discriminate between the number of lights, being about 1 min. of visual angle at 1000 feet for the display used.

In car-following experiments, Jolliffe et al. (1971) showed that drivers can use a velocity display to obtain information about the lead vehicle. However, no attempt was made in their experiment to see whether such information would improve car-following performance.

Such an experiment has been carried out by Nickerson et al. (1968) with a light display indicating speeds between 0 and 72 mph in 3 mph increments (all lights were on at 0 mph and none at speeds greater than 72 mph). The normal brake lights were also on the vehicle. After 4 learning trials, the RMS variation about a mean headway in a car-following task was as follows:

(a) No display	17.7 feet
(b) Standard brake lights	28.1 feet
(c) Velocity display	15.7 feet
(d) Velocity display and brake lights	12.9 feet

As noted by the authors, any conclusions drawn from these data "are speculative at best, based on insufficient and noisy data." In this experiment, velocity was displayed in small increments and, hence, the following driver was able to obtain acceleration information via the rate of change of the length of the light display. Consequently it is not known which was the most important source of information to the following driver; velocity or acceleration.

Rockwell and Treiterer (1968) tested a somewhat similar display, with lights indicating increments of 5 mph, and found it to be superior (to the standard lighting system) only in maneuvers beginning with a coast - the normal system was superior if the maneuver was started with braking.

It would appear that little can be said with any certainty about velocity displays. An approach to examine the performance of following drivers with such a display would be to use measures of information transmission and delay time as discussed in experiment 1. A "good" display would be one in which coherence between input and output is increased (i.e.,transinformation increased) and shorter driver delay times are obtained.

DECELERATION DISPLAYS. The simplest deceleration display is that tested by Mortimer (1971) in which a signal was shown on the rear of the vehicle when the accelerator was released. He concluded that such a signal "would not often give information of significant deceleration or advance warning of impending braking of a car being followed....a signal given only after about 5 sec of coasting.....would provide relevant information of deceleration and impending braking on most such occasions."

Rockwell and Treiterer (1968) report experiments on two deceleration displays (AID and TRI-light). The TRI-light consisted of three lights on each side of the vehicle, red, amber and green. The red light indicated actuation of the brake pedal and the green light actuation of the gas pedal. The AID system (acceleration information display) indicated 5 levels of acceleration and 5 levels of deceleration. Both systems resulted in a decreased response time, with the greatest reductions being with the TRI-light system. However, the differences from the standard rear lighting system were mainly in signaling slight decelerations, i.e.,coasting. There was a significant improvement in performance "as indicated by a significant reduction of the average relative velocity maintained during a maneuver beginning with a coast."

Evaluation of a similar concept as the TRI-light used by Rockwell and Treiterer, in both simulator and road tests (Mortimer and Sturgis, 1974) did not find it to lead to improved car-following performance.

Rutley and Mace (1969) carried out a similar experiment in which deceleration was displayed by a sequence of 3, 5 or 7 lights as deceleration was increased. They concluded that "...the advantage of the additional information given by multi-brakelight display is small, but it might be justified by a simple two-level system: for example, a low deceleration light (probably throttle operated) plus a warning signal given whenever deceleration is substantially increased."

Recent further simulator studies (Mortimer and Sturgis, 1974) did not find any benefits relevant to the reduction or rear-end crashes attributable to a high deceleration braking signal.

Voevodsky (1967, 1974) used a yellow light, on the rear of several hundred San Francisco taxicabs, whose frequency of flashing varied exponentially with vehicle deceleration. Rear-end collisions of the light-equipped taxis was 60.0% less than those for a control group.

It is not known whether following drivers actually used the flashing frequency of the Voevodsky display in order to scale deceleration, or whether the display was simply a more attention-getting braking signal. Voevodsky did not carry out any experiments to determine the reasons for the effectiveness of the display. For example, the question of whether a constant flashing rate would have had the same effect, or whether the varying rate is necessary, remains unanswered.

DISPLAY DESIGN FOR VISUAL CUE AUGMENTATION.

The possible design of a vehicle rear lighting system shall be discussed in terms of the following criteria (Mortimer, 1970b):

(a) "They should be coded in such a way as to rapidly alert following drivers.

(b) The nature of the information presented to following drivers should be that which is of greatest value to them."

Design considerations shall also be related to the conclusions of the foregoing experiments which are summarized as follows:

(1) Thresholds for angular velocity are about 3.5×10^{-3} rad/sec subtended at the eye of the following driver.

(2) Relative velocity can be perceived and scaled in short glance times when it is above threshold.

(3) In the car-following simulator, drivers transmit very little information regarding the relative velocity between their own car and a lead vehicle.

(4) Drivers were able to respond, on average, to 2.78 categories (which is little more than an opening-closing decision) of relative velocity but to 5.24 categories of lead-car absolute velocity.

(5) At low frequencies of lead car velocity variation (< 0.05 Hz) the following car driver appears to be using a velocity response to detected changes of headway. At higher frequencies a velocity response is used to changes in relative velocity.

(6) Even though a driver may readily scale relative velocity, the simulator experiments suggest that he makes little use of relative velocity information but is more likely to respond when he detects changes from a desired condition of headway.

In spite of the evidence in the present experiments that the following driver makes little use of relative velocity information, the experiments mentioned in the previous section show that, if he has this information presented to him in some form of display, he may make use of it. In the present experiments, relative velocity was often below threshold but, even when it was not, some drivers preferred to control on headway changes. This suggests that control based on headway may be a less demanding task for the driver, but one which is likely to produce greater variance in headway.

The experiments suggest that the driver is responding to headway changes at low frequencies and relative velocity at higher frequencies. At low frequencies of input velocity, the relative velocity is likely to be subthreshold. Hence, supplying relative velocity information could be useful in this situation.

The problem is how to impart this information through a rear lighting display. This is obviously not possible without complex electronic devices. However, as demonstrated by Farber and Silver in the case of overtaking vehicles, information about the absolute speed of the vehicle may be just as good as information about the relative speed.

When relative velocity is above threshold, the experiments show that the driver can readily scale it visually, and hence, at higher frequencies of input velocity a velocity display may not be of much use other than as a secondary source of information.

If the displayed velocity increments are sufficiently small, direct deceleration information may be obtained by the following driver. This, in effect, acts as a "preview" of the relative velocity of the lead vehicle at some future time and hence would allow a reduction in driver response time and improved car-following performance. But against this use of small increments in displayed velocity is the ambiguity of confusion that such a rear lighting display may create, reducing its effectiveness in displaying absolute speed categories.

The experiments also showed that drivers are able to distinguish more categories of absolute velocity of the lead vehicle than they could of relative velocity. When viewed in terms of the ranges of these velocities it is found that the velocity increment in each category is about 9.3 ft/sec of lead vehicle velocity and 12.4 ft/sec of relative velocity. These are not greatly different, but they definitely suggest that the use of a display indicating lead vehicle velocity may be just as effective as one displaying relative velocity.

The results of these experimental studies support the analyses (Mortimer, 1971) of effective augmenting cues for car-following and rear-end crash avoidance, as well as the findings of computer simulations (Carlson & Mortimer, 1974). Those studies have also suggested that car-following and rear-end crashes could potentially be reduced by the use of vehicle rear lighting displays which provide information of the speed of a vehicle being followed or approached from the rear. The accident data analyses which have been presented in this report also confirm that such a signal may be effective.

In its broadest terms, a velocity signal should provide information over the total likely range of the vehicle speeds. The accident data analyses indicate that this should include the condition where a vehicle is moving slowly or is at a standstill. It is evident (e.g.,Mortimer and Sturgis, 1974; Carpenter, 1966; Mortimer and Post, 1972) that many rear-end collisions involve a vehicle that is moving slowly or is stopped in the road lane. Therefore, a signal indicating this condition is expected to be very effective in reducing this class of crash.

The need for a display which indicates speed of a lead vehicle, in discrete categories, is exemplified by rear-end collisions with trucks that have been discussed in this report, and supported by the car-following and perceptual experiments.

Since the perception of relative velocity or changes in headway have been found to be improved by the use of an array of four rear presence lamps (Mortimer, 1970) these might be incorporated also as part of an improved vehicle rear lighting system.

Additional rear-end crashes may also be reduced by a closer examination of the elements entering into those crashes which involve parked vehicles. The analysis reported here has indicated that the visibility of parked vehicles at night may be a part of this problem. This suggests, that the current standards of vehicle rear retroreflectors may need to be re-examined, and that drivers need to be continually reminded to keep these items of a vehicle lighting system, as well as others, in clean condition.

The recommendation that vehicle speed should be coded by the vehicle rear lighting system, will increase the complexity of that system. This raises questions as to the potential increase in the confusion of following-car drivers in interpreting such signals, or the effect of the added displays in distracting the driver from other aspects of the driving environment or other important signals shown by the vehicle rear lighting system.

In this respect the study on the interpretability of signals has indicated that drivers are able to comprehend the intended meaning of complex signals to which they have not been previously exposed, in a remarkably rapid way. This finding should provide a high degree of optimism that a parsimonious and effective vehicle rear lighting display can be developed which minimizes the undesirable aspects of increased complexity of such systems.

GENERAL CONCLUSIONS

The findings of these studies of accident data, laboratory, driver simulator, and driving tests suggest that:

1. The basic signals now presented by vehicle rear marking and signaling systems should be retained, consisting of turn, stop, and hazard warning signals.

2. Evidence from this study indicates that four presence lamps, mounted in a rectangular array (Mortimer, 1970) should be used to provide improved sensitivity of following-car drivers to changes in headway. However, tests of one such configuration found it to be relatively poor in detection of stop + turn signals. Further tests, aiming to upgrade signal presentation performance, are indicated.

3. A stopped/slow-moving vehicle display should form part of a velocity signal, coded in a few (e.g.,three) categories by the illumination of various numbers of lamps. While other types of signals are frequently misidentified as stopped/slow-moving, these errors are not potentially dangerous.

4. The basic concept of an integrated vehicle rear lighting and signaling system such as that defined in conclusions 2 and 3 may be similar to that proposed earlier (Mortimer, 1971). The overall effectiveness of such a display should be evaluated.

5. The marking of parked vehicles and the effectiveness of current standards of vehicle retroreflectors requires further evaluation.

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Appendices

Appendix A

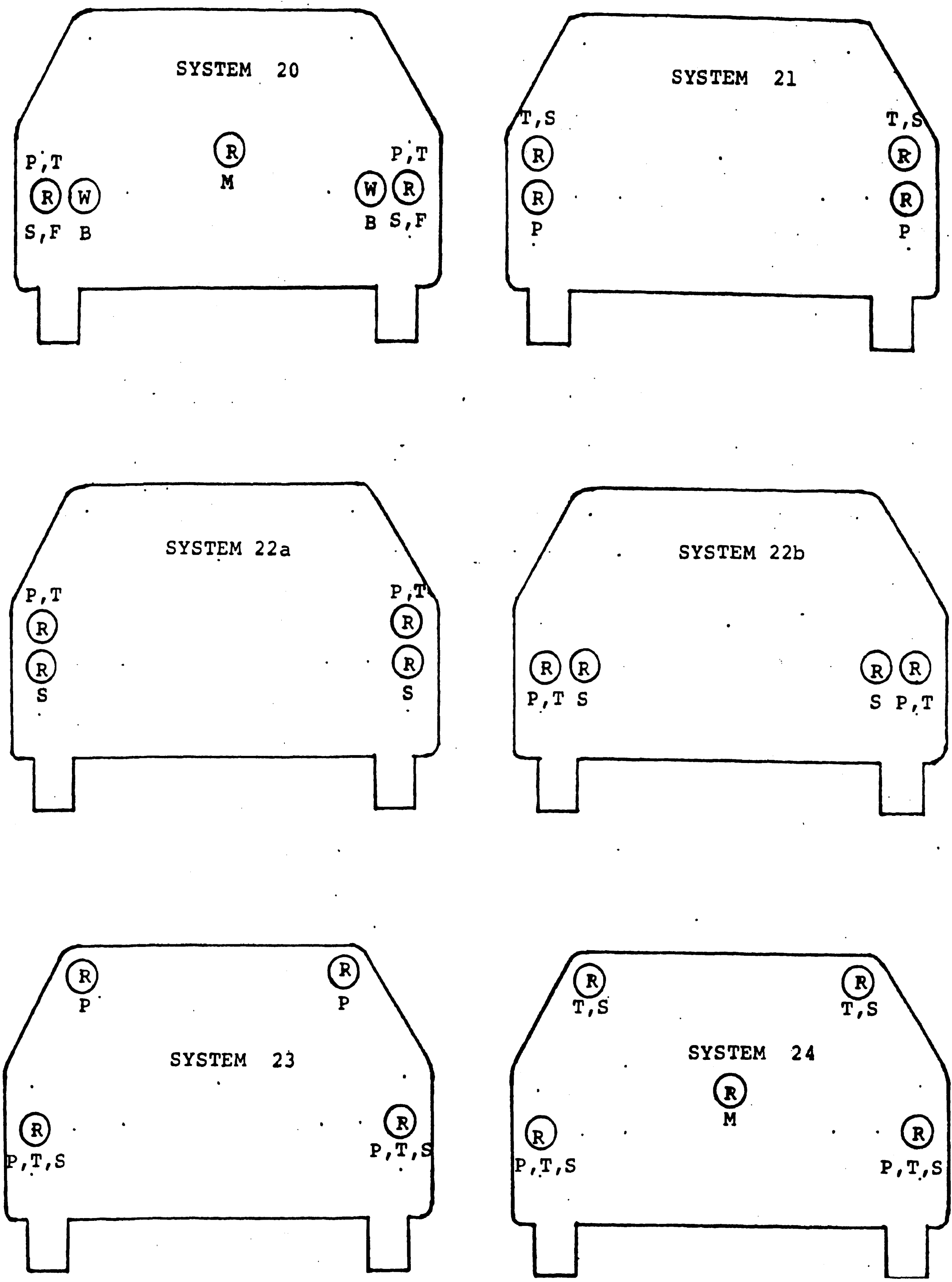
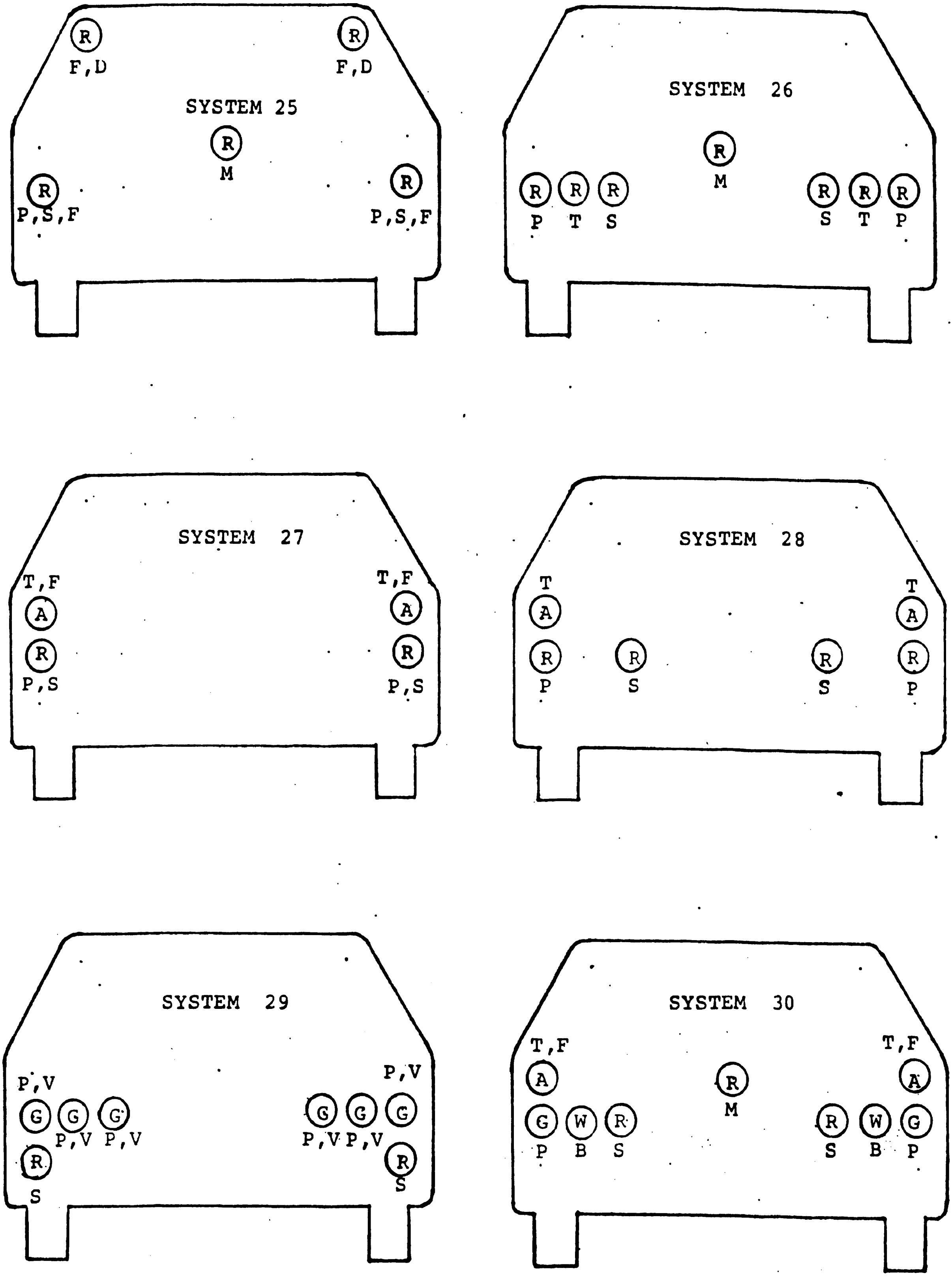


Figure A.1 The rear lighting systems used in the car simulation.
Symbol Code:
R - red
Y - yellow
G - green
W - white
P - presence
S - stop
T - turn
B - back-up
M - stopped/slow moving
D - high-deceleration
V - velocity
F - hazard warning



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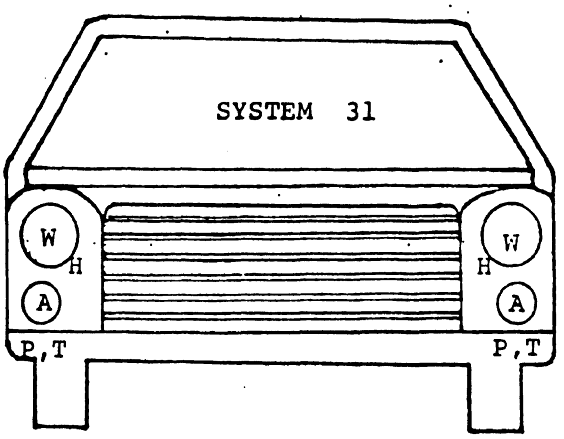

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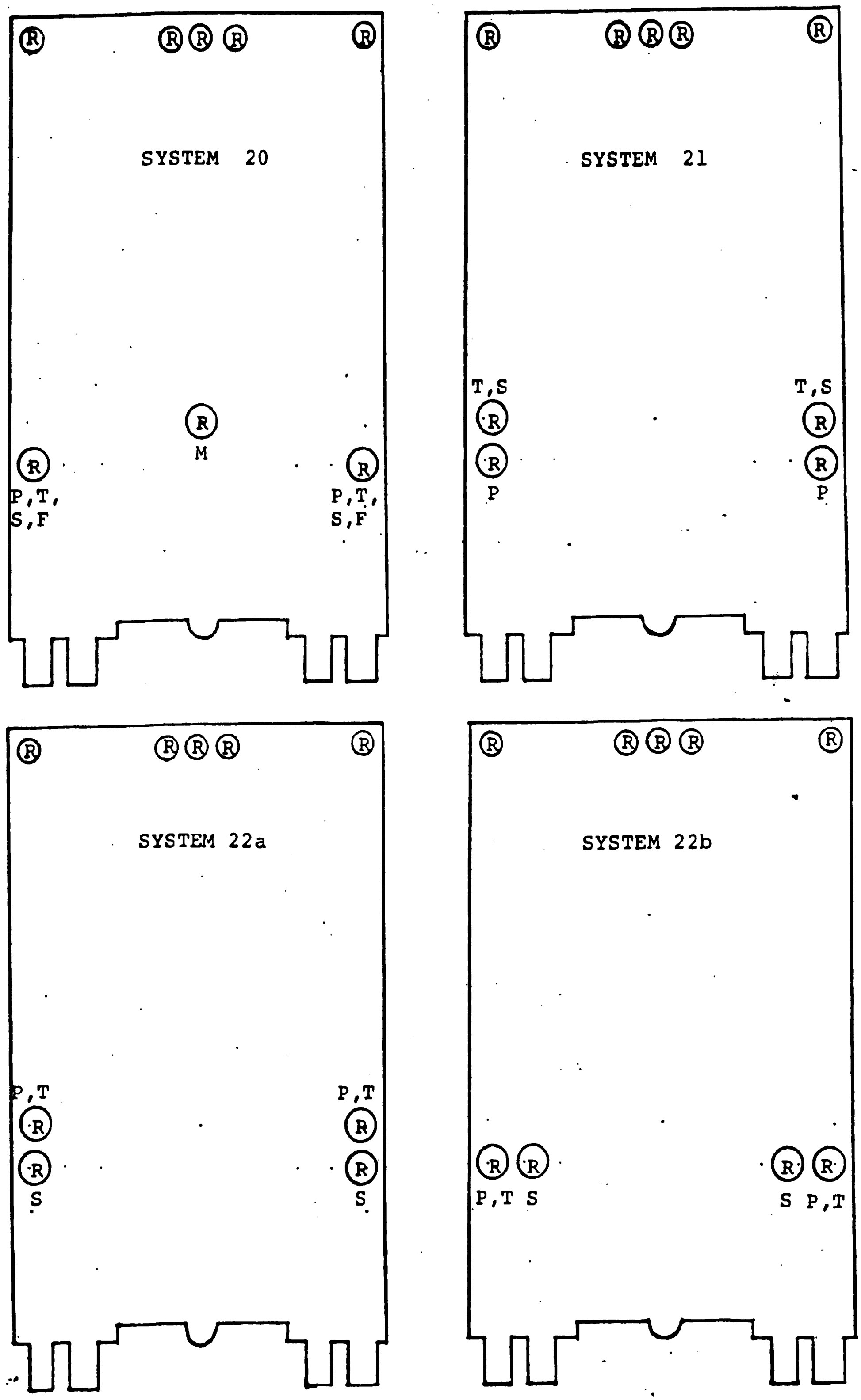


Figure A.2 The rear lighting systems used in the truck simulation.
Symbol Code:

R - red
Y - yellow
G - green
W - white

P - presence
S - stop
T - turn
B - back-up

M - stopped/slow moving
D - high-deceleration
V - velocity
F - hazard warning

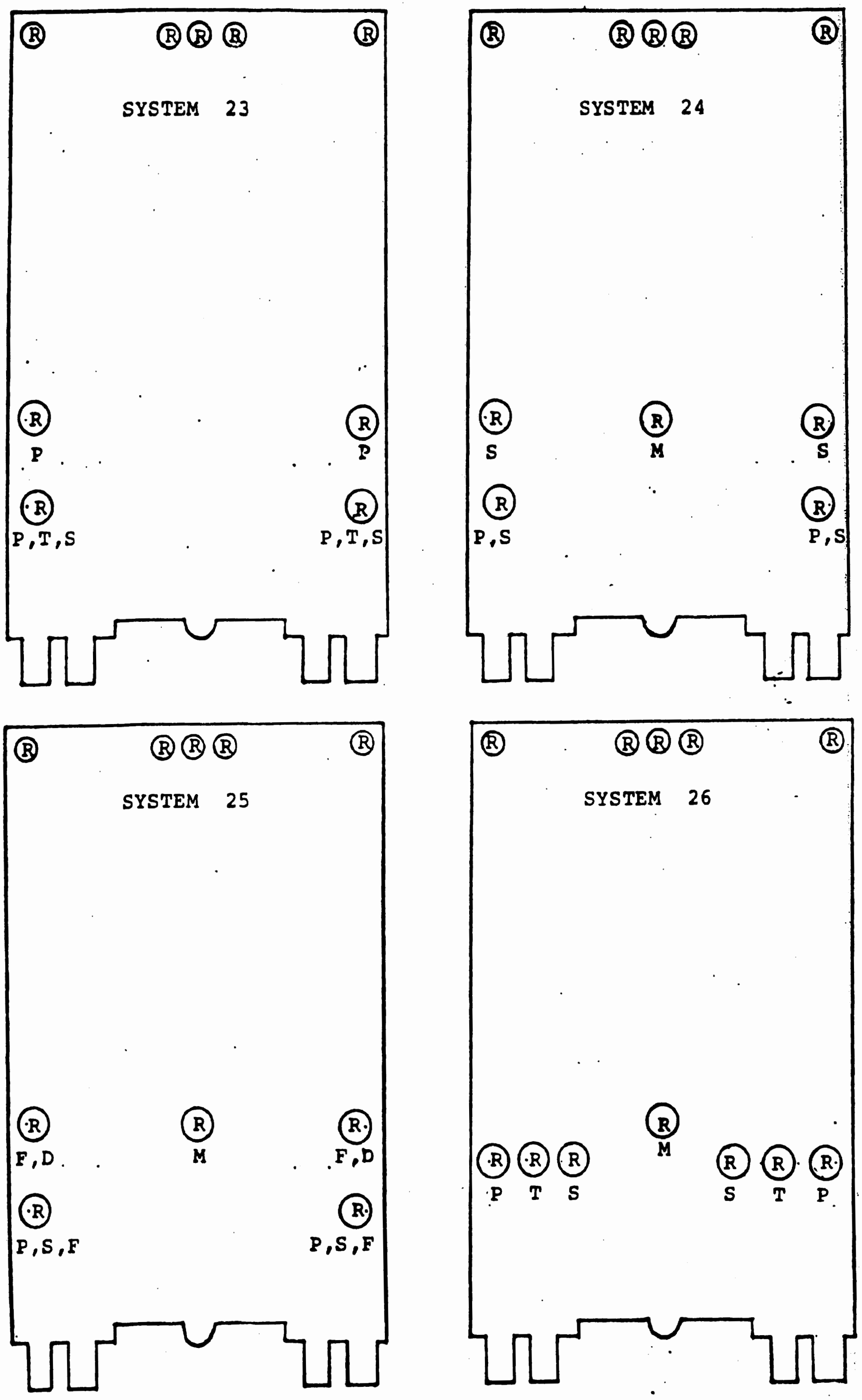
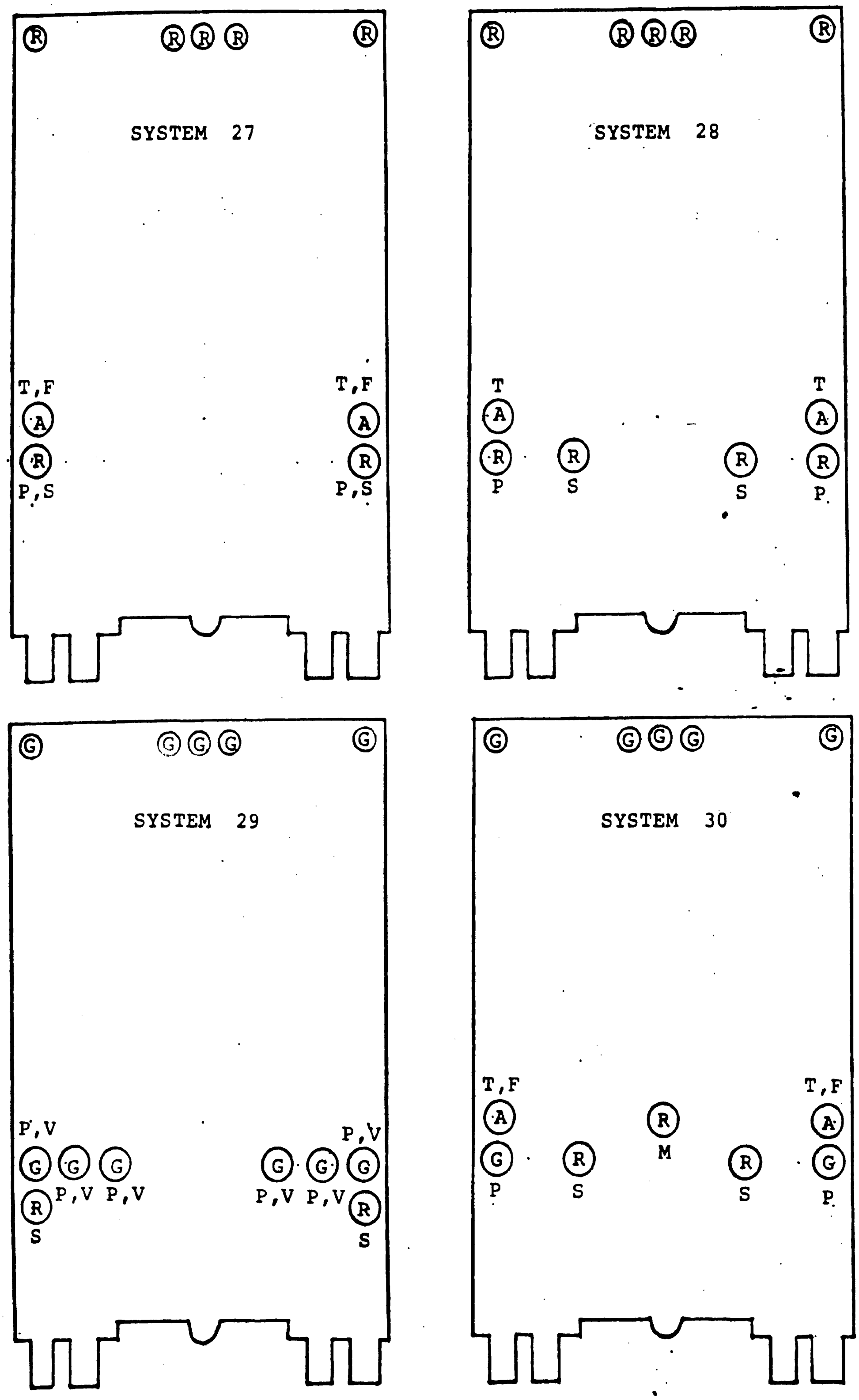


Figure A.2 (continued)



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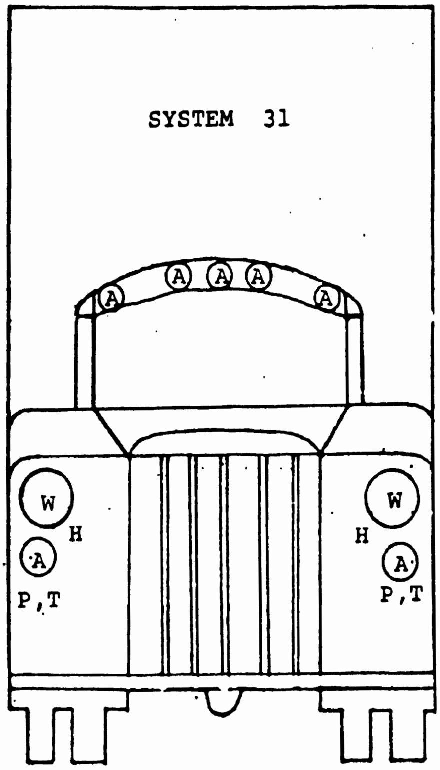


Figure A.2 (concluded)

Appendix B

OBSERVER INSTRUCTIONS: STUDY OF INTERPRETATION OF SIGNALS

On the Observer Data Sheets please fill in your observer number which will be as follows: Print your name; indicate your sex by circling 1 for male and 2 for female. Fill in your age and the number of years you have held a driver's license. For vehicle circle (1 for car or 2 for truck) and circle observation 1.

The purpose of this experiment is to explore the possibility of improving signaling and marking on vehicles. You are going to be shown film segments of various lighting systems on the front and rear of (cars or trucks) as a means of comparing new and old lighting configurations. Your task is to identify the meaning, at the end of each film segment, of all the signals you saw during that segment. (Show sample segment.) The rows on the observer data sheets indicate the film segment numbers; the columns indicate the various types of signal presentations. The first two columns are titled "Front" and "Rear". Place a check mark in the "Front" column if the front of the vehicle was shown and a check mark in the "Rear" column if the rear of the vehicle was shown. One of these two columns must be checked by you after each segment. The next column indicates presence lights which are also known as taillights, parking lights, or running lights (trucks only - clearance lights and identification lights). Their purpose is to mark the vehicle, to make it visible at night. The following two columns should be marked if either headlights or backup lights are seen by you. The next column should be marked if you see a braking signal, which occurs when the speed drops to about 5 mph or less. The high deceleration or braking signal occurs when the vehicle is braking unusually hard. The change in speed signal occurs when there is a fairly large increase or decrease in the speed of the vehicle such as a change in speed from 0 to 35 mph, 35 to 55 mph, and 55 to 75 mph. These experimental signals are always supplemental to the regular signals; that is, they do not replace the conventional signals but are in addition to those signals. The conventional signals are, however, sometimes altered in color or number. The last two columns indicate turn and hazard warning signals. The turn signal indicates the intention to turn to the right or left, or to change lanes. The hazard warning signal indicates a vehicle that is disabled and stopped on or off the roadway.

Is there anyone who is confused at this point as to what each column represents? (If so, repeat above instructions.)

The following information should assist you in making correct observations.

1. All film segments show the vehicle you are viewing at night.

2. The films are made from the viewing position of an occupant in a car following the observed vehicle or approaching the observed vehicle.

3. The distance between the vehicle you are in and the preceding or approaching vehicle will change within some of the film segments just as the distance would in real life. You should assume that any change in distance between vehicles is due to "normal expected actions" such as the preceding vehicle decelerating and the vehicle you are in slowing down or stopping to avoid a collision. If the distance between the car you are in and the vehicle you are following does not change, you should assume that you are following the vehicle at a fixed distance, or that you are both stopped at a traffic signal. You will have to choose which instance is more appropriate for each film segment.

4. Each film segment should be viewed independently of other film segments. In other words, view each segment as if it represented a different vehicle. One or more signals will always be

presented in a film segment. If a signal is unfamiliar to you indicate what you think it was. You must respond to each film segment by indicating how you interpreted the meaning of each of the signals that were shown. Be alert to view the entire segment, not just part of it, and identify all of the lights you saw.

5. Indicate only the lights or signals you view directly. For example, if you see the flow of headlights but do not actually see the headlights themselves, you should not indicate seeing the headlights.

At the end of each film segment the picture will go black. A buzzer will sound and a light will appear on your clipboard to illuminate your data sheet. When you have responded to that film segment by indicating all of the signals or messages you saw push the button below the light to indicate that you are ready for the next presentation, and then look up at the screen. I will let you know when the next film segment will start by saying "next" or calling out the trial number and the procedure will be repeated. <u>Never go back to a previous trial to change your answers</u>.

(Show sample film segments.) Are there any questions?

Let me reemphasize the following points: (repeat before showing film for second time).

1. Every row should have a check mark in either the "front" or "rear" column and "presence" will frequently be checked.

2. The stopped or almost stopped signal comes on at speeds less than 5 mph. The high deceleration-braking signal comes on during the time the vehicle is braked extra hard. The change in speed signal comes on to indicate a fairly large change in speed in the vehicle. These signals occur in addition to the normal signals now on vehicles.

3. Remember that the vehicle you are in is usally moving too and responding to the actions of the vehicle you are following.

4. Use only check marks or X's on the data sheets and please do not smoke during the experiment. Does anyone have any more questions?

DO NOT ASK QUESTIONS AFTER WE BEGIN AND DO NOT MAKE ANY COMMENTS REGARDING THE FILM SEGMENTS TO ANYONE IN THE ROOM. WE ARE INTERESTED IN HOW YOU INTERPRET THE MEANING OF EACH PRESENTATION OF SIGNAL AND MARKING LIGHTS.

Appendix C

A CRITERION FOR THE DETECTION OF SPACING CHANGES

Evans and Rothery (1972) in an experiment involving detection of spacing changes between vehicles concluded that

"The probability of judging positive relative motion between a lead car and a subject in a following car can be expressed as a response either to average relative velocity divided by spacing ($\frac{U}{S}$) or to spacing change divided by spacing ($\Delta S/S$)." In the major part of their experiment, the exposure time available to the subject for viewing the relative velocity was held constant at 4 seconds so that, for this condition above, it was not possible to distinguish between these two ratios as a detection criterion.

One subject was, however, run with an exposure time of 2 seconds with the following stated result (p. 17):

"The response thresholds for both U/S and $\Delta S/S$ are exposure time dependent. There is at most only a suggestion that $\Delta S/S$ is slightly more exposure time dependent than U/S. One function which is consistent with the data, and underlines the similarity of the exposure time dependence of $\Delta S/S$ and U/S is $T^{\frac{1}{2}}U/S$, or equivalently $T^{-\frac{1}{2}}\Delta S/S$."

Evans and Rothery give the following values for subject 10 with exposure times of 2 and 4 seconds (Table C.1).

TABLE C.1. Rate Detection Thresholds for a Single Subject (from Evans and Rothery (1972).

Intercategory Threshold	T = 2 Sec	T = 4 Sec	Ratio of 2 Sec/4 Sec
$\frac{U}{S}$ (Sec^{-1})	.018	.0135	1.33 ($\sqrt{2}$ = 1.41)
$\frac{\Delta S}{S}$	.038	.053	0.717 ($\frac{1}{\sqrt{2}}$ = 0.707

The suggestion of Evans and Rothery (1972) as to the time dependence of U/S and ΔS/S is of interest, as it may fit into a model for discrimination formulated by Crossman (1955).

The idea is extended further in this section as it is felt that the discrimination model may allow a decision to be made as to which of $\frac{U}{S}$ or $\frac{\Delta S}{S}$ is being used as a detection criterion. (Note that only in the extreme case of the high relative velocities and low headways was the threshold for angular velocity exceeded in the study of Evans and Rothery).

Harvey and Michon (1971) carried out experiments with simulated rear tail lights and, using the methods of signal detection theory, determined velocity thresholds at varying headway and exposure times. The writer has reanalyzed this data in the form suggested by the criteria of Evans and Rothery (1972). (In these experiments also, angular velocities are likely to be subthreshold, having a maximum value of 2.6×10^{-3} rad/sec). The relevant results from Harvey and Michon (1971) - their Figures 13, 17, 18, 20 - are reproduced here as Figures C.1, C.2, C.3, and C.4.

By means of fitting approximate straight lines to the log-log plots of these Figures, the following deductions may be made:

(1) $U_{threshold} \propto S$ (Fig. C.4).
(2) $U_{threshold} \propto 1/\sqrt{T}$ (Fig. C.1).
(3) $\Delta\theta \propto \sqrt{T}$ (Fig. C.3).
(4) $\Delta\theta \propto 1/S$ (Fig. C.2).

From (1) and (2) we have, at threshold,

$$\frac{U\sqrt{T}}{S} = \text{Const.}$$

which is the result of Evans and Rothery for the condition at detection. From (3) and (4)

$$\frac{D\Delta\theta}{\sqrt{T}} = \text{Const.}$$

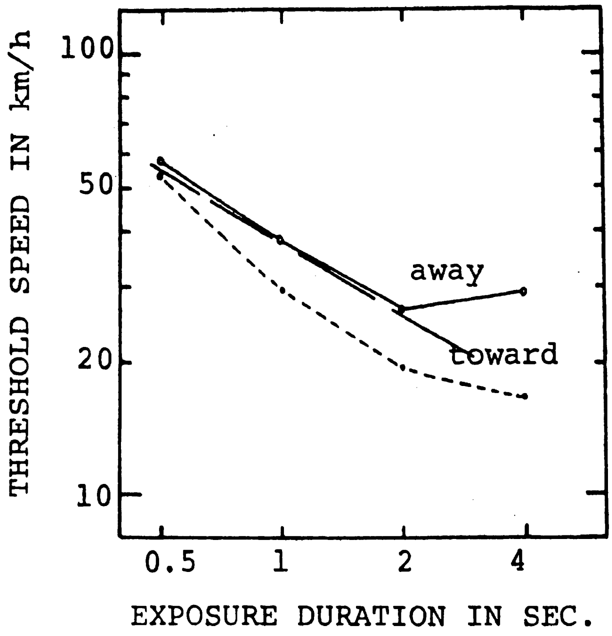


Figure C.1 - Mean threshold speed in kilometers per hour as a function of exposure duration for simulated motion away from and toward the observer. Long dash line indicates slope of -1/2.

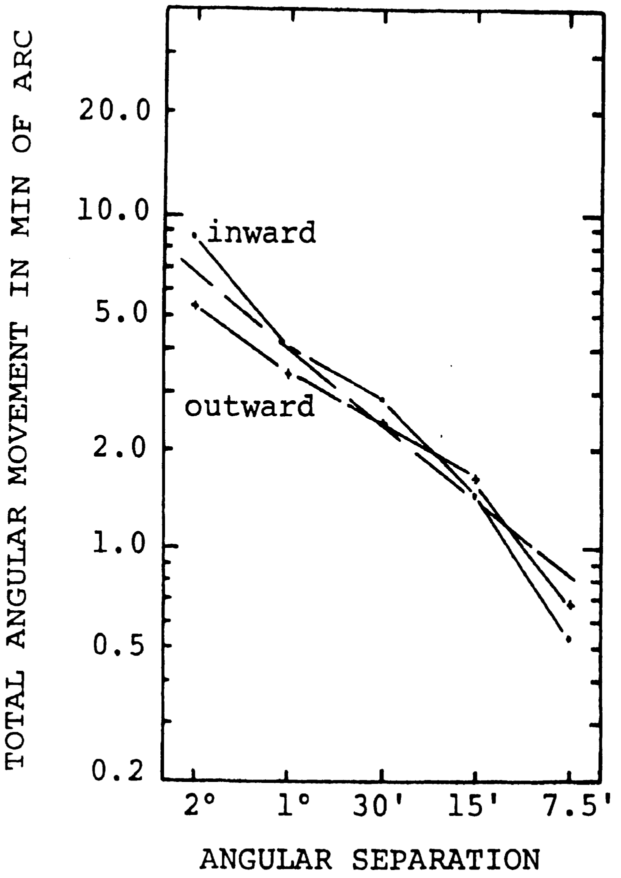


Figure C.2- Total angular distance moved at threshold during exposure as a function of angular separation for inward and outward movement. Dashed line indicates slope of -1.

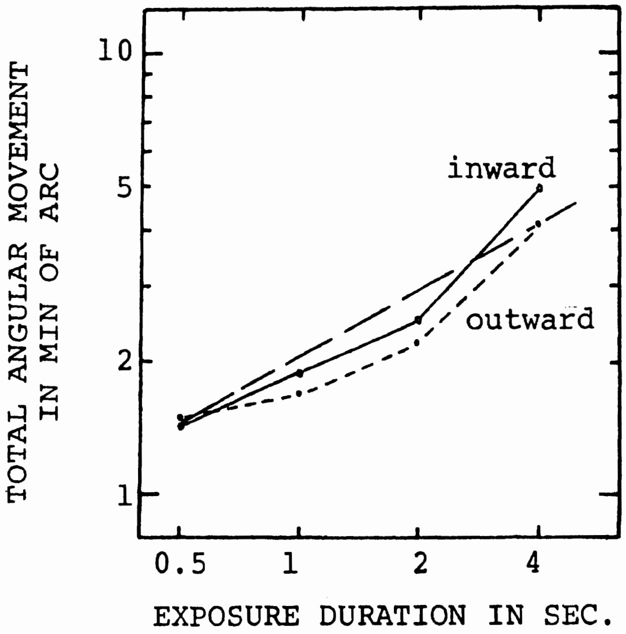


Figure C.3 - Total angular distance moved at threshold during exposure for inward and outward movement. Long dashed line indicates slope of +1/2.

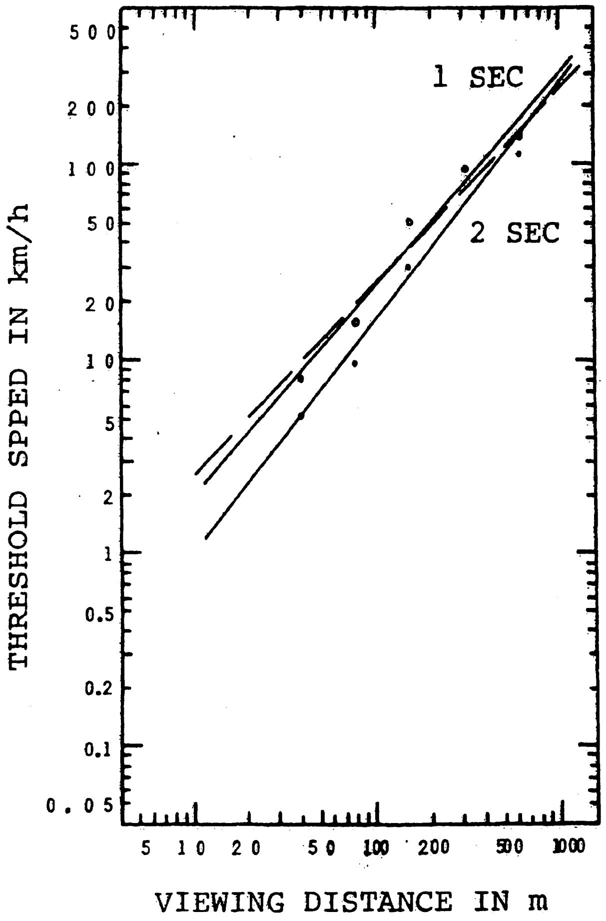


Figure C.4 - Threshold speed in kilometers per hour as a function of viewing distance for two spots of light, with 1 and 2 sec exposure, for movements away from the observer. Dashed line indicates a slope of +1.

Now $\Delta\theta \doteq \frac{WUT}{S^2}$ where W = width of the vehicle, hence (2) gives

$$\frac{U\sqrt{T}}{S} = \text{const as in equation A1}$$

The magnitude of the constant is expected to be different to that of Evans and Rothery due to the different experimental conditions and techniques employed. It is noted that equations (A1) and (A2) are valid for viewing times of about 2 seconds and less; the data suggests that at viewing times greater than 4 seconds all information in the stimulus has been extracted and further increases have no effect. The detailed study of Harvey and Michon appears to give support to the suggestion of Evans and Rothery.

EFFECTS OF TIME ON DISCRIMINATION

The two possible forms of detection criteria, $\frac{U\sqrt{T}}{S}$ = const and $\frac{\Delta S}{S\sqrt{T}}$ = const, both fit the experimental data with equal accuracy as one form is easily transformed to the other. The problem is then to find some basis on which a decision may be made as to which is actually being used.

By transposing these equations, it is seen that the threshold value for $\frac{U}{S}$ decreases with viewing time and that for $\frac{\Delta S}{S}$ increases with viewing time. First, it would appear unreasonable to accept a criterion whose sensitivity decreases with more time available to take in information. On this basis $^{\Delta S}/_{S}$ would be rejected. Secondly, the well validated model of Crossman, (See Welford, 1968) for the effect of time on discrimination, predicts that

$$d^1 \propto \sqrt{T}$$

where d^1 is the distance between the distribution means of signal detection theory. This model would then predict that, as viewing time increases, so the subjects' ability to discriminate increases, i.e., his threshold is lowered. The criterion based on the measure

U/S is in agreement with this requirement. If, in the signal detection model, d^1 is approximately proportional to U/S and the threshold is taken at $d^1 = 1.25$ (corresponding to an unbiased detection probability of 0.75 in a Yes-No form of experiment) then the relationship of equation 1 would be predicted by the signal detection model. In general the value of d^1 is not simply proportional to U/S but is likely to have a constant added to it, hence the predicted relationship may not be exactly that of equation A1.

EVIDENCE FOR HUMAN PERCEPTION OF U/S

The evidence available is indirect. Farber and Silver (1967) demonstrated in an overtaking study, that subjects could approximately estimate 5 and 10 second headways when they were overtaking a lead vehicle. This headway time is in fact S/U which is simply the inverse of the detection criterion. In these experiments, it was apparent that subjects could <u>scale</u> S/U; nothing was reported on detection in these terms. A study by Hurst, Perchonok and Seguin (1968) on gap acceptance also indicates that time estimations of this type are used by drivers in accepting or rejecting gaps in a traffic stream. In a similar way, a number of car-following models (which provide a reasonable fit to the data) assume that the driver's acceleration is to the stimulus of a relative velocity divided by the headway (Herman and Potts, 1961).

There is also evidence contrary to the model of Evans and Rothery. The data of Baker and Steedman (1961), as analyzed by Evans and Rothery, show a decrease in the threshold value of U/S only for T>2 sec, possibly due to time lost in accommodating and fixating. The experiments of Todosiev and Fenton (1966) give results which may be approximated by

$$\frac{UT}{S^2} = \text{const} \propto \Delta\theta$$

i.e., in this experiment, the effect of viewing times between 0.3 and 5 seconds was simply to alter the threshold relative velocity in such a way that detection occurred at a constant change in the subtended visual angle. Nowhere else in the literature has such a result been obtained and the result may well be due to an artifact of the experiment.

LIMITS OF THE U/S CRITERION

It is noted that in the two experiments in which the data support equation A1, the angular velocity of the lead vehicle, under nearly all conditions, was below threshold. Further investigation of the effects of angular velocity is needed.

Appendix D

INSTRUCTIONS (EXPERIMENT 2)

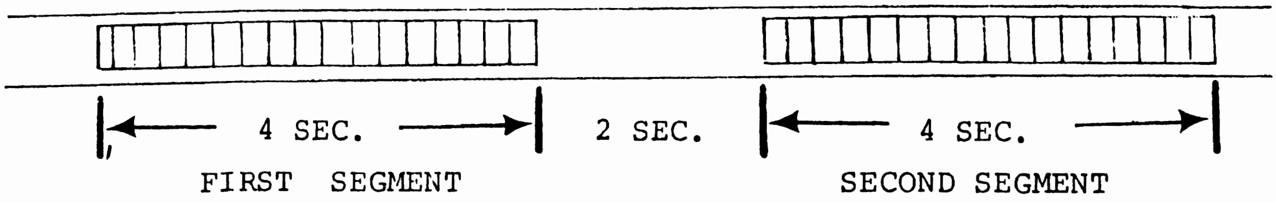
STUDY OF ESTIMATION OF RELATIVE SPEED

Sealing Experiment

In this experiment you will be shown a series of short film segments and you are required to make some estimates about the relative speeds of the cars you see in the films.

The films have been made from a car which is approaching a car ahead of it. In all cases the car is approaching, but in some cases the approach speed is very small.

(In each trial) you will see two film segments, each 4-seconds long, and separated by blank film of 2-seconds duration.



After viewing these two segments, the projector will be stopped and you will be required to record on the response sheet:

(a) Which of the two segments had the faster speed of approach between the two vehicles? If the speed of approach was faster on the first segment, write a "1" on the sheet provided. If the speed of approach was faster on the second segment, write a "2" on the sheet provided.

(b) The <u>ratio</u> of the speeds of approach of the two vehicles. Write a ratio for each comparison which indicates how many times faster one pair of cars is approaching than the other. For example, after viewing the two film segments of 4-seconds each, if you think that the cars on the first segment are approaching at a faster speed than the two cars on the second film segment, and that the approach speed on the first segment is twice as fast as on the second segment then you would write:

(a) "1" in the first column of the response sheet.

(b) 2 (the speed ratio) in the second column.

You can use fractions or decimals for the ratio, i.e., 1.5, 1½ or 1.5 to 1 to indicate that one pair of cars is approaching at 1½ times the speed of the other pair.

Appendix E

INSTRUCTIONS (EXPERIMENT 3)

STUDY OF ESTIMATION OF TIME TO CLOSURE

In this experiment you will be shown a series of 48 short film segments of a car being approached from behind. The film is stopped after a short interval and you are required to estimate the moment at which the two vehicles would collide if the approach speed remained the same. In all cases the leading vehicle is being approached, although the approach speed may be small. Some of the film segments are presented for only a small time so it is essential to give the task your full attention once the projector has been started.

At the end of each film segment you should estimate the moment of collision and press the response key when you consider the collision to have occurred, that is, the vehicle in which you are traveling has made contact or touched the rear of the vehicle being approached.

When you have made your response, the next film segment will be shown.

Any questions?