DETERMINATION OF THE TIME LAG TO

PERCEIVE VELOCITY CHANGES IN CAR FOLLOWING

A METHODOLOGY

by

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Lucien Duckstein　　　　21 June 1966

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ABSTRACT

A general discussion of car following theory is given and experimentation described. The purpose of the experiment was twofold; first, to determine whether photographic simulation can be used in the laboratory to conduct valid observation on human detection time to change in velocity of the car directly ahead of the subject's car; and secondly, to determine actual road test detection times for gaps of 80 feet and base speeds of 40 mph. Both acceleration and deceleration trials were held. Preliminary results showed that the simulation is feasable and detection times are given in the thesis. With photographic testing, experiment time and costs are decreased considerably. An unexpected result was obtained. Detection time for deceleration was found to be greater than detection time for acceleration for the conditions under which the test was run. An explanation is given and a hypothesis set forth. Detailed explanations of statistical design and analysis and test instrumentation is given. The thesis ended with recommendations for future work.

CHAPTER I

CAR FOLLOWING:

THE MAN-MACHINE SYSTEM

Introduction and Scope

Modern Engineering rests on a base of experimental and theoretical work in the sciences as well as on the works of centuries of our engineering predecessors. The time lag between scientific discovery and engineering application has in recent years been shortened tremendously. A new tool in the engineering field is the "systems approach" where the area under study is treated as a complete system encompassing all phases of operation to include human, automata or a combination of both.

Presently a program is underway in the Systems Engineering Department of the University of Arizona which concerns itself with the problem of traffic flow on road networks. The basic problem of traffic flow is to maintain the greatest volume of flow on a thoroughfare while still adhering to the principles of road safety and driver competence. Montroll and Potts (1964) have indicated that "traffic phenomena is largely characterized by the behavioral sciences rather than the physical sciences because of the man-machine dynamics of the system." From this statement, it is proper to suggest that traffic flow is really a study of an isolated driver-car system which will interact with similar systems under conditions of close proximity. Until more explanation is given, close proximity will be assumed to be within the range of vision of either driver.

The scope of this thesis is concerned with a study of visual sensing of velocity changes and the time taken to perceive these changes. Specifically, the questions to be answered are:

1. In a car-following situation, how long does it take the driver of the following car to detect a speed change in the car ahead of him?
2. Can this experimentation be performed in the laboratory by using two-dimensional motion pictures to simulate the road test?

Some experimentation has already been done in answering these questions, however, the most precise work was done under fairly "sterile conditions" on a restricted test track or under other prearranged conditions. Other studies have been open to question because of failure to control or accurately measure car separations. The experiment described in this thesis was done on normal stretches of desert highway. In addition the subject under test was not driving the car so that he was not concerned with familiarization of the test car. This in itself saved much costly testing time. The photographic simulation is an attempt to further reduce test time and lead the way to large scale testing of small groups. The simulation may be especially valuable to the military services or the trucking industry who, in an effort to attenuate the accordion effect in convoys, may select drivers whose perception times are low and place them strategically throughout the column.

Early Investigation

Greenshields (1934) conducted one of the first significant experiments in the area of traffic flow. By taking motion pictures of traffic leaving a sports stadium, he developed an empirical formula for the recommended spacing between vehicles at various speeds. The formula in its original form is

$$S=21+1.1V.$$

S is the spacing in feet.

V is the velocity of the second car in miles per hour.

The formula is similar to the California law of 15 feet in spacing for every ten miles per hour of velocity. He also developed equations describing the flow of vehicles past a point. A significant note in Greenshields' paper was the mention of a variable in his calculations which he called the driver performance term. Unfortunately, the matter was not investigated and lay dormant until a later time.

The Flow-Concentration Curve

In order to gain a basic understanding of traffic flow phenomena, it is necessary to introduce the largely empirical description of the flow-concentration curve. If we recall the familiar formula, distance equals velocity multiplied by time, we may write it in reciprocal form:

$$\rho = \lambda \mu$$

where ρ=flow in cars per time unit

λ=concentration in cars per distance

μ=speed.

From this relation, we should be able to plot a function which theoretically has no limit. However, even the person ignorant of traffic theory has experienced the slow movement of cars in a traffic jam. Therefore a limit on the number of cars concentrated in an area must exist and consequently limits must exist on flow and speed. Lighthill and Witham (1955) in their hydrodynamic approach to traffic flow have hypothesized the existence of a curve which describes the flow of traffic past a point on a roadway. Empirical data has supported the hypothesis.

The fundamental hypothesis of the theory states that at any point of a road the flow $\underline{\rho}$ (vehicles per hour) is a function of the concentration $\underline{\lambda}$ (vehicles per mile).

We must now examine the quantities $\underline{\rho}$ and $\underline{\lambda}$ to determine their variations and functionings. If a section of roadway is observed from a point (x), a small increment dx may be selected with the point (x) at its center. Let us also establish a time (t) in the middle of a time increment τ. Assume that n vehicles pass point x and clear dx in time interval τ. (n is a large number.) The flow may now be expressed as:

$$\rho = \frac{n}{\tau} \tag{1}$$

Similarly, the concentration figure,

$$\lambda = \frac{\sum_{k=1}^{n} t_k}{dx} \tag{2}$$

where the quantity under the summation sign indicates the time required for vehicle to cross dx and has the dimensional unit, car-time. A dimensional analysis of formula (2) results in λ being equal to the cars per unit length of road.

The quantity μ may now be defined as:

$$\mu = \frac{\rho}{\lambda} = \frac{dx}{\frac{1}{n}\Sigma t_k} \tag{3}$$

The limits on the summation have been dropped for convenience. A close look at μ shows that it is the ratio of the increment of road, dx, to the average time it takes to cross dx. The quantity is known as <u>space-mean speed</u> and represents the average of vehicle speeds weighted according to the time they remain on the increment of road. The relation between flow and concentration may take on different forms. At low values of concentration the space-mean speed is a function of the flow. In other words as flow or the number of vehicles passing point x increases, the mean speed will decrease. The decrease may be attributed to interference caused by overtaking slower vehicles and passing them. When concentration is high, mean headway or the time interval between cars passing point x is considered a function of space-mean speed μ. This behavior is caused by driver interaction and the attempt to prevent rear-end collision. The effect is one of almost linearly increasing headway with increasing speed. Of the three quantities ρ, λ and μ, only λ has a theoretical upper bound or maximum which corresponds to the situation of cars on a road with zero headway between them. The flow, ρ, will assume an observed maximum which is called the capacity of the road. μ has a practical limit and we may assume that it is nominally the legal speed limit on the roadway under observation.

From experimental observation and logic there are sufficient grounds to assume that the conditions of low and high concentrations may be combined into a single curve as shown in figure 1.1. If concentration is zero, then flow is also zero for the simple reason that if there are no vehicles, there can be no flow. Similarly, if the concentration is a maximum, flow again is zero because in this case the condition of a road jam exists. Now between these two values $(0<\lambda<\lambda')$, since we have assumed a continuous curve, some maximum must occur which may now be considered the capacity of the road. Haight (1963) has arrived at two forms for the fundamental diagram which have been obtained from experimental data without theoretical consideration.

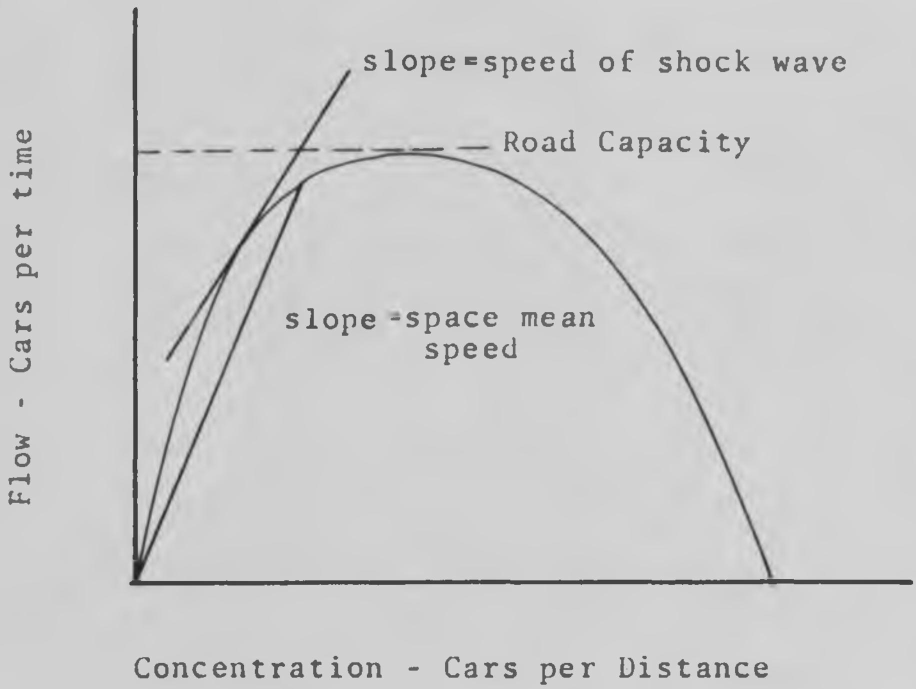

Figure 1.1. The flow-concentration curve.

Using parameters μ_o which represents the mean speed at zero concentration and λ' which is equivalent to maximum concentration, he obtained:

$$\rho=\lambda\mu_o(1-\frac{\lambda}{\lambda'}) \tag{4}$$

and
$$\rho=\frac{\mu_o\lambda(\lambda'-\lambda)^{1/2}}{A\mu_o\lambda^2+(\lambda'-\lambda)^{1/2}} . \tag{5}$$

Where A is a suitable constant.

An idea of the practical use of the fundamental diagram or flow-concentration curve can be obtained from the following geometric example. For any point on the curve we may apply equation (3) to determine the space-mean speed. This is however, equivalent to the slope of the radius vector from the origin to the point on the curve. Now if some perturbation in flow occurs, a shock wave will be generated which will propagate backward through the stream of vehicles and cause a reduction in velocity. The speed of the shock wave may be defined as:

$$\nu_s=\frac{d\rho}{d\lambda} \tag{6}$$

This is geometrically defined as the slope of the flow-concentration curve. ν_s may also be defined as follows:

$$\nu_s=\frac{d}{d\lambda}(\lambda\mu)=\mu+k\frac{d\mu}{d\lambda} \tag{7}$$

<u>ν_s is equal to μ only at very low concentrations where cars do not interact with one another.</u>

One final point should be emphasized with regard to the fundamental diagram. No single diagram is applicable to all roads and situations. The shape of the diagram is largely one of empirical determination and a good mathematical model of the curve does not exist. In addition, the portion of the curve with negative slope is very unstable. The concept is a valuable working tool which can be applied to a particular road at a particular time. Manual and/or automatic counting equipment will assist in gathering data for an empirical plot or family of curves which then may be used in the traffic analysis for that area.

Car Following

Car following or follow-the-leader theory attempts to model the behavior pattern of a single lane of heavy concentration traffic. No passing is allowed. The emphasis is on how cars follow one another in the line of traffic.

A definition of the Weber law (Scientific Encyclopedia, 1962) is:

"A psychophysical relationship which states that the minimum perceptible difference between the physical magnitudes of stimuli is a constant fraction of one of them". In less rigorous terms the law says that an automobile driver's response is a function of the product of the environmental stimuli and a factor known as the driver's sensitivity constant. Herman and Gardels (1963) point out that the driver's response is manifested through his accelerator and brake in the one lane, no passing situation. This corresponds to positive and negative acceleration. Experimentation in car following (Herman and Potts, 1961) indicates that variations in spacings between cars are caused primarily by the driver's reaction to the speed differential between his car and the vehicle ahead of him. The distance between vehicles has a secondary effect of varying the sensitivity of differential detection of the driver. The driver will vary the speed of his car to minimize any detectable difference in relative speeds. Two hundred feet of spacing between vehicles at 25 mph is a good example of where detection sensitivity is very low and we may say that the following car at this distance is not greatly influenced by the actions of the lead car.

Chandler, Herman and Montroll (1958) have written an equation to describe the stimulus-response behavior of the driver-car system. The differential-difference equation is expressed as follows:

$$\ddot{X}_n(t)=b[\dot{X}_{n-1}(t-h)-\dot{X}_n(t-h)] \tag{8}$$

X is the following distance of the nth vehicle.

n is the length of the queue (long).

t is time.

h is the time lag or latency of response of the system.

b is a constant of proportionality with dimensions of $\frac{1}{\text{time unit}}$.

The latency of response may further be broken down into three terms which represent the time it takes the driver to detect a change in relative velocity, the driver's reaction time and the response time of the vehicle. <u>The subject under investigation in this thesis is the first term.</u>

Equation (8) was arrived at in the following manner. The equation of motion for vehicles which have the same mass, M, can be written as:

$$M\ddot{X}_n(t)=\lambda(\dot{X}_{n-1}(t)-\dot{X}_n(t))$$

λ is now a constant of proportionality representing the sensitivity of the system. The equation can be generalized to include the lag in driver-car response by introducing a weighting function $s(\tau)$ as follows:

$$M\ddot{X}_n(t)=\int_0^\infty[\dot{X}_{n-1}(t-\tau)-\dot{X}_n(t-\tau)]ds(\tau)$$

and $s(\tau)$ is made equal to the expression, $\lambda\nu(\tau-h)$ where $\nu(\tau)$ is a unit step function.

$$s(\tau)= \begin{array}{ll} 0 & \tau<h \\ & \tau>h \end{array}$$

signifying that the function $s(\tau)$ vanishes when τ is less than latent response.

$s'(\tau)=\lambda\delta(\tau-h)$ where δ is a dirac delta.

The condition of $\tau<h$ may be ignored.

$$M\ddot{X}_n(t)=\lambda[\dot{X}_{n-1}(t-h)-\dot{X}_n(t-h)]$$

and

$$\ddot{X}_n(t)= \frac{\lambda}{M}[\dot{X}_{n-1}(t-h)-\dot{X}_n(t-h)].$$

$\frac{\lambda}{M}$ may now be replaced by the constant b which is the form of (8). The equation (8) described is really an empirical speculation of a form of Newton's second law and is not wholly satisfactory even though the logic in its derivation is plausible. The relationship does indicate that following car response is a function of the relative velocity between cars.

Gazis, Herman and Potts (1959) went further into the theory to try and obtain an equation which included an expression for the sensitivity variations caused by spacings. Equation (8) was written as follows:

$$\ddot{X}_n(t)=A\left[\frac{\dot{X}_{n-1}(t-h)-\dot{X}_h(t-h)}{X_{n-1}(t-h)-X_n(t-h)}\right]$$

This equation may be obtained directly from Weber's law which states:

$$\Delta V=\alpha\frac{\Delta S}{S}$$

where V=velocity, S=spacing, and α is a constant of proportionality, dividing by Δt,

$$\frac{\Delta V}{\Delta t}=\frac{\frac{\Delta S}{\Delta t}}{S}$$

and
$$\ddot{X}_n(t)=\alpha\left[\frac{\dot{X}_n(t)-\dot{X}_{n-1}(t)}{X_n(t)-X_{n-1}(t)}\right]$$

the latency term may be incorporated in similar fashion to that described previously.

Haight (1963) summarizes the car-following approach very nicely by the following quotation:

"The method of 'car following' is psychological conjecture supported by empirical verification. It is assumed that each car follows its leader in a purely deterministic way which can be expressed by a certain differential equation. The differential equation is simply guessed at; the resulting flow-density diagram is then compared with data."

CHAPTER II

PREVIOUS EXPERIMENTATION IN DRIVER RESPONSE TIME

Engineers and Psychologists have conducted many experiments in car-following, driver response time, speed judgment and distance judgment, however, some of the experimental techniques have lacked precision or realism. Foote (1964) mentions three immediate factors which tend to limit traffic experimentation. These are:

1. The inaccessibility of experimental situations for most theorists.
2. The expense of instrumentation for the experiments.
3. Data reduction time.

In the analysis of the past experimentation, it appears that the second reason is the major concern; the first reason is a close second.

Four road tests will now be described. They have been chosen as typical of the testing being done to date. Prior to going into the details of the experiments, a description must be given of the General Motors car follower (Montroll and Potts, 1964).

The car follower is an accurate instrument package which is used in a follow-the-leader situation. The base is mounted on the front bumper of the second car. On the base is a motor driven reel containing many turns of piano wire. The motor fulfills the function of maintaining a constant tension on the piano wire by means of a slipping clutch and is also used to rewind the piano wire. A d-c tachometer is coupled to the reel to measure revolutions per minute and a Helipot-battery circuit, also attached to the reel is used to measure revolutions. Under test conditions, the end of the piano wire is attached to the lead car. Readings from the tachometer generator and potentiometer are recorded on a multi-channel oscillograph. The instrument is capable of indicating separations and relative velocities. For this type of measurement, the car follower is entirely adequate and provides a fine degree of precision. The disadvantage of the device is the requirement for the piano wire link between cars. The technique cannot be used on an open highway for obvious reasons unless a police escort is provided. This was the major reason for not using the car follower in the experimentation conducted in this thesis. Furthermore, information obtained at the 45th Annual Highway Research board meeting (Jan., 1966) reveals that G. M. has given up this method for a telemetry system.

Single Lane Traffic Theory and Experiment

In a classic paper, Herman and Potts (1961) conducted experiments to determine validity of some of the formulae developed in car-following theory. Two cars were used to test eleven subjects. The General Motors car follower was used in the experiments. Oscillographic records were kept of spacing, relative speed, following car velocity and following car acceleration. The tests were conducted in the Lincoln, Holland and Queens Mid-town tunnels in New York City. Normal tunnel operating conditions prevailed with traffic flow densities varying from very high to very low. Further tests were conducted at the General Motors test track. The authors found that the results of the tests seemed to support the reciprocal spacing law,

$$\ddot{X}_n(t+T)=\frac{\alpha_o(\dot{X}_n(t)-\dot{X}_{n+1}(t))}{X_n(t)-X_{n+1}(t)}$$

where α_o is the characteristic speed. They also found that driver-car response time to changes in lead car velocity varied from 0.8 seconds in the Queens Midtown tunnel to 1.4 seconds in the Holland tunnel. Characteristic speed was approximately 20 miles per hour. Car spacing was not held constant and varied considerably.

The experiments were highly successful, however, the measurements made included detection, driver response and car response times lumped together. No attempt was made to differentiate between the times.

Japanese Experiments

Kometani and Sasaki (1961) conducted an experiment to determine driver detection time. Two cars equipped with "fifth wheels" and oscillographic recorders were used. Synchronization of the recorders was obtained through giving a verbal signal over a radio link. The authors reported the error in synchronization to be less than 0.1 second. Car speeds were recorded but the spacing between cars was not, due to lack of equipment. The experiment itself was simple and required the driver under test to follow a car through city streets and respond to speed changes in the lead car. Detection times of 0.75 second were reported, however, the authors indicate that the results were inconclusive due to large experimental error.

Effects of Intervehicle Spacings and Accelerations.

Braunstein, Laughery and Siegfried (1963) conducted a test which examined the effect of intervehicle spacings and accelerations on velocity change detection by the driver in a car following situation.

Two cars were used, with instrumentation in the lead car only. Radio communications were available between the two cars. The apparatus in the lead car consisted of a velocity measuring voltmeter and oscillograph which were driven by a tachometer generator coupled to a fifth wheel. Accelerator pedal displacement was also measured on the oscillograph. A motion picture camera in the lead car photographed the following car at a rate of two frames per second in order to get a record of spacing.

Tests on eight subjects were described. The subject was seated in the passenger seat of the following car and held a radio telephone handset. When the word "ready" was heard, the subject was to watch the lead car and try to detect a velocity change. His response was signalled to the lead car by pushing the talk button on the radio and saying either "plus" or "minus" to indicate detection of a velocity increase or decrease. The receipt of the voice response was displayed as a pulse on the oscillograph. Prior to the recorded tests, the subjects went through at least 20 practice trials. Distances maintained were 200 feet and 300 feet with a baseline velocity of 55 miles per hour. The driver of the following car attempted to maintain the specified distance using roadside reflector posts as a guide. Results of the test showed that the time to detect speed changes was significantly affected by distance but not by acceleration rate. On the deceleration tests, findings were that both distance and deceleration rate significantly affected the subject's response. It is also noteworthly that the latencies or detection times of a speed change varied from 4.7 to 5.9 seconds for the different acceleration treatments and from 5.2 to 6.6 seconds for decelerations.

The authors admit that their methods of controlling lead-car velocity, acceleration and spacing lacked precision. A second source of error was the driver response time in speaking into the transmitter. One of the more controversial points is that the spacings of 200 and 300 feet were not realistic and essentially made the following car response relatively insensitive to lead car maneuvers. The experimental results, although lacking precision do indicate that in acceleration, detection time increases somewhat linearly with distance.

Test of Total Reaction Time Using the GM Car Follower

Bierley (1963) investigated the use of an inter-vehicle spacing display in an effort to stabilize car spacing. The experiment had some by-products which are of value to the subject of this thesis. A 1961 Chevrolet was equipped with a car follower apparatus and the experiment was performed at the General Motors test track. A base speed of 45 miles per hour was used and acceleration and decelerations of 3 feet per second squared were the treatments. Eighty foot spacings was used. Twelve drivers were tested and of these only four were treated with no display information. The lead car would accelerate and the following car would accelerate in response to the lead vehicle. The reaction time which included car response, subject reaction time and detection time was read from the oscillograph record which displayed four functions:

a. Lead car speed

b. Following car speed

c. Relative speed

d. Spacing

Bierley found that average total reaction time for acceleration was 1.72 seconds and on deceleration 1.59 seconds. No standard deviations were given.

In a second test he found that average total reaction times were 1.69 seconds for both acceleration and deceleration. He also concluded that response time was virtually independent of the different acceleration and deceleration rates. After obtaining the figures, he then subtracted 0.50 from the reaction times in the second set of acceleration tests and 0.69 from the deceleration test data to get detection time. The constants .50 and .69 were obtained from previous literature and involved decision time for a two-choice situation. He appears to have left out the response time of the vehicle.

The data obtained is interesting, however, a truly accurate determination of detection time was not made due to the estimated decision and driver response constants.

Comments

In the four experiments described above, work on the two experiments designed to measure driver detection time lacks precision in that threre is much experimental error inherent in the experiments. The work is valuable however since it gives an estimate of the time area in which the detection time can be found. The two experiments on car following contained precision but measured total response time of the driver-car system under idealized conditions.

The experiment described in this thesis will attempt to measure only detection time exclusive of driver and car response times. Following distance and base speeds will be kept constant insofar as possible by using a speed regulatory device and stadia lines inscribed on the car windshield.

CHAPTER III

ROAD TESTING AND SIMULATION WITH RESPECT TO HUMAN FACTORS

The Conceptual Car Following Task

Algea (1964) at the Ohio State University developed a conceptual framework of the driver task based on observations of driver behavior under actual road conditions. Braunstein et al. (1963) did similar work at the Cornell Aeronautical Laboratory in an attempt to simulate a model of the task on a digital computer.

From the moment a human is placed behind the steering wheel of an automobile he becomes an integral part of a complex man-machine system. In the car following task, the driver becomes a pursuer tracking a target represented by the car directly in from of him. Under the more common situation, where traffic is congested, some influence is obtained from the actions of cars further up the line; however, we shall examine only the simple two car situation. An isolated driver will not be influenced by his traffic environment if the headway between himself and the nearest car is greater than 11 seconds or somewhat over 200 feet (Edie and Foote, 1958). As the driver approaches closer to a leading car and decreases his headway, he gradually becomes a pursuit tracker. The relative location of the lead car or target and his own vehicle are known by the tracker in the search link. Appropriate control gain will bring the pursuit driver to a set following distance behind the target. The distance is a function of the driver and usually results in increased vigilance if decreased. This action was noticed during the conduct of the road tests while the following car driver was adjusting distance. If the subject thought the gap was too small, he would become apprehensive and try to pump an imagined brake pedal on the floor. After reaching this distance the driver will, from a series of visual stimuli, lock onto the target even though it continues to move. On the long, relatively straight highway, the driver can anticipate the trajectory of the target and facilitate his tracking task. During accelerations or decelerations by the target, the input to the pursuer is a step function requiring a differential determination, which results in a compensatory speed change to maintain proper following distance by keeping the relative velocity of the two cars equal to zero. Under steady driving conditions, the input is theoretically a ramp function corresponding to a constant velocity. Actually, road grades, curves, wind, etc. make a pure ramp function impossible and a pseudo-oscillation, whose axis is the ramp function, occurs. Since the velocity changes are usually small, the oscillations are also small in amplitude. Olson et al. (1961) found that over a range of relative speed differences between cars of from 0 to 30 mph, humans tend to be quite accurate in determining whether a gap is opening or closing. He also determined that accuracy of judgment increases as the gap decreases and that judgments are more accurate when the gap is closing than when opening. McCormack (1964) hypothesizes that this type of behavior may be classified as rate control tracking where velocity is the controlled variable. Unfortunately, the human variable destroys the concept of perfect tracking and we must now examine the mechanism of perception and delay in responding to the speed change stimulus.

Weber's and Fechner's Laws

In prior portions of this thesis, inferences have been made to stimulus-response characteristics as implied by Weber's ratio. The Weber ratio is one of the best known laws of psychophysics and may be used as a basis for the derivation of the car following laws. The relationship has been found empirically to hold fairly well over most of the stimulus range but it does not hold true near the terminal stimulus values or in the proximity of the absolute threshold. Fechner simply integrated Weber's fraction and obtained a general statement about the relation between physical stimulation and mental stimulation:

$$\text{Sensation} = k \ln \text{stimulation},$$

which is known as Fechner's law. Similarly, if we take the Weber form of the car following law (Gazis, Herman and Potts, 1959)

$$X(t+T) = \alpha_o \frac{\dot{X}_1(t) - \dot{X}_2(t)}{X_1(t) - X_2(t)} \tag{1}$$

let $$i(t) = X_1(t) - X_2(t)$$

$$\int_0^{\frac{1}{L}} X(t+T)\,dt = \alpha_o \int_0^{\frac{1}{L}} \frac{di}{i}$$

$$\dot{X}(t+T) = \alpha_o \ln\frac{i}{L}$$

$$\dot{X}(t+T) = \alpha_o \ln\left[\frac{X_1(t) - X_2(t)}{L}\right] \tag{2}$$

where L is the length of a car. Equation (2) is now the Fechner form of the "reciprocal-spacing" car following law.

Perception of Sagittal Motion

The problem of relative motion judgment may be classified into three separate cases.

I. Fixed subject, moving object

II. Moving subject, fixed object

III. Moving subject, moving object.

Case I has been studied extensively by Brown (1931) and Ludvigh (1949) and summarized in Graham (1965).

Case II has been studied primarily from the moving aircraft or aerospace systems approach. The major problem here is with direction of relative motion and methods of indicator design. Gardner (1957) and Fitts (1951) were two of the principal investigators.

Case III information is relatively sparse however, information is being collected more frequently with the increased activity in studies of the human variables influencing traffic flow.

Let us now define the area which is being studied in this thesis as a division under Case III and refer to it as "sagittal" or "radial" motion.

Sagittal motion as differentiated from transverse motion is the motion phenomenon seen when the subject remains stationary and observes an object moving parallel to his visual axis. In the car following sense the motion will be on the driver's visual axis or very close thereto. Leeper (1963) provides a definition of perception which is as follows:

"A mental complex or integration which has sensory experiences at the core."

The definition is particularly applicable to car following since in this type of motion, the driver of the second car is required to reconcile a mental set of conditions which involve variables such as distance and size expressed as rates with respect to time. The variables involved are known as perceptual cues. In the static case or the situation where the velocities of the two cars are exactly the same, the following driver will perceive the lead car to have a constant size and be of a fixed distance from him. As soon as the velocity of one of the cars changes, the following driver will see a corresponding change in size and distance. These changes together provide a cue to the observer that a speed change is taking place. A third cue is a change in visual acuity. Ludvigh (1949) has found that visual acuity is relatively poor for a moving test object even when the eyes appear to be successfully pursuing it. A contributing factor may be the central inhibition of vision which seems to be coupled with voluntary eye movements. The cue is not a prime factor in radial motion because the eye in tracking an object varying slightly about its visual axis does not move in sufficient amount to cause the inhibition, however, if the target is moving with sufficient velocity the blurring effect is noticeable.

Brown (1960) has surveyed the literature on visual discriminations of velocity and analyzed some of the data. The data was taken from experiments in which viewing distance varied. Therefore, Brown decided to express speed in units of visual angle per second. The ordinates and abscissae of the curve were differential thresholds and speed, both expressed as angular velocities. A linear fit was made to the data and the slope found to be 0.10 which represents the Weber fraction. The Weber ratio now provides a measure by which velocity discriminations may be compared with other sensory perceptions. Brown also points out that the linearity may be inherent only to a restricted range of stimuli. Chandler et al. (1958) previously reported that drivers react mainly to relative velocity rather than distance in following. Brown claims that because of the restricted range of stimulus, this report may be questioned and that future research may show that under varying conditions, the systematic effect of other variables will become apparent.

An area which has not undergone extensive research in the literature is that of rate and displacement thresholds in car following. Some work has been done in the laboratory. Brown (1931) found that a lower threshold for just discernible movement is of the order of 2 to 6 minutes of arc per second. Length and width of the field of view, as well as object size and distance are the important parameters to determine threshold magnitude. Graham (1965) mentions the work of Aubert who in 1886 determined the absolute threshold for rate under several conditions to be of the order of 1 to 2 minutes of arc per second. Thresholds for peripheral vision are about 10 times higher.

<u>Latency of Response to Velocity Changes</u>

As mentioned in Chapter I, the latency of response of the driver-car system is the sum of three variables: perception time, reaction time and car response time. Perception time may be further broken down into detection time and decision time.

Mashour (1964) conducted a series of laboratory tests on reaction times to moving light stimuli. Reaction time was defined as "the global time of latency which stands between the moment when the stimulus is presented and the moment when the overt response is registered." The global time can be dichotomized into a series of delays that occur at various levels of the nervous system. The majority of the delay (70 to 90 percent) is caused by the slow response of the motor processes of the brain which is from 7 to 32 times larger than the perceptual delays. Mashour in his experiments was actually using transverse motion which detection time is less than that for sagittal motion. Unfortunately Mashour could not measure detection time but calculated it from an empirical formula. In car following, detection time of motion may be very short, however decision time may be an order of magnitude larger and is dependent upon the time it takes the driver to resolve his mental functions involving distance, size, time and possibly visual acuity.

Photographic Simulation of Car Following

A major portion of experimental work in the Human Factors area deals with observations of human actions and conditions. Unfortunately the investigator is forced in many cases to conduct his research experimentation under conditions over which he has limited or no control. For example, in the experiments described in this thesis, the lead car operator had very little control on the exact magnitude of a high, low or negative acceleration. The magnitudes varied because of automobile ageing, grade of gasoline, atmospheric pressure, etc. In addition the cost of road testing has been described previously. If it is possible to obtain desired results with a motion picture, conditions can be controlled much more closely and costs reduced. As an example, from analysis of the film taken during road testing, values of accelerations, following distances, base speeds, etc. are known. The only variable left uncontrolled is the human variable for which we can get an approximation within confidence limits by testing large numbers of subjects. The road test from start to finish required two hours of subject time which included movement to the test area, installation and calibration of equipment, the test runs, removal of equipment and return to the base of operations. The laboratory test requires at most fifteen minutes of the subject's time. Photographic simulation seems to be a good answer to the problem however, it too has its limitation.

The major difference in the two dimensional mode is between visual observation and cinematographic recording. The human eye has an effective field of vision covering a horizontal angle of 120° (somewhat less for persons who wear glasses). The normal 25mm lens in a 16mm movie camera covers an angle of only 21°. Wide angle lenses are available, however a distortion of perspective is produced. This narrow angle of vision has an important influence on the viewer. It immediately focuses attention on the viewed object. In car-following, some of the attention gainers, such as roadside environment, are lost in photographs because of the narrow viewing angle. In order to compensate for this loss, the test site was chosen in a desert environment where distractions are attenuated by the bare landscape. In addition, under the condition of vigilance, the subject was concentrating on the lead car with possibly an effectively reduced visual angle characterized by foveal vision.

A second difference which could not be overcome at this time was the problem of stereopsis. Initially, an attempt was made to obtain a camera which contained two lenses at inter-ocular spacings, each exposing a separate roll of film in synchronism. The approach was temporarily abandoned due to the non-availability of standard equipment and high costs of custom fabrication. The problem is still under consideration in another phase of work in the Human Factors studies presently being conducted at the University. Another and possibly more practical reason for deleting the three dimensional requirement was the mild loss of stereopsis sensitivity at the distances over which the test were carried out (80 ft). If tests are carried out at shorter distances, stereopsis may prove to be the major problem.

Further considerations were size of the film and exposure speed. Two films were considered; 16mm and 35mm Kodachrome II daylight film. Here, costs and size limitations were the major factors in selecting the smaller film. In a small theater, one can project 16mm film and get results which are almost indistinguishable from 35mm film as far as stability (bounce) of the picture is concerned. Kodachrome film was used because of its direct reversal and color fidelity properties. If a negative film were used, the printing process requires direct match of negative to positive film. Occasionally, if processing machines are not properly adjusted, slight mismatches may occur with resulting picture instability. Film exposure speed was determined from the following equation (Waddell, 1953):

$$\text{camera speed} = \frac{(40)(\text{subject speed in inches per second})}{\text{Total width of the subject field in inches}}$$

The calculation resulted in approximately 24 frames per second as camera speed which was very fortunate since standard sound movie projectors operate at 24 frames per second.

Projection

Projection in professional motion pictures involves the successive presentation of 24 physically still pictures per second, each being presented three times. As long as the projector and viewing conditions remain within certain limits, the displaced image on the screen will appear to move smoothly. Motion picture projection is manifested by the beta phenomena of apparent movement. Beta movement is usually concerned with two types of apparent movement; stroboscopic and phi. Most experimenters seem to agree that phi movement is absent in motion pictures (Levonian, 1960). A number of factors contribute to the perception of apparent movement in motion pictures. They are:

a. Displacement of the image between successive frames.

b. Number of shutter interruptions per frame.

c. Projection intensitities of the object and its background.

d. The visual viewing angle.

Factors a through c were compensated for by photographing and projecting at 24 frames per second and regulating the porjection lamp intensity to attenuate flicker and maintain professional quality in the production. Visual viewing angle was taken care of by adjusting the camera as close to the subject's eye level as possible. In the projection room the subject was seated in front of a screen which simulated the windshield of the automobile. The projector throw was arranged so that the object image size and visual angle on the screen was very close to that seen on the road. Sound effects were not used with the film because of the lack of a realistic motor noise sound track and secondly, motor noise was virtually absent in the second car. Wind noise was evident but the noise of the projector masked the attempt to simulate the noise and since no velocity changes were signalled by noise, it was felt that acoustic contributions to the test would be superfluous.

The major lack of realism in the simulation occurred in the loss of driver peripheral vision due to the limited size of the screen in comparison to a windshield and the absence of lateral scenery flashing by. Attempts to enlarge the viewing area resulted in non-realistic lead car sizes on the screen. A second deficiency was the lack of a curved screen to simulate windshield curvature.

CHAPTER IV

THE EXPERIMENT

Road Test Instrumentation

In the conduct of the road test with subjects, control and/or recording was required for the following parameters

a. Lead car velocity changes

b. Following car velocity

c. Intervehicle spacing

d. Subject response

The test cars used were 1964 Pontiac and 1955 Ford Station Wagons. The lead car was the Ford. Some recording trouble was experienced with this car due to a tendency for its body to resonate at accelerations within the 30 to 40 mph range. The Pontiac was selected as the following car primarily for its clear windshield and response. The experimental area was a 3 mile relatively straight section of Interstate Highway 19 located within the Tucson (Arizona) city limits between Ajo Way and Valencia Road. Access and egress points were at the two cross streets. The road bed contained three lanes in each direction-two of concrete slab construction and the third of black top composition. Traffic on the road is normally light and the roadside environment, largely desert scrub. Speed limits on the road are 40 mph minimum and 60 mph maximum.

Initially, some thought was given to the use of the GM car-follower but road traffic risk considerations caused abandonment of this technique. This created a problem in measurement of car spacings and determination of relative vehicle velocities. The car spacing problem was handled in the following manner. Target stripes were placed on the tailgate of the lead car. The following car was fitted with a headrest so that the position of the driver's head would always be at the same distance from the windshield. The two cars were spaced at 80 feet and two stadia lines placed on the windshield of the following car. In order to set distance, the driver of the second car closed one eye and sighted through the stadia lines. When the target stripes were framed, the proper distance had been obtained.

In operating at fixed base velocities, human variation is too great at times to hold a constant speed by pressure on the accelerator pedal. A solution to this problem was arrived at through the use of a device commercially called "Cruise Control". The control was installed in each of the two cars and attached to the accelerator linkage. Upon stabilizing his car at a set velocity, the driver engaged the control and removed his foot from the accelerator pedal. If the car remained on a level stretch of roadway, the desired velocity was maintained with little variation. The control could be disengaged by application of the brakes, manually, or by switching off the ignition. Overriding for increased velocities was accomplished by applying more pressure to the accelerator pedal. Upon release of the pedal, the car returned to its base velocity. Some of the human error of spacing was also removed by the control because once speed and spacing were set, the control theoretically would hold them constant. Actually, some variation occurred because of small grades in the road and differences in car response.

Measurement of vehicle velocities and changes was performed by a combination fifth-wheel and recorder system. The fifth wheels were locally fabricated and used 26 inch bicycle wheels on a frame which was attached to the rear bumper of the car concerned. Balloon tires were used on the fifth wheel for maximum contact with the road bed. In order to keep the wheels on the ground and eliminate "bounce" effects, the wheel was spring loaded. Initially, the fabricator neglected to put a swivel on the apparatus with the result that, on mildly curving sections of road, the wheels were dragged and the frame developed a severe lateral oscillation. Incorporation of a spring-return swivel eliminated the oscillation. A Weston Model 750a tachometer generator was directly coupled to each wheel by installing a Chevrolet speedometer drive on the bicycle wheel axle. The generator was rated at 6 volts at 1000 RPM and had a linear output voltage over the range of 100 to 5000 RPM. Calculations initially showed that the voltage range generated in this application would be from 3 to 5 volts. Some question was raised as to whether ignition interference and stray fields would impair the accuracy of these low voltages; however, with the use of shielded cables, no interference was experienced. Both wheels were painted red and equipped with reflectors to make them conspicuous to other drivers. In the event of night testing, provisions are available for mounting of a red warning light. The recording device in the lead car was a 2-channel Sanborn Model 322 oscillograph recorder. The instrument in the second car was a single channel Esterline-Angus Model 0-291 recorder. Both recorders were capable of speeds of up to 100 millimeters per second and provided linear response from d-c to 90 cycles per second. Event markers and one second timers were basic to each recorder. Pens were of the inkless variety. Automobile vibration was a severe factor in the lead car during accelerations but the problem was overcome by shock mounting the recorders. Power for the recorders was furnished by Sanborn Model 53 battery converters. The full rated output of the converters was 125 volts at 60 cycles per second. The converters contained their own 12 volt batteries and were built with a 1 amp trickle charger to keep the batteries at full charge when not in use. Voltage and frequency was well regulated with a tolerance of 1 cycle.

A single channel voice-telemetry system was used for command control of the test vehicles. The radios used were Midland Model 13-120 transistorized transmitter receivers. Frequency used was 27.035 megacycles with a power output of 100 milliwatts. For voice operation, normal push-to-talk procedures were used and for the telemetry signals, a 400 cycle tone was available. The output of one radio was connected directly to channel 2 of the lead car recorder. The driver of the lead car also wore a headset bridged across the recorder input terminals so that he could hear both voice and tone. Test arrangements were such that channel 1 of the Sanborn recorder measured the velocity of the lead car while channel 2 indicated receipt of the tone corresponding to subject detection of speed changes. The Esterline-Angus recorder showed the constancy of the speed of the second car along with event pulses indicating turn-on and turn-off of photographic equipment. The instrumentation and chart appearances are shown in Figures 4.1, 4.2 and 4.3.

Photographic coverage was achieved through the use of a Bolex H-16mm movie camera. The camera was equipped with an electric drive motor and filmed at a rate of 24 frames per second. Kodachrome II daylight type color film was used. Exposure settings were determined by light conditions and read from a Bolex Lightmeter. A 25mm f1.4 camera lens was used. The camera was mounted on an automotive tripod adjacent to the subject under test and filmed the scene very closely as the subject saw it.

The test run sequence is given in Appendix B. Photographs of instrumentation are given in Appendix C.

Laboratory Procedure and Instrumentation

Laboratory testing involved two problems:

a. What is the normal reaction time of a subject to a low level stimulus?

b. What is the detection time of the subject to the road test accelerations when viewed photographically?

Test a was performed rather simply. A light source was placed in front of the subject. The lightbulb was operated at low voltage so as to provide low stimulus intensity to the subject. The light was operated from a push button switch which was connected to channel 1 of the Sanborn Recorder. The subject held the Midland Radio set in his hand and the output of the second set was connected to channel 2 of the recorder. The subject was instructed to activate his radio when he saw the light. This was done ten times. The average of the tests was classified as the subject response time and subtracted from the figures obtained on the road test. (Measurement of times was determined from the pulse separations on the same time scale.)

The instrumentation of the photographic test presented a more difficult problem, particularly in timing. The processed film was placed on a film editing machine and checked frame by frame for the start of an acceleration.

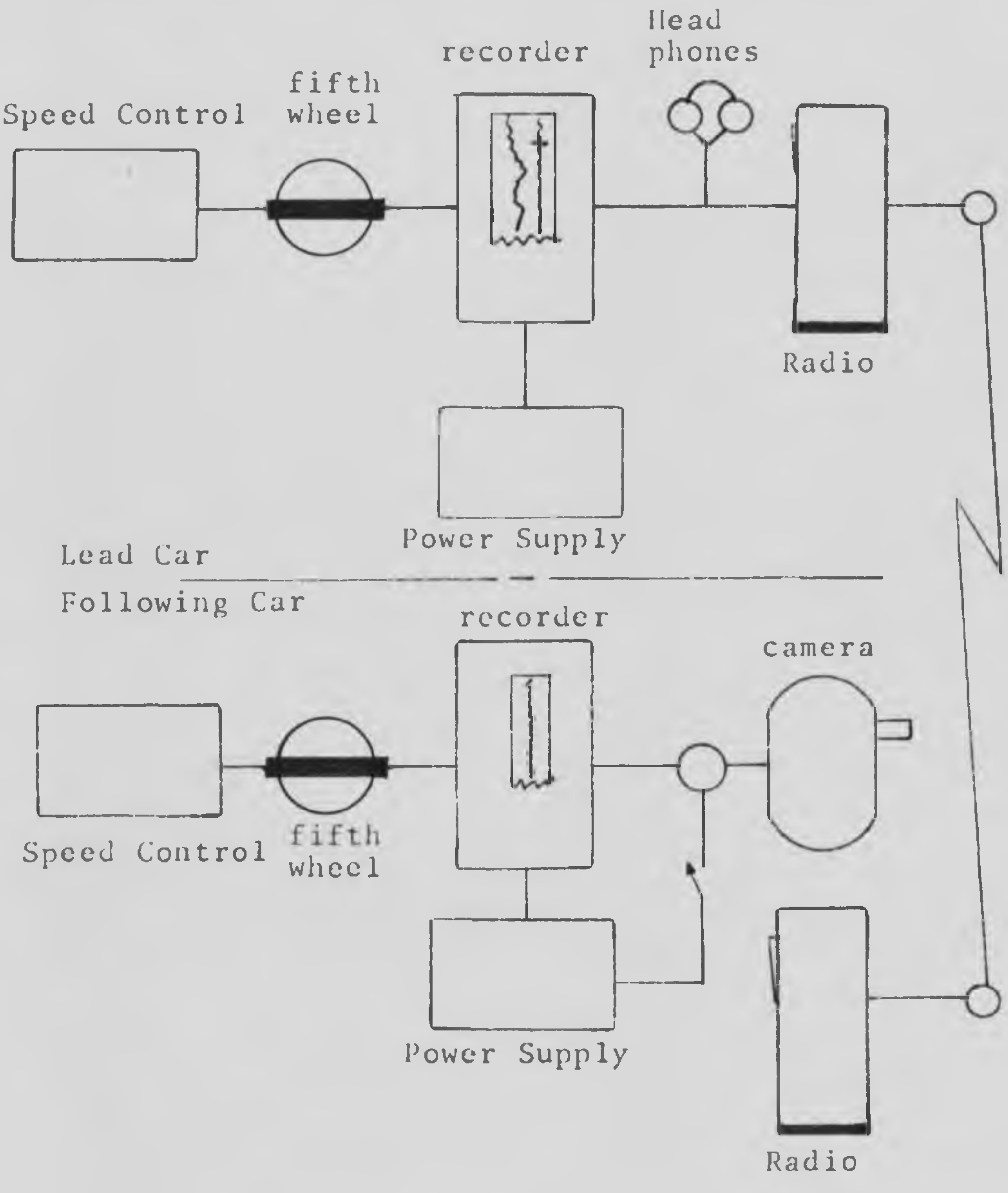

Figure 4.1. Road Test Instrumentation

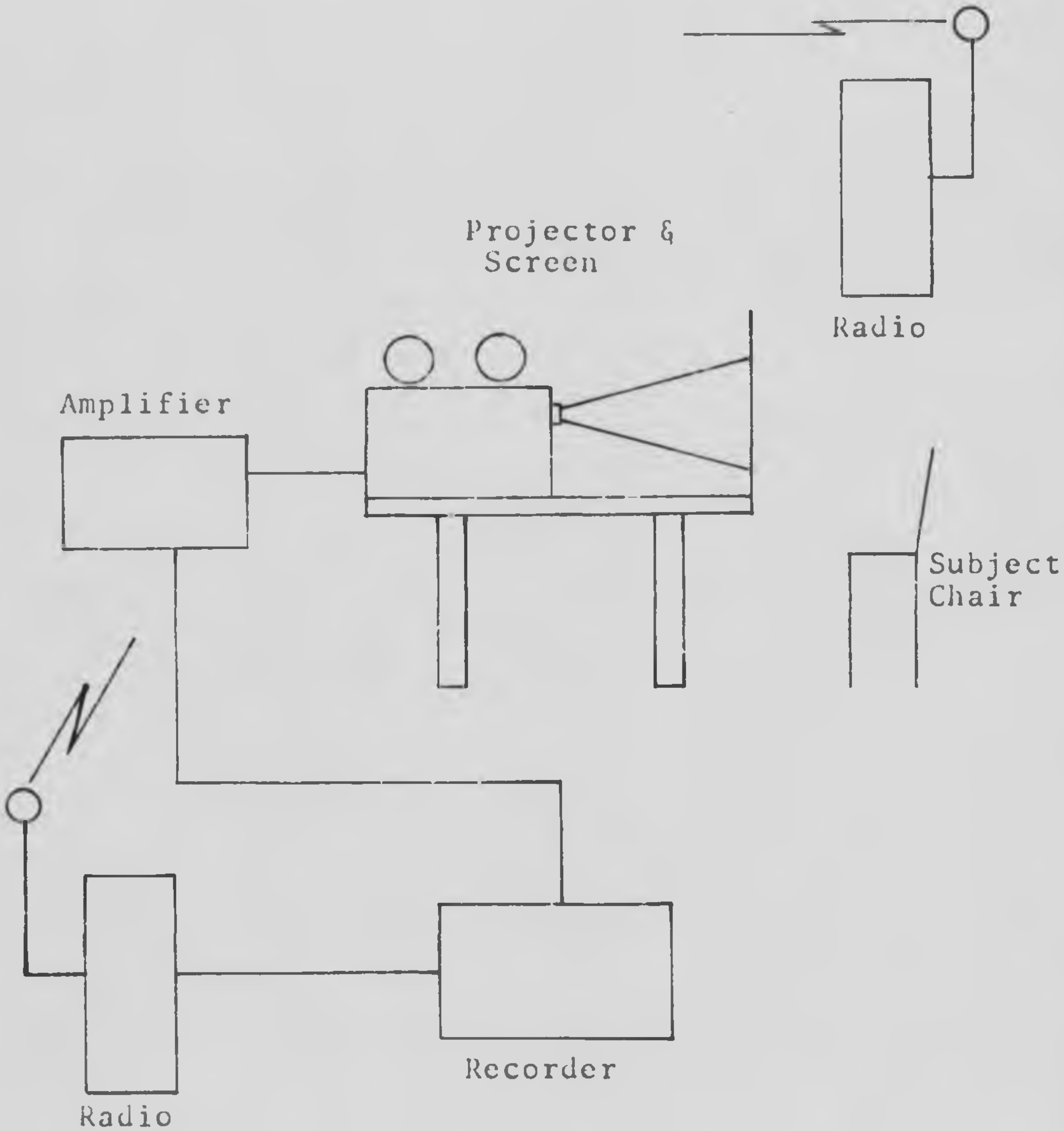

Figure 4.2. Laboratory Instrumentation

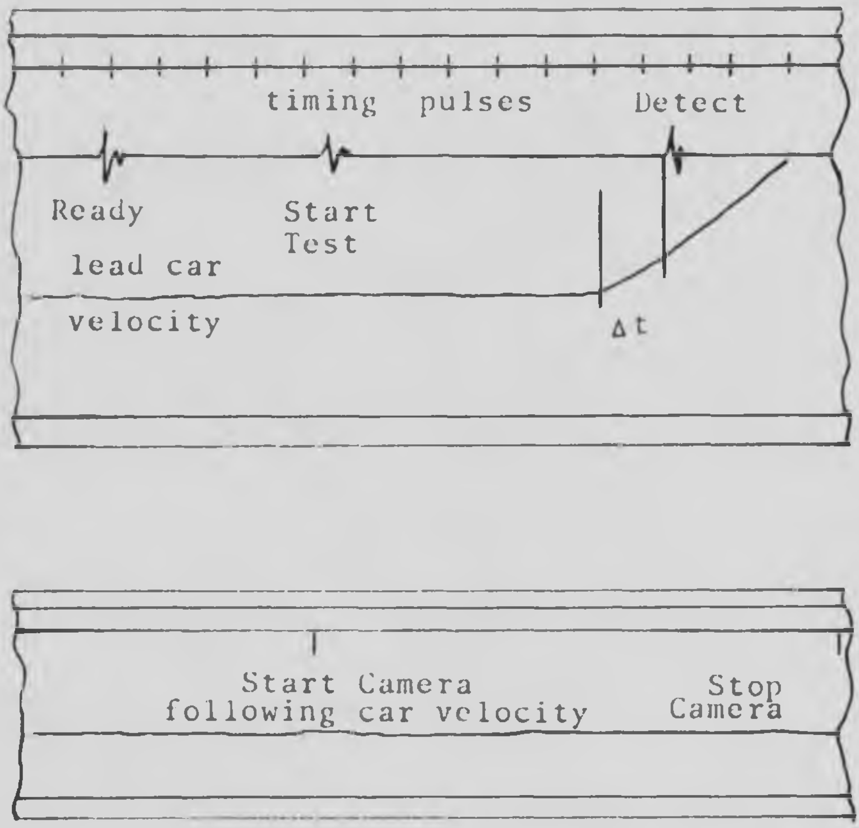

Figure 4.3. Chart Appearance

Minor fluctuations in speed created the greatest difficulty. The size of the car image at its widest point was the criteria for determining the critical point. After much tedium, the start of the acceleration was determined and a pulse was placed on the sound track of the film. The film was put on a standard synchronous motor driven 16mm sound projector. Rear screen projection was used with the subject seated 18 inches in front of the screen which distance roughly simulated the windshield view on the subject's side of the car. Projector throw was arranged so that the size and visual viewing angle of the screen image was equal to that on the road. The output of the sound amplifier was placed on Channel 1 of the Sanborn Recorder. The subject held the two-way radio as in the road test and the output of the second receiver was put on Channel 2 of the recorder. Upon detecting the speed change, the subject pulsed the transmitter. Delay time was measured as the time lapse between the onset of tone and the detection pulse.

Some further experimental instrumentation was done in conjunction with the car separation measurements on the road test. The amplitude of the received tone pulse was measured in an attempt to use the principles of variation of field strength with distance under line of sight conditions. Unfortunately time did not permit development of a suitable linear detection device and this part of the instrumentation will be studied separately at a later date.

Conduct of Tests

A detailed format giving instructions to the subject and the test sequence is given in Appendix B. Generally, the road test proceeded as follows. Recorders were set for 1mm per second speeds. The driver of the lead car accelerated to a steady state speed of 40 mph and set his speed control. The following driver arrived at the proper spacing and speed and set his speed control also. Tone pulse instructions to start the test were given by the driver of the second car who also activated the camera. The lead driver switched his recorder speed to 5mm per second and after a random (predetermined) number of seconds accelerated (or decelerated). The subject had previously been instructed to push the tone-sending switch and say "Mark" when the speed change had been detected. Upon hearing tone, the lead driver continued the acceleration for five seconds and then released his accelerator pedal thus returning to 40 mph. Upon hearing the word "Mark" the driver of the second car waited two seconds and shut off the camera. Distances and speed were again readjusted and the test repeated for the next acceleration treatment. Decelerations were handled by releasing the speed control in the lead car and allowing the car to decelerate normally. The brakes were not used. Each subject was warned of the impending test prior to initiation. (Warning was given to preclude the effect of wild data. The cost of movie film is such that repeated testing becomes very expensive.) The effect of cues such as exhaust puffs or stop lights was attenuated due to the manner of acceleration and decelerations (i.e. no down shifts or brake lights). The persons awaiting test were separated from the person under test. The laboratory test was conducted under essentially the same conditions as the road test. The scene sequences on film were separated by leaders during which the test was stopped for about 5 seconds to give the subject instructions. The timing pulses on the sound track were completely inaudible to the subject and provided no cues. Approximately two weeks elapsed between the time that the subject was given the road test to the time he was given the laboratory test. This lapse was due to difficulties in film processing and analysis.

Experimental Design (Statistical)

Cochran and Cox (1957) recommend that the draft of proposals for any experiment will in general have three parts:

a. a statement of objectives

b. a description of the experiment covering treatments, size and material

c. an outline of the method of analysis of the results.

The statement of objectives has been given previously however, it will be repeated here.

Objective I is the statistical estimation of time lag to perceive a change in lead car velocity for a human subject in a following car at low acceleration rates and normal car following distances.

Objective II is a test of the hypothesis that the estimation may be determined in a laboratory test which uses motion pictures of the road situation in lieu of a physical road test.

The population tested was composed of graduate students in the Systems Engineering Department at the University of Arizona. The population selected was largely chosen for convenience and availability for laboratory testing at a later date. Twelve subjects were chosen at random from the population of 26 names. An additional three names were drawn in order to substitute for any of the original twelve who could not be available for the test. The sample size of twelve was arrived at in an attempt to limit the cost of the experiment in time, film, chart paper and automotive expenses. Testing cost was estimated to be twenty dollars per block of three subjects exclusive of equipment procurement.

Because of the nature of the experiment, three treatments were given, corresponding to a high value of acceleration, a low value of acceleration and a deceleration.

An analysis of the factors involved in the tests considered the following:

environment	length of test	film
weather	driver	vigilance
time	subject	noise
velocity	laboratory	camera
acceleration	road	stadia lines
deceleration	vehicles	windshield
spacing		

Further study and definition of experimental conditions showed that all factors with the exception of acceleration, deceleration and subjects would be constant. Constancy in the weather was determined by test day rules. Rain, wind and heavy clouding were sufficient grounds to cause cancellation of a test on a given day. The other important determination was that the road test and laboratory test should be treated as separate experiments. Experimental error sources were considered to be

Automatic speed control mechanism

Car spacing determination

Equipment speed and linearity

Bicycle wheel contact with roadbed

Automobile response

Human variation

The experiments were set up as split-plot randomized block designs. The comparison was analyzed as a split-plot in time and space after the models described in Steele and Torrie (1960).

The split-plot design was used to allow the factor of experimental environment to be split out from the data. The design also allowed more precision for comparisons among the acceleration-deceleration data. For the data desired, analysis of the design is relatively easy and may be concluded rapidly with an existing computer program (Weldon, 1965). Possible effects of ordering have been balanced out by arrangements of treatments per day.

The experimental linear model can be written as:

$$t_{ijkm}=u+d_i+s_{ij}+a_k+e_m+(ae)_{km}+(de)_{im}+\varepsilon'_{ijm}+\varepsilon''_{ijkm}$$

where t= the observed value of detection time

u= the general mean

d_i= the day contribution, (i=1,2,3,4).

s_{ij}= the jth subject contribution (j=1,2,3) on the ith day.

a_k= the acceleration treatment, (k=1,2,3).

e_m=the experiment contribution (m=1,2).

$(de)_{im}$ = the error due to the interaction of days and experiments.

ε'_{ijm}= the error due to subjects in days and experiments.

ε''_{ijkm}= the residual error.

The experimental plan is shown in Table 4.1.

Each day's subjects were briefed on the purpose of the experiment prior to leaving for the road test. During the road test, the subject was placed in the following car and the others placed in the lead car. No communication about the test was permitted between persons tested and persons awaiting test. Instruction was given to the subject on the use of the telemetry system and each subject was allowed to send one training pulse. The laboratory test was conducted under similar conditions except that subjects awaiting test were kept in an ante room. Total elapsed time for road and laboratory tests for each block was approximately 30 minutes. The structure of the analysis of variance for the experiment is given in Table 4.2.

Pilot Testing

Prior to the conduct of the actual experiment, several pilot runs were held which were designed to check out equipment and techniques. As mentioned previously, the fifth wheel assemblies were initially fabricated without a swivel. On the first run both wheels developed a severe horizontal oscillation which threatened to damage the wheel rim. The test was stopped immediately. Analysis showed that the car bumpers had small dents and inperfections in them and the oscillation could be attenuated considerably by selecting smooth areas on the bumper for attachment. A second defect noted was the tendency of the wheel to slip laterally on slight turns. The defects were overcome prior to the next run by putting a spring return swivel on both wheels. More serious problems prevailed on the second pilot run. Initially a 1958 Ford station wagon was used as the second car. A great deal of variation in speed control was noted. Upon investigation, it was found that its motor condition was marginal and as such could not maintain a constant speed at any one acceleration setting. A second problem related to human operation of the system. A task analysis of the second car driver showed the following prime requirements:

1. Adjust and maintain speed and distance.
2. Set speed control.
3. Call the lead car on the radio to start the test run.
4. Set the tone switch on the radio.
5. Hand the radio to the subject.
6. Start the camera.
7. Depress marker foot switch.
8. Listen for test completion.
9. Shut off camera.
10. Depress marker foot switch.
11. Take the radio from the subject.
12. Switch to voice.
13. Call the lead car.
14. Reset speed and distance.

Table 4.1. Split-Plot Randomized Block Design

Day 1	Day 2
S_1 S_2 S_3	S_4 S_5 S_6
a_2	a_1
b	a_2
a_1	b

Day 3	Day 4
S_7 S_8 S_9	S_{10} S_{11} S_{12}
a_2	b
a_1	a_1
b	a_2

a_1=low acceleration   b=deceleration

a_2=high acceleration

Note: Presentation of Treatments to Subjects in days is identical for road test and laboratory tests.

Table 4.2. The organization of the analysis of variance showing the composition of component terms.

Factor	df		Term Composition	
Day	i-1		D	
Subjects in Days	i(j-1)		S in D	
Experiments	m-1		E	
Error I	(i-1)(m-1)		DxE	
Error II	(j-1)(i-1)(m-1)		S in DxE	
Acceleration treatments treatments	(k-1)		A	
Acceleration vs deceleration		1		a vs b
High acceleration vs low deceleration		1		a_1 vs a_2
Acceleration x Experiment	(k-1)(e-1)		AxE	
(acc. vs decel.)x Experiment		1		(a vs b)xE
(Hi acc vs lo acc.)x experiment		1		(a_1 vs a_2)xE
Error III	residual		AxD+AxDxE+S in DxA+ (S in D)xAxE	
Total	ijkl-1			

The major problem encountered was that somewhere during the sequence the speed of the car would drift downward and manual adjustment would be required. If the drift occurred after task 3, the observation was invalidated. Two solutions were considered. The first, and best, concerned getting a third assistant to act as test controller and take over all switching and calling tasks. This solution was infeasible at the time due to non-availability of qualified personnel. The second solution, which was adopted, gave some of the tasks to the subject and proved satisfactory during the test runs. The final problem had to do with the paper charts on the recorders. Wind motion caused the tails of the charts to be fed back into the paper winding reels of the recorders and cause a jam. This was overcome by fastening the ends of the chart paper to the car floor. A small amount of vertical vibration was noticeable in processed movie film but it was not considered serious enough to affect experimental results.

CHAPTER V

ANALYSIS OF EXPERIMENTAL DATA

This chapter presents an analysis of the detection times observed in the experiment described in the previous chapter. Of the four blocks run, the data on one of the blocks could not be used due to poor photographic results. Accordingly the analysis was run using only the data on three blocks with a total of nine subjects. The results in the form of means and standard errors are shown in Table 5.1. Accelerations, gap distance and base velocities are also given. Appendix A gives a table of complete experimental data.

Analysis of Variance

An analysis of variance with single degree of freedom contrasts is shown in Table 5.2. The main effect, experiments, is not significant for the data shown, therefore, the null hypothesis, stating that road testing can be simulated photographically in the laboratory, cannot be rejected at the 0.05 level of significance.

The acceleration treatments were highly ($P < .01$) significant and the linear comparison showed that there was a large difference between acceleration and deceleration detection times. The contrast between high and low accelerations was also significant.

Other effects and interactions were not significant for the data shown.

Regression Analysis

A regression analysis was run on the data in Figures 5.1 and 5.2. Linear Regression lines were plotted through the data points. The 95% confidence intervals are also plotted. The regression line equations for individual values were as follows:

accelerations: $\hat{t}=-.5a+3.5$

decelerations: $\hat{t}=-1.7a+6.9$

where $(\hat{t})$ is the estimate of detection time in seconds and (a) is the value of acceleration (+ or -) in feet per second squared.

A correlation coefficient of -.5, with 16 degrees of freedom, which was significant at the 0.05 level was obtained for acceleration and a coefficient of -0.6, with 7 degrees of freedom, which was significant at the 0.10 level was obtained for the decelerations. The correlation coefficients indicate that there is a relation between detection time and acceleration (or deceleration), however the regression lines are poor for prediction. The test of reaction time indicated a rather homogeneous group in that

Table 5.1

Experimental Results

Experimental Treatment	Acceleration (ft/sec^2)		Base Speed (MPH)		Initial Distance (Feet)		Road Test Detection Time (sec)		Photo Test Detection Time (sec)	
	M	SE	M	SE	M	SE	M	SE	M	SE
High Acceleration	2.5	.24	43.7	1.1	77.8	2.0	1.9	0.4	1.6	0.4
Low Acceleration	1.6	.12	42.4	0.6	77.4	2.0	2.8	0.4	2.6	0.4
Deceleration	1.3	.12	42.8	0.8	77.4	2.9	4.7	0.4	3.2	0.4

Table 5.2

The Analysis of Variance of the Time Data

For the Car Following Experiment

Source	df	SS	MS	F
D	2	.79	.395	<1
S in D	6	13.54	2.26	1.85
E	1	5.42	5.42	3.93
Error I	2	2.44	1.22	<1
Error II	6	8.30	1.38	
A	2	44.65	22.32	15.3**
A vs b	1	37.80	37.80	26.6**
a_1 vs a_2	1	6.85	6.85	4.72*
AxE	2	2.81	1.42	
(a vs b)xE	1	2.71	2.71	1.86
(a_1 vs a_2)xE	1	0.10	0.10	<1
Error III	32	46.91	1.46	
Total	53	124.80		

*Significant at $P< .05$

**Significant at $P<.01$

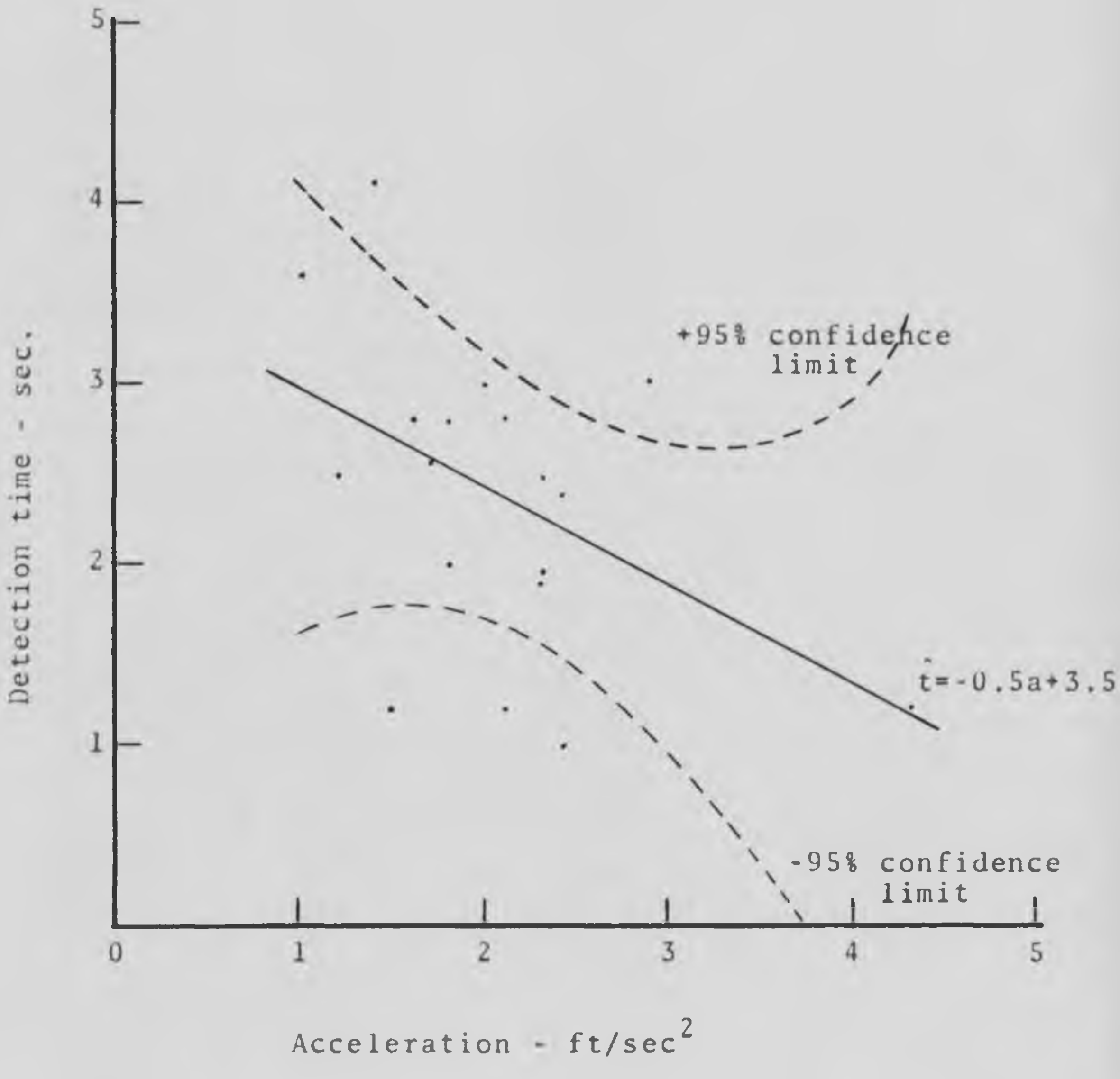

Figure 5.1. Acceleration Detection--Road Test

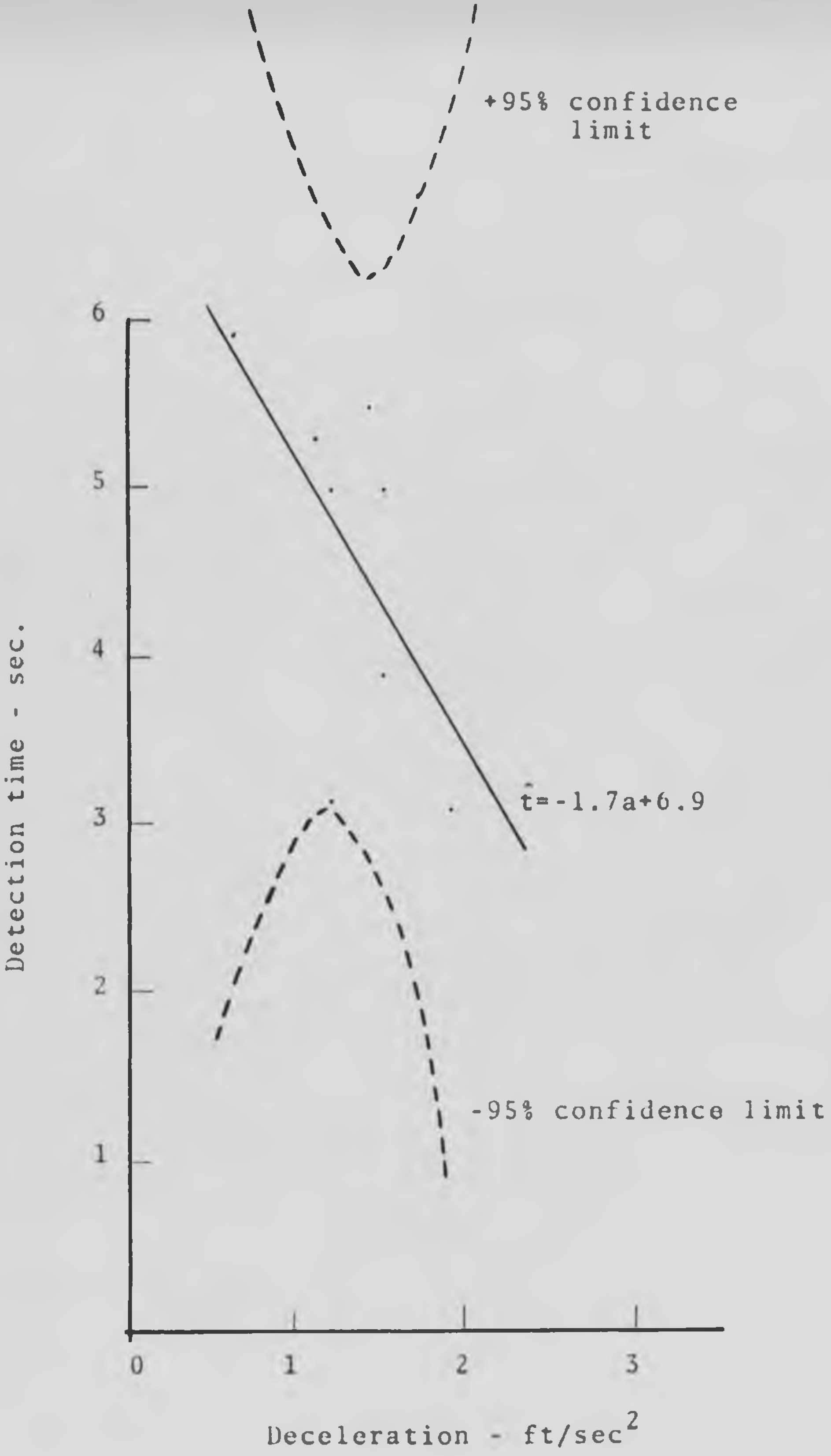

Figure 5.2. Deceleration Detection--Road Test

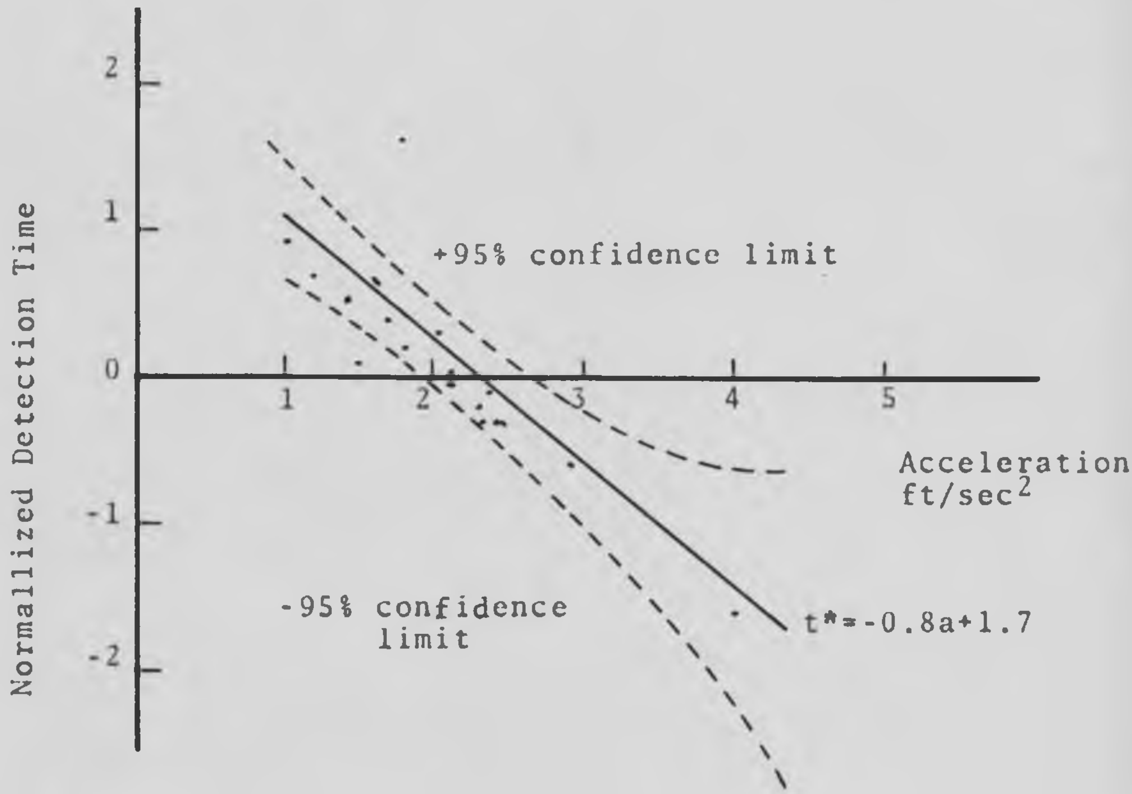

Figure 5.3. Normallized Acceleration Data Road Test

all subjects were found to have a reaction time of 0.2 seconds. No attempt was made to get a finer determination since the figure of 0.2 is in accord with the number of significant figures obtained in road testing. Any fractions less than tenths would be meaningless. The reaction time figure was not subtracted from the data since it is small and would shift the regression lines very little. A normalizing transform was applied to the acceleration data in an effort to get a better straight line fit. The two observations on each subject were connected by a straight line. It was noticed that the lines thus drawn appeared to be parallel to one another in the majority of cases. The lines were extrapolated to the mean value of acceleration and a time t' found for each subject. This value was subtracted from the original data points and a new line plotted. The regression line now had the equation (Figure 5.3):

$$t^* = -0.8a + 1.7.$$

The correlation coefficient now was found to be -0.9 which was significant at $p < 0.01$. The results indicate that detection time decreases linearly with increasing acceleration for the distance upon which the tests were run. The normalizing transform served to minimize individual differences. Unfortunately, the same procedure could not be applied to the deceleration data because of the limited number of observations. A logarithmic transform was tried on this data but the results did not improve the situation.

Controversy

An interesting and possibly controversial point in the data analysis is that detection times for decelerations were somewhat longer than those for accelerations at similar values of velocity change with respect to time. This is somewhat in agreement with the findings of Braunstein et al. (1963), although the latter paper makes no attempt to explain the difference. The finding is in opposition to the results of an experiment performed by Forbes et al. (1958). In the experiment, the driver of the following car was instructed to respond to the behavior of the lead car. The driver thus was occupied with the task of driving the car and watching for changes in the actions of the car ahead of him. The lead car was equipped with functioning brake lights and it is suggested that the drivers were responding to the visual brake light stimulus rather than to velocity changes in high values of deceleration where the brake was used.

Reference to the regression lines plotted in Figures 5.1 and 5.2 seems to support Forbes' experiment however, it should be noticed that data at the high values of deceleration contains much scatter and the confidence interval is very wide. Further experimentation with more data points should help to resolve this question.

Looming

The following discussion will also attempt to resolve the difference and present an area for further investigation. In the two experiments, the subjects have assumed different postures. Forbes et al. required the subjects to drive the car and in so doing, be concerned with the variety of tasks concerned in addition to detecting a change in velocity of the lead car. In the experiment conducted in this thesis, the subjects were free of all tasks and were concerned only with the actions of the lead car. In the car following situation, the driver of the second car is normally conscious of the possibility of a collision with the vehicle in front of him. His sensitivity will increase as headway becomes shorter. Let us now insert the psychological concept of "Looming" where the approach of an object causes an expansion of its contours in the visual field. Schiff, Caviness and Gibson (1962) have investigated fear responses in Rhesus monkeys which was caused by "Looming". They found that a sudden increase in size of an optical image created a tendency for the monkeys to retract or "duck". A decrease in size had no noticeable effect. In the experiment conducted by Forbes et al., the drivers were relatively close to the car ahead. As the lead driver applied his brakes, the car decelerated rapidly and appeared to loom in the subject's field of vision. The avoidance response in this case was to release pressure on the accelerator pedal and slow down. When the lead driver accelerated, the avoidance response was absent and the subject took time to decide upon a proper response. Decision time was longer because no danger was considered.

In the experiment conducted in this thesis, the gap between cars was considerable and deceleration rates were low. Stop lights were not used. The "Looming" effect was not great and the subject had no control of nor was he concerned with the actions of his car. Decision time was very low and consisted of deciding to "push" or "not-to-push" the detection switch. At this point, no further argument should be given since experimentation is indicated on gap effects on avoidance response. It appears that in the contrasting experiment with short gaps, "Looming" has a marked effect on response time, however on a high speed highway, where gaps are large, the "Looming" effect may be secondary to other velocity change cues.

Retinal Image Size

A second hypothesis will be presented in terms of the retinal image found during the car following. Ogle (1962) states that the discrimination of motion is greatest in the fovea centralis. Sensitivity to real motion change is related to visual acuity so that the motion detection in the periphery of the retina is less than that at the foveal region. The fovea centralis is a small depression in the retina approximately 250 microns in diameter.

Let us now calculate the size of the retinal image for our situation. The distance between the lead car and the subject's eye is of the order of 77 feet. The size of the retinal image at this distance has been calculated in the following manner from Ogle (1962). The visual angle subtended by the eye in looking at the lead car is determined as follows:

$$\theta=2 \arctan \frac{2.6}{77} = 0.0669 \text{ radians}$$

where the height of the car is 5.2 feet and the distance from observer to car is 77 feet. The image size on the retina is now a function of the distance from the exit pupil of the eye to the retina and the refractive index of the vitreous humour. The distance in the normal unaccommodated eye (infinite focus) is approximately 20.5mm. while the index of refraction of the humour is 1.336. Image size on the retina is now given as:

$$s=\frac{(.0669)(20.5)}{1.336} = 1.02\text{mm}$$

This places the image both on the fovea and the macula which has slightly less sensitivity. Now if we accelerate or decelerate by the mean values found in the experiment and use the well known relationship

$$S= \frac{1}{2} at^2+(v_1-v_f)t$$

to determine the distance change, we find that for low acceleration and for deceleration

$S=6.28$ feet.

$S=-14.35$ feet.

Now if we recalculate the retinal image size for both cases:

In acceleration:

$$\theta=2 \arctan \frac{2.6}{77+6}$$

$$=.0625 \text{ radians}$$

and $$s=\frac{(20500)(.0625)}{1.336} = 960 \text{ microns.}$$

In deceleration:

$$\theta=2 \arctan \frac{2.6}{77-14}$$

$$=.0825 \text{ radians}$$

and $$s=\frac{(20500)(.0825)}{1.336} = 1250 \text{ microns.}$$

From the calculations it is seen that the retinal image in the car following case is always on the macula (2000-3000 microns in diameter) whose most sensitive point is the circular depression known as the fovea centralis. Teichner (1954) has found that there is faster reaction time to visual signals that strike the center rather than the peripnery of the eye.

At this time, the hypothesis may be stated more formally.

Hypothesis: Detection time for perception of a positive velocity change is less than that for a negative velocity change in sagittal motion. The time is dependent upon the direction of change of size of the retinal image. In the positive case, the image size decreases and comes to impinge on the fovea while in the negative case, the image size increases to the periphery of the macula with a resulting increase in detection time due to lowered retinal sensitivity.

The hypothesis should be accepted or rejected by further experimentation which is beyond the scope of this thesis.

Angular Thresholds

An attempt was also made to determine angular thresholds for velocity detection changes. Unfortunately, one cannot hypothesize in determining these values since the actual position of the objective with regard to the visual axis must be known. However, if the center of the automobile image is assumed to be the center of focus then the angular thresholds are in the following areas:

High acceleration: $\frac{d\theta}{dt} =$ 13 minutes of arc per second

Low acceleration: $\frac{d\theta}{dt} =$ 16 minutes of arc per second

Deceleration: $\frac{d\theta}{dt} =$ -33 minutes of arc per second

In conclusion, it should be pointed out that the values of detection time for accelerations are in fair agreement with previous experimentation (Chandler et al., 1958) although conditions were somewhat different.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

Findings

The objectives of the investigation have been achieved and the results of the detection time investigation given in Table 5.1 and Figures 5.1, 5.2 and 5.3 along with 95% confidence intervals. Detection time appears to decrease linearly with increased acceleration. The analysis of variance has also shown that the photographic technique is satisfactory for subject testing.

The main failings of the experiment were those dealing with human variation. For example, the ability of an operator to hold speed and gap constant, even with semi-automatic controls, is very limited. The stadia lines on the windshield were very useful but required a great amount of practice in order to use them with reasonable accuracy. A better system of "real-time" distance measurement should be developed. A pair of tellurometers adapted for mobile use may give the required accuracy although costs are high. A second possibility is the inverse-square law equipment described in Chapter IV. Another recommendation is the use of two identical automobiles equipped with commercially available servo-type speed controls. Use of special cars would also allow them to be instrumented permanently and save wear and tear on the equipment caused by installation and removal for each block of experiments.

The photographic experiment while successful has some shortcomings. There is a large discrepancy between the visual field of the human and that of a camera lens. During the photographic tests, some of the subjects admitted that they were using the edge of the projected frame as a reference point to judge gap changes. If a cinemascope or equivalent wide angle, low distortion lens were used, the horizontal visual field would be distributed as in actuality.

Large scale testing may be accomplished in two ways. The first and least expensive is to set up a small theater with rear screen projection facilities. Image size and projection angle will depend on the theater layout. Approximately twenty subjects could be tested simultaneously with their output connected to a multi-channel event recorder. The second method would entail the purchase of a closed circuit television system over which the film could be shown. Eac subject would be seated before an individual television monitor with his output recorded as before. The second scheme has the advantage of ensuring that each subject sees the same size of object at the same viewing angle.

Areas for Further Study

Some areas for further investigation are as follows:

1. Repeat the experiment using a cinemascope lens in the camera and projector.
2. Investigate the acceleration - deceleration detection time conflict under rigidly controlled photographic simulation.
3. Photograph several car-following situations at different base speeds and accelerations. Show the films to large numbers of subjects in order to obtain families of characteristic curves.
4. Night time conditions may be simulated by the use of special filters and the effects of darkness on detection times determined.
5. Three car convoys may be investigated to determine the effect of changes in the lead vehicle velocity on the last car.
6. Effects of whitetop and blacktop road surfaces on detection times during daylight and darkness may be determined.

Finally, experimentation of the types described above is limited only by the resourcefulness and imagination of the investigator. Data of this type is scanty at present and much in demand by designers of safe high speed highways of the future.

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Appendix A

Table of Complete Experimental Data

Day	Subject	Acceleration (Ft/sec^2) a_1	a_2	b	Detection Times (Seconds) Road Test t_1	t_2	t_b	Laboratory t_1	t_2	t_b
I	1	2.1	1.8	-1.5	1.2	2.8	5.0	1.7	2.2	1.8
	2	2.3	1.7	-1.4	1.9	2.6	5.4	1.7	1.0	2.8
	3	1.8	1.2	-1.4	2.0	2.5	5.3	1.1	5.8	6.6
II	4	2.4	1.0	-1.5	2.4	3.6	3.9	1.5	1.7	2.6
	5	2.9	1.4	-1.2	3.0	4.1	5.0	2.2	5.4	2.1
	6	2.3	2.0	-1.9	2.5	3.0	3.1	1.0	2.0	2.1
III	7	2.4	1.5	-1.1	1.0	1.2	5.3	3.4	1.2	3.2
	8	4.3	2.1	-1.2	1.2	2.8	3.1	0.9	2.8	4.1
	9	2.3	1.6	-0.6	1.9	2.8	5.9	1.0	1.2	5.3

Day	Subject	Distance (Ft) d_1	d_2	d_b	Base Velocity (MPH) v_1	v_2	v_b
I	1	87	85	85	47	40	47
	2	72	79	82	37	41	41
	3	87	85	92	44	40	44
II	4	71	73	77	44	44	44
	5	77	80	79	47	42	44
	6	80	80	80	40	43	44
III	7	79	77	73	45	44	40
	8	75	69	63	45	45	40
	9	72	69	69	44	43	41

APPENDIX B

Instructions to the Test Subject

Road Test

1. You are about to undergo three tests to determine your response time to speed changes in the car ahead of you.
2. This is a transmitter which when activated will transmit a pulse to the receiver in the lead car. The tone is sent by pushing the switch. Try it once.
3. Watch the car ahead of you. I will give you a command "Mark". When you hear this, push the switch on the transmitter and say "Mark."
4. At some randomly prearranged time after you say "Mark," the lead car will change speed. When you detect the change, push the switch and say "Mark."
5. We will repeat the test three times.
6. Do you have any questions?

Laboratory Test

1. You will see three scenes which correspond to the situation you underwent on the road test.
2. When you detect the speed change, press the transmitter switch and say "Mark."
3. Do you have any questions?

Test Sequence

Road Test

1. Install all equipment with the exception of the fifth wheels at the University of Arizona.
2. Check out radios and power supplies.
3. Drive subjects to the test location.
4. Mount the fifth wheels.
5. Place subject 1 in the second car and the others in the lead car. Set camera exposure.
6. Subject on command from driver sends tone pulse to lead car.
7. Lead car and following car move to the roadway.
8. When the lead car has achieved the desired speed, speed control is set and a tone pulse sent to the second car.
9. Driver of the second car sets speed and distance and commands the subject to send a "Mark". At the same time, the movie camera is turned on.
10. At some random time between 0 and 10 seconds, the lead car driver changes speed.
11. Subject detects the change and says "Mark". The camera is then turned off about 2 seconds later.
12. The two cars return to base speeds and repeat the tests.

Laboratory Test.

1. Set up equipment
2. Seat subject with his face 18 inches from the rear screen.
3. Project film.

APPENDIX C

Photographs of Instrumentation