INVESTIGATION OF TRAFFIC DYNAMICS BY AERIAL PHOTOGRAMMETRY TECHNIQUES

by the

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Transportation Research Center
Department of Civil Engineering

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PREFACE

This report summarizes the work performed to date on EES 278, "Investigation of Traffic Dynamics by Aerial Photogrammetry Techniques". The work was conducted by the Research Staff of the Transportation Research Center of The Ohio State University under the direction of Dr. Joseph Treiterer, Associate Professor in the Department of Civil Engineering. The research is sponsored by the Ohio Department of Highways and the U.S. Bureau of Public Roads.

Section 2 of Chapter IV of this report represents a summary of a study conducted by Mr. Burkhard E. Horn and submitted as a thesis for the M.Sc. degree in Civil Engineering. Dr. Treiterer acted as thesis advisor for the study entitled, "Safety Criteria in Car-Following Situations for Freeway Traffic". The report in its entirety appears in the Appendix.

The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the (State or the) Bureau of Public Roads.
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I. INTRODUCTION

Traditionally traffic data has been collected by either using roadside observers or some sort of mechanical and/or electrical equipment placed either along the side of the road or on the road. This is a microscopic approach for obtaining traffic data, that is, individual vehicles are observed and recorded. This yields data to measure volumes, time headways, arriving rates past a fixed point on the roadway, and travel times.

The gathering of data by aerial photogrammetric methods provides the further advantage of making available a macroscopic view of the traffic situation. In this way a picture of the roadway at a given instant in time is obtained. This enables direct attainment of traffic densities and space headways. Another important advantage of this method is the ability to observe any propagation of disturbances through the traffic stream and the location of the origin of such disturbances.

The data thus obtained may be used to test and evaluate many of the present traffic flow theories.

II. DATA COLLECTION AND REDUCTION

Collection of the necessary data is accomplished by photography from an Ohio Department of Highways Bell helicopter. Flights over Interstate 71 have been made using two different cameras.

The corridor used consists of Interstate 71 from the downtown area of Columbus, Ohio, north to Route 161 in Worthington, Ohio. This is illustrated by the shaded area in Figure II.1. The northbound portion of I-71 changes from 3-lanes to 2-lanes near East North Broadway. This reduction in the number of lanes leads to disturbances in the traffic flow and generates kinematic and shock waves moving in the southerly direction. These kinematic waves have been photographed in this area.

The first camera used was the Maurer P-2 70 mm. reconnaissance camera. The P-2 is not a metric camera and is not equipped with a vacuum back. Thus any distortions due to film warping were unpredictable. To compensate for any lens and film distortions an extensive system of ground control points had to be established. This reduces the application of this method to areas where such a ground control system has been established which requires an extensive survey. Thus this is un-
satisfactory for practical applications. It was decided that a better camera would be needed for the further development of the method.

After much discussion with the Air Force and representatives from industry it was decided the KA-62A aerial camera from Chicago Aerial Industries would be the camera best suited for our purposes. The KA-62A is a metric camera with 5-inch film roll, 3-inch focal length, automatic exposure control, and 250 feet film capacity. It provides better resolution and higher quality photographs along with covering a larger area along the roadway. Use of this camera required designing and building a new camera mount and control system for the helicopter. Requirements for this new mount include the possibility of rotating the camera in a controlled manner and a limited range of vertical movement. Difficulties were encountered due to the relatively large bulk and weight of the camera unit and the small size of the only available mounting location in the helicopter; modification of the existing aircraft structure would have been impractical.

The camera mount permits rotation of the camera within approximately 15° limits to compensate for the drift angle of the helicopter when flying in a cross wind. The design of the vibration absorbing mount was based on the experience gained with the Maurer P-2 camera. A similar device made of rubber components of different elasticities was built to control any vibrations transmitted to the camera from the helicopter. Figure II.2 shows the KA-62A and the helicopter. A total of six flights and five films have been taken to date. All flights have been made during either the morning or evening peak traffic flow hours. A typical photograph of I-71 taken with the KA-62A aerial camera is shown in Figure II.3. Over 3,000 frames have been obtained.

Reduction of data previously obtained with the Maurer P-2 camera was accomplished in cooperation with the Ohio Department of Highways using a Nistri AP/C Analytical Plotter. The reduction of photographic data to ground data and the computation of headways and velocities of the vehicles were accomplished by means of a computer program written for the IBM 7094 digital computer.

Using the output from the computer, time-distance diagrams for each lane of traffic were drawn. The cumulative time was plotted on the x-axis against the cumulative distance on the y-axis. This results in vehicle trajectories as shown in Figure II.4.

The following information may be obtained readily from the vehicle trajectories:
Figure II.2: The KA-62A Aerial Camera and Bell Helicopter
Figure II.3: A Typical Photograph of I-71
Taken With the KA-62A Aerial Camera.
1. The number of vehicles crossing a certain point along the road during a certain time interval. This is represented by the number of trajectories intersecting Line A in Figure II.4.

2. The headway distributions in time at certain cross sections of the traffic lane studied. (Line A, Figure II.4).

3. By counting the number of trajectories intersecting Line B in Figure II.4 we may obtain the traffic density over a certain length of the roadway at a given instant.

4. Line B, Figure II.4, also provides us with the spacing of vehicles at a given instant in time.

5. A continuous record of velocity, acceleration, and deceleration of each vehicle is obtained by the tangent and changes in the tangent to the vehicle trajectory at any given time.

6. The generation, magnitude, propagation, and causes of disturbances may become obvious from the visual inspection of vehicle trajectories in many cases.

7. A visual study of gap acceptance in weaving maneuvers can be made and their frequency and influence on traffic flow can be evaluated.

III. AUTOMATIC EVALUATION TECHNIQUES

The manual evaluation of aerial photographs is very time consuming and expensive. It is for this reason that automatic evaluation techniques are considered to be a necessity. Large quantities of statistical data and records of vehicle movement must be evaluated.

All data reduction and analysis thus far has been done by mounting negatives on glass plates and inserted in the OMI-Bendix AP/C Analytical Stereoplotter at the Ohio Department of Highways.

A computer program was written for the IBM-7094 digital computer to reduce the photographic data to ground data; time-distance diagrams for each traffic lane were constructed. Figure II.4 shows such a diagram. For each photograph the accumulative distance to each vehicle was plotted in a vertical line at the corresponding time. The vehicle
trajectories were drawn by connecting the consecutive accumulative distance points for each vehicle. Automatic evaluation techniques would eliminate much of the work involved here. The determination of information related to the problem right at the start of the evaluation process and discarding information irrelevant to the problem is another problem associated with photogrammetric techniques.

Techniques applied in the biomedical field have been studied and their applications have been investigated. It can be expected that such factors as contrast and background density, definition and grain, particle shape and size, will have strong influence on the automatic scanning process and this will influence the limitations of the method.

Study of these techniques revealed that the Flying-Spot Particle Analyzer built by Airborne Instruments Laboratory in New York will be the most promising and economical method for automatic measurement of the traffic data on films and the transfer of such data to tape or cards.

Preliminary tests were carried out on the Flying-Spot Particle Analyzer located at the Agricultural Engineering Research Division, U.S. Department of Agriculture in Wooster, Ohio. Both infra-red films and black and white films were used. Good results were obtained in filtering out the unnecessary information and enhancing the images of vehicles.

In the tests it was found that since the width across the freeway did not exceed 10 mm and the scan area is 18 x 18 mm on the film, the lateral scan range would be sufficient for traffic studies.

However, since the length of the highway covers more than 18 mm, some method of transporting the film through the scanner is necessary. Discussion of this point revealed that it should be possible to feed the film through the scanner in steps or at a uniform speed while scanning laterally across the highway.

Tests of this technique cannot be carried out at the Wooster, Ohio, Agriculture Experiment Station since it is impossible to obtain the necessary time on their instrument. They are unable at the present time to accept outside contracts.

Arrangements have been made with Airborne Instruments Laboratory for test runs on their new Electronic Flying-Spot Particle Microscanner, which has been developed for the U.S. Army. These tests will be carried out toward the end of August, 1967, at their factory in Deer Park, New York. Five-inch black and white film obtained from test flights with the KA-62A aerial reconnaissance camera at altitudes
ranging from 2500 feet to 5000 feet above ground will be used. The arrangement to carry out tests at the factory was suggested by Airborne Instruments Laboratory personnel since they have the skilled technicians and scientists who developed the instrument readily available for adjustments and possible modifications.

As an interim measure before the testing and use of a fully automatic evaluation method can be realized, work is being done on the design of semi-automatic equipment which will produce charts of vehicle trajectories on light sensitive paper by a projection process. This system will allow a fairly quick evaluation of traffic flow data, although some accuracy over the A.P/C Analytical Stereoplottor will be lost. Extraction of digital data from such charts will require further evaluation, possibly by some sort of scanning process.

Comprehensive literature surveys have continued on studying the existing principles and techniques which have been and are being used in photogrammetric science to extract data automatically from aerial photographs and charts. There is considerable development at present of new automatic scanning and digitizing devices, especially with the possible use of laser equipment.

IV. APPLICATIONS

IV.1. Investigation of the Propagation of Disturbances Through a Traffic Stream.

The Lighthill-Whitham "Theory of Traffic Flow on Long Crowded Roads" has never been verified by traffic measurements. It appears that the fundamental characteristics of traffic flow are well covered by this theory. This is a macroscopic approach to traffic flow theory. Knowledge of the propagation of disturbances in a platoon of vehicles, the amplification or attenuation of such disturbances and their influences on capacities and volumes is not yet understood. This is due partly to the methods presently used to measure traffic flow parameters and also to the lack of theory describing these phenomena explicitly. Figure IV.1. shows the theoretical relationship between flow, density, and speed. Since the maximum flow does not necessarily represent the optimum traffic condition, the special value of any traffic flow theory is the possibility to define and determine the most desirable traffic conditions.

The generation and the propagation of disturbances are important factors in the achievement of optimum traffic conditions. As of this time, few field measurements are available on kinematic and shock waves, although these phenomena have
Figure IV.1 - "Safe" Flow - Concentration. The Straight Lines Intersect the Flow - Concentration Curves at those Points Corresponding to the Indicated Speed. The "Safe" Flow at 50 mph is about 15 percent less than the "Safe" Flow at 20 mph.
been blamed on being the underlying cause of the breakdown of traffic flow when the density becomes too high. The aerial survey technique provides an excellent opportunity to study the generation and propagation of disturbances, i.e., kinematic and shock waves.

The testing of the Lighthill-Whitham Theory of traffic flow will be based on the evaluation of vehicle trajectories obtained by following a platoon of vehicles with the helicopter on Interstate Route 71 in Columbus, Ohio. The relationship of traffic flow, traffic density and speed will be tested for different traffic conditions, since this appears to be a basic requirement for optimum flow. Emphasis will be placed on the study of the critical conditions associated with maximum traffic flow which are considered to occur within a range of rather unstable flow conditions. Since such conditions cause frequent changes in the flow of traffic, the waves which carry such disturbances through the stream of vehicles will be studied with regard to their generation, magnitude, and velocity. An attempt will be made to determine the underlying causes for the generation of disturbances such as the influence of geometric design features, roadside furniture, on and off ramps, sight distance, and extensive weaving movements. Previous investigations have shown that there is a wide variance in the magnitude of disturbances which also influences the rate of attenuation of disturbances.

Figure II. 4 shows the trajectories of a platoon of vehicles along a section of I-71 in Columbus, Ohio. Line A indicates the data which can be obtained by gathering information from a fixed location along the roadway. These data consist of types of vehicles, numbers of vehicles per time interval (volume), time gaps between vehicles and—by making use of the appropriate equipment—the velocities of vehicles when passing section A. No direct information on traffic density can be obtained although the average density may be calculated from the equation \( k = q/v \) where \( q \) = volume, \( v \) = velocity. However, this gives unreliable results. Line B indicates the data that can be obtained from a single photograph. This gives information on traffic density, but no information on traffic volumes or velocity. The method chosen for this study is a combination of the two methods described.

This method consists of introducing a control vehicle into the traffic stream, and following this control vehicle by a helicopter from which photographs are taken at fixed time intervals. The control vehicle has three functions: (a) it serves as a guide for the pilot flying the helicopter by carrying two high intensity beam lights on the roof facing upward, (b) it serves as a generator for disturbances which can be initiated by radio contact from the helicopter to study certain traffic situations, and (c) some of the data obtained by aerial photography can be checked against data on velocity, acceleration, and decelerations collected by a recorder in the test vehicle.
IV.2. Safety Criteria in Car-Following Situations

This section of the report is a summary of a study conducted to evaluate the degree of safety as found in real world car-following situations and as implied in the "classical" models of traffic flow. Comparisons between theoretical and empirical concepts are presented. For the reader interested in detail, the study in its entirety is presented in the Appendix.

Investigation of Intervehicular Spacings in Freeway Traffic

Through the accident rate for high design roadways remains quite low, these highways carry such large volumes of traffic that the absolute number of accidents remains quite high. One of the more frequent types of accidents associated with freeways and expressways is the rear-end collision. With the fast approaching completion of the Interstate Highway System, safety considerations dictate the need for research geared toward an understanding of the critical parameters involved in the car-following situation. The high incidence of rear-end collisions is usually considered to be related to the pattern of driving and the relative risk accepted by the majority of drivers when involved in car-following situations. Based on this hypothesis an investigation was conducted to evaluate the degree of traffic safety in car-following by comparing safe spacing criteria against real world data.

As a means of avoiding rear-end collisions, two different concepts of safe spacing were introduced: the concept of absolute safety and the concept of marginal safety. Applying the concepts to a queue of passenger cars traveling in a single lane with no opportunity to pass (conditions found in dense urban traffic), the following conditions were assumed:

1. All vehicles travel approximately the same speed.
2. Deceleration patterns and capabilities are similar for all vehicles.
3. Road conditions are identical for all vehicles.

Though the car-following model has been proven to provide a valid description of traffic flow, it seems to be questionable whether traffic safety in car-following can be comprehensively analyzed by safe spacing criteria based on a simple two-car model. The variance in human responses, road conditions, and vehicle capabilities, though important factors in the likelihood of rear-end collisions, cannot be realistically taken into account. Also the propagation of disturbances in dense traffic, an important factor in chain collisions, cannot be considered in the simple two-car model. However,
it is felt that the concepts of absolute and marginal safety can be considered to establish valid boundaries for the comparison by which the relative degree of safety in car-following situations can be tested.

The absolute safety concept may be defined as follows:

The leading vehicle is brought to a sudden stop by some object in the roadway (running into a suddenly appearing obstacle, heavy truck or container). The driver of the trailing vehicle reacts on the incidence of the collision and is able to stop his car without hitting the leading car in a rear-end collision. No space is left between the vehicles after the stopping maneuvers.

The spacing required by the following car to avoid a collision is known as safe stopping distance and would guarantee absolute safety in the car-following situation. The required distance is a function of 1) velocity, 2) driver's reaction time, and 3) vehicle deceleration rate. In mathematical terms, the relationship between these parameters is given by:

\[ S_a = 1.47 \, V_T + \frac{V^2}{30f} \]

where:

- \( S_a \) = absolute safe spacing, feet
- \( V \) = velocity, mph.
- \( T \) = reaction time of driver, secs.
- \( f \) = coefficient of friction or % of braking/100

The marginal safety concept may be defined as follows:

The driver of the lead car is forced to bring his car to a standstill in an emergency and tries to stop his vehicle in the shortest possible distance. After some delay caused by reacting on the maneuver of the lead car, the driver of the trailing vehicle duplicates the braking maneuver of the lead car, and both vehicles come to a safe stop. No rear-end collision will occur although no space remains between the vehicles after stopping.

The distance between the two vehicles required to avoid a rear-end collision is the marginally safe spacing since the basic assumptions stipulate that both cars travel at about the same speed and are subject to the same deceleration pattern. The required spacing is a function of 1) velocity and 2) driver's reaction time. In equation form, the relationship is given by:
\[ S_b = 1.47 \, VT \]

where:

\[ S_b \quad = \quad \text{marginally safe spacing, feet} \]
\[ V \quad = \quad \text{velocity, mph.} \]
\[ T \quad = \quad \text{reaction time of driver, secs.} \]

In order to calculate theoretical safe spacings based on these concepts, it is apparent that knowledge of the various factors affecting the response times of drivers as well as those factors affecting a vehicle's deceleration capabilities is essential. It is not realistic to consider the entire range of perception-reaction times found in the driving situation nor the broad spectrum of values of friction coefficients. Therefore, an attempt was made to select values of the parameters which would be representative of conditions most commonly found.

A literature search revealed 1) varied opinions as to a definition of a realistic range of response times found in the driving task, and 2) inconsistencies and inadequacies in the methods and results of on-the-road friction measurements. Considering that both the absolute and marginal safety concepts used in this investigation refer to emergency conditions - panic stops - in the car-following situation, the following values were adopted:

1. reaction time ranging from 0.7 to 2.0 seconds.

2. coefficient of friction data obtained by the experimental stopping distance method on dry pavement and shown in Figure VI.2.1. (Dry pavement conditions are used throughout this report to permit comparison with empirical data obtained by aerial photography.)

The literature revealed several different approaches useful for obtaining minimum distances for safe spacings. Three approaches - theoretical, experimental and by the use of recommendations - were selected for analysis in this report.

1. Theoretical safe spacings were computed using the relationships presented for the absolute and marginal safety concepts. These spacings were based on reaction times of 0.7 and 2.0 seconds and on the deceleration rate range presented in Figure IV.2.1.

2. Experimental safe spacings were obtained by combining reaction time distances with actual measurements of braking distances on dry pavement. Normann, in a study involving 53 vehicles representing 10 of the most common American motor vehicles, established the following relationship
Figure IV. 2. 1: Velocity-Coefficient of Friction Relationship as Determined by Stopping Distance Method
between velocity in miles per hour and average braking distance in feet:

\[ d = 0.00101 V^{2.92} + 0.82 V \]

Stark and Lister of the Road Research Laboratory investigated panic braking distances of British passenger cars and established the following relationship:

\[ d = 0.053 V^2 \]

3. Recommended safe spacings provide a rule of thumb to the motorist indicating the approximate magnitude of spacing to maintain in a car following situation. American safety association and automobile clubs recommend one car length for each 10 mph. increment of speed as minimum spacing. Two different recommendations are known in Europe:

1. \( S = V \)

2. \( S = \left( \frac{V}{10} \right)^2 \)

where:

\( S \) = recommended spacing in meters

\( V \) = velocity, km/hr

A fourth possible approach, the use of stopping distances presented in the AASHO design standards, was not considered. These distances are established for highway design purposes and are based on low coefficients of friction and a rather high perception-reaction time of 2.5 seconds. Consequently, they cannot be considered practical in computing realistic data on safe spacings.

A comparison of the minimum distances for safe spacings obtained by the three approaches is given in Figure IV.2.2. Several points of interest are apparent from the graph.
Figure IV.2.2: Comparison of Safe Spacing Concepts
1. Two distinct spacing criteria exist: absolute (characterized by a quadratic dependence on velocity) and marginal (characterized by a linear dependence on velocity).

2. The results of the American and European recommendations imply quite different degrees of safety. The American multiple car length recommendation can be validly compared with the marginally safe spacings. The quadratically increasing spacings calculated from the European recommendation give approximate values for the entire absolute safety range. However, this recommendation does not provide a convenient rule for the American driver since it is based on the metric system of measurement.

3. A good correspondence between Normann's braking distances, increased by reaction time distances, and the absolute safe spacings can be noted. Up to 60 mph Normann's spacings coincide closely with the spacings based on the upper friction limit. From 60 to 80 mph, Normann's spacings agree closely with the spacings based on the lower friction limit.

4. For speeds above 60 mph, Starks and Lister's measurements result in spacings too small to be considered valid. Extrapolation of the original curve beyond 60 mph does not seem to be valid.

Five safe spacing sets for dry pavement conditions were finally selected as the bases for data analysis. The aim was to comprehensively describe the entire range of driver reaction times and road friction conditions most commonly found in car-following practices.

Concepts of Absolute Safety:

1. "A" sub 1, reaction time \( T = 0.7 \text{ sec.} \); upper friction limit of Figure IV.2.1
2. "A" sub 2, reaction time \( T = 2.0 \text{ sec.} \); lower friction limit of Figure IV.2.1

Concepts of Marginal Safety:

3. "B" sub 1, reaction time \( T = 0.7 \text{ sec.} \)
4. "B" sub 2, reaction time \( T = 2.0 \text{ sec.} \)

American Safe Spacing Recommendation

5. "R", one car length per 10 mph velocity.
The method used for collection of car-following data consisted of data acquisition by aerial photography and consequent reduction of headway and velocity information by means of an analytical stereoplotter. This macroscopic method, developed by the Research Staff of the Transportation Engineering Center of The Ohio State University, provided car-following data both in space and in time for a whole platoon of cars travelling along a freeway.

Vehicle movements on a 6800 foot urban section of Interstate Highway 71 in Columbus, Ohio, were recorded during the summer of 1964. Covering a time range of 130 seconds during the evening peak, 70-mm photographs recorded the movements of 48 passenger cars traveling in the northbound median lane of the six lane divided highway. Total observation time was 3756 seconds (1 hour, 2.6 minutes).

The total traffic flow is graphically depicted by individual vehicle trajectories in Figure II.4. Accuracy of the associated computer output data used in calculations is ±0.5 mph for velocity values and ±1.0 foot for spacing values. The flow parameters of interest in this investigation, volume and density, can be simply computed by sectioning the time-distance diagram, such as Line A or Line B, and relating the number of trajectories to the corresponding time or distance intervals. The ranges of the parameters depicted were:

Volume: 1750-2250 veh/hr
Density: 75-95 veh/mile

In order to provide a basis for evaluating the different "degrees of safety" attendant with the selected safety criteria, the quotient of measured spacing and safe spacing was defined as the "safety factor". That is,

\[ \text{Safety factor } = \delta = \frac{\text{measured spacing}}{\text{safe spacing}} \]

\( \delta \) is a dimensionless parameter principally indicating a "safe" car-following situation if \( \geq 1 \) and an "unsafe" car-following situation if \( < 1 \). The former indicates an additional margin in car-following safety as a supplementary distance available in which to brake. Care must be exercised when interpreting a safety factor less than unity. Meaningful results can only be obtained by relating safety factors less than 1.0 to initial car-following speeds since \( \delta \)'s \( < 1.0 \) of the same order of magnitude demonstrate quite different "degrees of unsafety" or better still "degrees of collision severities". This is quite apparent from Figures IV.2.3 and IV.2.4. These figures illustrate the interrelationship between safety factor,
Figure IV. 2. 3: Collision Velocities for Various Safety Factors Below 1.0 (Absolute Safety Concept). Dry Pavement Conditions.
Figure IV.2.4: Collision Velocities for Various Safety Factors Below 1.0 (Marginal Safety Concept). Dry Pavement Conditions.
car-following and collision velocities, as based on the following formulae:

Concept of Absolute Safety

\[ V_{\text{coll}} = \sqrt{V_{\text{cf}}^2 - 30 \cdot f \left( S \cdot s_a - 1.47 \cdot T \cdot V_{\text{cf}} \right)} \]

Concept of Marginal Safety

\[ V_{\text{coll}} = \sqrt{V_{\text{cf}}^2 - 30 \cdot f \left( S \cdot s_m + \frac{V_{\text{cf}}^2}{30f} - 1.47 \cdot T \cdot V_{\text{cf}} \right)} \]

where:
- \( V_{\text{coll}} \) = collision velocity, mph.
- \( V_{\text{cf}} \) = car-following velocity, mph.
- \( s_a \) = absolute safe spacing, feet
- \( s_m \) = marginal safe spacing, feet
- \( S \) = safety factor (dimensionless)
- \( f \) = coefficient of friction (dimensionless)
- \( T \) = reaction time of driver, seconds

Specifically, these equations denote the collision speed of the trailing vehicle at which it will strike the lead vehicle and are derived from the available braking distance. Though collision velocities increase absolutely with increasing car-following velocities their relative values for a given safety factor actually decrease. Thus it is important to interpret safety factors with values less than 1.0 in light of their respective velocity values.

The availability of accurate flow data continuous in time and space enabled the following objectives to be met:

1. Analysis of the variation of traffic safety as found in traffic bunching situations when vehicles progress along the roadway both in space and in time.
2. Determination of the proportions of "safe" and "unsafe" driving times in car-following.

3. Testing of the policies of safe driving by their actual acceptance by the majority of drivers.

4. Investigation of the velocity - traffic safety relationship in car-following.

Figure IV.2.5 shows a typical safety factor diagram of a single vehicle progressing along the studied section for 38 seconds. The following points are of interest:

1. Safety criteria $A_2$ and $B_1$ consistently resulted in the lowest and highest safety factors, respectively.

2. In the velocity range of 40 to 50 mph, safety factors gradually increased in the following sequence: $A_2$, $A_1$, $B_2$, and $B_1$. Below 40 mph safety factors increased in the sequence $A_2$, $B_2$, $A_1$ and $B_1$.

3. The multiple car length safe spacing recommendation exhibited safety factors between concepts $B_1$ and $B_2$.

Defining unsafe driving time as that time in which the safety factor, $S$, exhibits a value less than 1.0, a weighting procedure was used to calculate the average unsafe driving time for each of the five selected safety criteria. Results are presented in Table IV.2.1. In addition, Table IV.2.2 reveals the degree of acceptance of the safety criteria in the traffic conditions studied.

The following observations can be made from the tables:

1. About 90% of the drivers consider criterion $B_1$ as the minimum safety criterion in car-following.

2. About 60% of the drivers implicitly accept the American multiple car length recommendation as a safe spacing criterion.

3. Safe spacings based on the absolute safety criterion $A_1$ are maintained 10% of the driving time and are accepted by 40% of the drivers.

4. Safe spacings based on the absolute safety criterion $A_2$ are maintained 30% of the driving time and are accepted by only 4% of the drivers.
Figure IV. 2. 5: Degree of Safety - Velocity Relationship
### Table IV.2.1: Frequencies of Unsafe Driving Time for Various Safety Criteria

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<tr>
<th>Safety Criterion</th>
<th>Average Unsafe Driving Time (As % of Total Observation Time)</th>
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<td>$A_1$</td>
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<td>A₁</td>
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<tr>
<td>A₂</td>
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<tr>
<td>B₁</td>
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<td>B₂</td>
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An interesting relationship was found between velocity and degree of traffic safety. Ten 5 mph velocity classes were established for each safety criterion and for each class an average safety factor was computed. Figure IV.2.6 shows the mean safety factors plotted against the midpoints of the 5 mph speed ranges. Of significant interest is the existence of a distinct minimum safety range for velocities between 30 and 40 mph.

The findings in Figure IV.2.6 agree essentially with accident rate-speed data presented by Solomon. In an investigation of traffic accidents as related to travel speed, Solomon reported higher accident involvement rates at the extremities of the range of travel speeds studied (20-60 mph) than for the remaining speeds considered (Figure IV.2.7). Comparison of Figures IV.2.6 and IV.2.7 reveal the following pertinent observations:

1. The minimum safety range of 30-40 mph established in this study accords with the steep increase of accidents below 40 mph as given by Solomon.

2. The increase of safety factors for velocities above 45 mph as established in this study corresponds with Solomon's findings of lower involvement rates for velocities above 40 mph.

Velocities over 60 mph were not covered in this study (speed limit at test site - 60 mph) making a comparison of the graphs in the upper speed range impossible.

Investigation of Safety Concepts in Theory of Traffic Flow

It is evident that the simple concepts of safe spacing introduced in the preceding section cannot constitute a valid theory of traffic flow. However, though dependent on certain assumptions, the absolute and marginal safety concepts do comprise safety criteria based on realistic ranges of vehicle capabilities, road variables, and human elements. Consequently, it was felt that computed safe headways could be used as inputs to derive limiting relationships between speed, volume, and density and thus, shed light on past traffic flow models and their inherent degrees of traffic safety.

Assuming a single lane of traffic with vehicles moving at a uniform speed, the following relationship applies:

\[
\text{flow} = \frac{\text{speed}}{\text{headway}}
\]
Figure IV. 2.6: Mean Safety Factor - Velocity Relationship
Figure IV. 2.7: Accident Involvement Rate by Travel Speed,
Daylight (Solomon (43))
Based on the minimum headway providing absolute safety in the car-following situation, flow can be expressed as a function of velocity, rate of deceleration, and driver reaction time.

\[
q = \frac{5280}{1.47 T + \frac{V}{30f} + \frac{1}{V}}
\]

where:

\(q\) = flow, vehicles per hour

\(l\) = car-length, feet

The other variables are as defined in the preceding section.

Based on an average car length of 17.5 feet, speed-volume relationships are presented in Figure IV.2.8 (dry pavement) and Figure IV.2.9 (wet pavement). An analysis of these graphs reveals that:

1. Optimum speeds range between 16 and 20 mph depending on pavement conditions,

2. Optimum speeds, and consequently maximum flows, exhibit higher values for dry than for wet pavement conditions,

3. Longer reaction times result in flatter curves and appreciably lower maximum lane volumes (up to 40% less), and

4. The influence of the lower limits of the deceleration ranges is more pronounced in the case of wet pavement conditions than for dry pavement conditions.

At uniform speed, density (vehicles/mile) is related to velocity by

\[
\text{density} = \frac{1}{\text{headway}}
\]

where headway is a function of speed.
Figure IV.2.8: Speed-Flow Curves for Dry Pavement
Figure IV.2.9: Speed-Flow Curves for Wet Pavement
Based on the absolute safe headway, density can be expressed as a function of velocity, rate of deceleration, driver reaction time, and length of car:

\[
k = \frac{5280}{1.47 VT + \frac{V^2}{30f} + 1}
\]

where \( k \) = density, vehicles per mile

In graphical form the relationship is presented in Figure IV.2.10 (dry pavement) and Figure IV.2.11 (wet pavement). It is apparent that densities at given speeds decrease in accordance to changes

1. from dry to wet pavement conditions
2. from high coefficients of friction to low coefficients, and
3. from short to long reaction times.

The fundamental diagram of traffic flow for the absolute safety concept can be obtained by equating volume to the product of density and speed where density is expressed as in the preceding equation. The resulting volume-density curves for dry pavement conditions and wet pavement conditions are shown in Figures IV.2.12 and IV.2.13, respectively. The relationships reveal that:

1. optimum conditions occur between densities of 80 and 120 veh/mile for \( T = 0.7 \) sec., and densities of 40 to 80 veh/mile for \( T = 2.0 \) sec.,
2. maximum flows occur between 1600 and 1900 veh/hr (\( T=0.7 \text{sec.} \)) and 1030 to 1130 veh/hr (\( T = 2.0 \) sec.)
3. long reaction times decrease possible maximum flow and associated optimum densities,
4. the lower deceleration limit notably decreases traffic volumes only in the case of wet pavement conditions,
5. maximum flows for dry pavements are about 14% higher than those for wet pavements, and
6. optimum flow for wet pavement conditions occurs at a slightly higher density than for dry pavement conditions.
Figure IV. 2.10: Speed-Density Curves for Dry Pavement
Figure IV.2.11: Speed-Density Curves for Wet Pavement
Figure IV.2.12: Volume-Density Curves for Dry Pavement
Figure IV.2.13: Volume-Density Curves for Wet Pavement
The results presented thus far pertain only to the absolute safety concept. Speed-volume-density relationships predicated on the marginal safety concept are not presented here because the results do not conform to characteristic shapes as established by empirical means. For more detail on this matter, the interested reader is referred to Chapter Five of the Appendix.

A comparison between the volume-density relationship deduced from the absolute safety concept, Greenshield's empirical model, and Greenberg's analogy model is presented in Figure IV.2.14. The comparison was based on the assumption that the parameters of the "classical" models expressed by average statistical volume-density-speed values can be considered as uniform parameters as introduced by the absolute safety criterion. This assumption appears to be justified when regarding traffic flow from a macroscopic viewpoint. Optimum conditions of $k_{\text{opt}} = 90 \text{ veh/mile}$ and $V_{\text{opt}} = 20 \text{ mph}$ have been used to determine the relevant curves necessary for comparison.

It is apparent that those portions of the curves which pertain to low traffic densities do not differ very much. However, within the range between optimum and jam density, the "classical" models show considerably smaller volumes than those derived from the safe spacing concept whereby the difference increases with increasing densities. In the light of traffic safety, the "classical" models also indicate spacings which are larger than the spacings based on the absolute safety criterion and, therefore, provide an even higher degree of safety than the absolute safety concept.

In summary, based on the information presented in this section of the report, the following conclusions, with a view to the future, can be made:

1. Traffic flow can be considerably increased by eliminating the retarding effect of driver reaction times.

2. The problem of improving traffic safety in the car-following situation without decreasing traffic flow is reduced to the problem of "distributing" vehicles along the highway with sufficient "safe" spacings by making use of distances between platoons.

Both conclusions point toward the desirability of some type of automatic control system for controlling traffic both efficiently and safely in the future.

V. FUTURE PLANS

The future plans for the project center on the evaluation of the automatic
Figure IV.2.14: Fundamental Diagrams of Traffic Flow

- **q** = Lane Volume
- **k** = Density

**Absolute Safe Spacing Curve**
(T = 0.7, Dry Pavement)

- Greenshields
- Lighthill-Whitham-Greenberg

\[ q = c \cdot k \cdot \ln \left( \frac{k}{k_j} \right) \]

**Parameters**
- \( k_{opf} = 90 \text{ VEH./MILE} \)
- \( v_{opf} = c = 20 \text{ MPH} \)
- \( q_{max} = 1602 \text{ VEH./HR.} \)
techniques available for data reduction and the testing of different traffic flow theories.

As mentioned previously the Flying-Spot Particle Analyser of Airborne Instruments Laboratories will be tested in the latter part of August, 1967, at their factory in Deer Park, New York. If no major difficulties are experienced, automatic evaluation of the films will begin. The possibility of having vehicle trajectories automatically plotted out will also be investigated.

With the data thus obtained the testing of different theories of traffic movement will commence. In addition to the testing of the Lighthill-Whitham Theory as mentioned before, the concept of an energy level in traffic flow will be investigated. This will be directed towards the investigation of a possible relationship between the magnitude of the propagated disturbances and the change in the level of energy of the moving traffic. Since a platoon of vehicles travelling at a constant velocity represents a level of kinetic energy of

\[ E = v^2 \sum \frac{(m_1 + \cdots + m_n)}{2} \]

the change in kinetic energy level is proportional to change in \( v^2 \). Any changes in speed are limited by the energy absorbing capacity of vehicles, and the waves which can safely carry such changes in kinetic energy must be collateral to the internal capacity of traffic flow to absorb or release energy. This concept of a new relationship between the variables entering traffic dynamics may provide a better understanding of the generation, propagation, and control of disturbances.

Since the concept of energy level is somewhat similar to the concept of car-following and acceleration noise, and since both concepts provide some measure of the efficiency of traffic flow, it may be of interest to compare the two approaches. Smooth flow is supposed to show little acceleration noise and should run at a high energy. It is intended to carry out a comparison at the two approaches - energy level and acceleration noise.

Other studies which are intended to be carried out are car-following behavior and headway distribution. The basic relationship between relative velocity-spacing and acceleration will be tested for fairly free flowing traffic with small disturbances and high density conditions with larger disturbances.

Results thus far received indicate strongly that the lognormal probability distribution is the best distribution for use. The investigation of the use of the lognormal with more data from different areas in the ranges previously tested is a necessary continuing path to follow. A reliable and consistent means of estimating the parameters involved in the lognormal is necessary for application of this distribution to traffic studies. This could perhaps be either a fixed method or the development of a table with the values to be used for different flow-levels. The establishment of a reliable method for estimation of the parameters may lead to widespread use in many traffic situations.
Other study areas which have been chosen in cooperation with the Ohio Department of Highways covering some specific operational problems are:

(a) Behavior of drivers at on-ramps. The photographs will be evaluated to cover the aspect of the design of the acceleration lane at on-ramps influencing the entering pattern and driver's attitude in gap acceptance.

(b) Influence of the type and location of guide signs on traffic flow. Proper location of guide signs and their design may help to distribute weaving movements over a longer section of freeway on the approach to a specific off-ramp and thus extensive friction in the flow of traffic can be avoided. It is intended to evaluate photographs for these aspects and to assess the value of changes by comparing vehicle trajectories before and after the changes have been made.
APPENDIX
SAFETY CRITERIA IN CAR-FOLLOWING SITUATIONS

FOR FREEWAY TRAFFIC
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CHAPTER I

INTRODUCTION

1.1 General

Driving is a complex task. The higher the number of vehicles on the roads and the higher the velocities, the more complex is the driving task and the greater are the attention, the alertness, and the rapidity of reactions required to drive safely.

Though the accident rate per 100 million vehicle miles on high-type highways with heavy traffic, as expressways and freeways, is considerably below the average rate found on lower type highways, the percentage of rear-end collisions is rather high. Rear-end collisions had a percentage of 52.9 and 60.5 in investigations of 1100 accidents on the Detroit John C. Lodge and the Edsel B. Ford Expressways, respectively (1). In a study of accident involvements on main rural highways conducted by the U.S. Bureau of Public Roads (2), rear-end collisions were the most common type of accident ranging from 78 to 42 percent for travel speeds below 50 mph.

In these premises, one of the main traffic safety considerations, especially with regard to freeways, should be directed to the safe spacings
between vehicles as they are required for safe traffic maneuvers in car-following.

1.2 Scope and Objectives

Congestion and accidents are the characteristics of the traffic problem of today. The challenge is to achieve a better understanding of the factors involved and to provide means to improve and increase traffic safety and traffic flow, respectively.

Within this framework, the principle objective of this study was to determine the safe spacing between vehicles and to compare the results with actual spacings as they appeared in common freeway traffic conditions.

To achieve this, concepts of safe spacing with different risk levels were set up and used for testing the validity of the recommendations of various traffic safety agencies. These concepts resulted in reliable and reasonable envelopes of safe intervehicular spacings as they may be used in most of the common car-following operations.

To evaluate how safe or unsafe drivers actually operate, the safe spacing concepts were tested on data collected by the Research Staff of the Transportation Engineering Center, The Ohio State University.

Since operational safety concepts frequently affect traffic flow, the safe headways were used as inputs to derive theoretical characteristics and limits of the fundamental parameters of traffic flow and were
analyzed in the light of the theory of traffic flow.

1.3 Field Studies

The field data were gathered on a 6800 foot urban section of Interstate Highway 71 located between Fifth Avenue and Morse Road in Columbus, Ohio.

The study was confined to the investigation of traffic movements during the evening peak flow on the inside northbound lane of the six lane divided highway.

A more detailed description is given in Chapter VI, Section 6.3.
CHAPTER II

CONCEPTS AND CRITERIA

2.1 Policies of Safe Driving

Little is known about the policy of safe spacing that the major part of the driver population chooses. The factors that influence this decision cover the entire system of driver, vehicle, and road. The choice depends on human attitudes, vehicle capabilities, traffic conditions, and the quality of the road.

However, with different levels of risk-taking, these individual choices of driving policies will be distributed around or between two concepts, namely

1. the concept of absolute safety, and

2. the concept of marginal safety.

Both concepts represent interpretations of the safe spacing as the critical measure to avoid rear-end collisions. They principally assume that a queue of vehicles is travelling on a single lane and that vehicles cannot change lanes. Furthermore, they shall be based on a car-following model with two cars following each other.

To simplify the task to study the rather complex car-following
problem and its variations, the concepts shall be limited to passenger cars travelling on level roads under the following conditions:

1. all vehicles travel at about the same speed,
2. deceleration patterns and capabilities are similar for all vehicles,
3. road conditions are identical for all vehicles.

These assumptions are not in accordance with real life conditions but are expected to give reasonable approximations of most existing conditions for the car-following situation.

The Absolute Safety Concept (Case A)

This concept may be defined as follows:

The leading vehicle is brought to a sudden stop by some object in the roadway (running into a suddenly appearing obstacle, heavy truck or container). The driver of the trailing vehicle reacts on the incidence of the collision and is able to stop his car without hitting the leading car in a rear-end collision. No space is left between the vehicles after the stopping maneuver.

The spacing required by the following car to avoid a collision is known as safe stopping distance and would guarantee absolute safety in the car-following situation. It is composed of the distance travelled during the reaction time of the driver and the braking distance:
\[ s_{\text{min}} = s_A = vT + \frac{v^2}{2d} \]

where:

\( s_{\text{min}} = s_A \) = safe spacing, ft.

\( v \) = speed, ft/sec.

\( T \) = reaction time of the driver, secs.

\( d \) = rate of deceleration, ft/sec²

Employing the dimensions generally used:

\[ s_A = 1.47VT + \frac{V^2}{30f} \]

where:

\( V \) = speed, mph.

\( f \) = coefficient of friction or \( \text{percent of braking} \)

\( \frac{100}{100} \)

The factors influencing safe spacings are

1. velocity,

2. driver's reaction time, and

3. vehicle deceleration rate.

The Marginal Safety Concept (Case B)

The concept can be defined as follows:

The driver of the front car is forced to bring his car to a standstill in an emergency and tries to stop his vehicle on the shortest possible distance. After some delay caused by reacting on the maneuver of the lead car, the driver of
the following vehicle duplicates the braking maneuver of
the lead car, and both vehicles come to a safe stop. No
rear-end collision will occur although no space is left
between the vehicles after stopping.

The distance between the two vehicles required to avoid a
rear-end collision is the marginally safe spacing since the basic assumptions
imply that both cars travel at about the same speed and are subject to the
same deceleration pattern. This spacing is determined by the distance
travelled during the reaction time of the driver. Thus:

\[ s_{\text{min}} = s_B = 1.47 VT \]  \hspace{1cm} (2-2)

where:

\[ s_{\text{min}} = s_B = \text{marginally safe spacing, ft.} \]

\[ V = \text{speed, mph.} \]

\[ T = \text{reaction time of the driver, secs.} \]

Hence, the marginally safe distance between vehicles is determined by:

1. velocity, and

2. driver's reaction time.

2.2 Individual Components

In the previous paragraphs, basic assumptions have been
made. These suppositions are not satisfactory to describe all existing
safety criteria in the car following situation. However, though hypothetical
to a certain degree, they appear to determine reasonable safety concepts for
the majority of drivers. The resulting safe and marginally safe spacings are dependent on a variety of factors.

**Speed**

The safe distance at high speeds is greater than at low speeds. In case A, with increasing speeds, the spacing must be augmented at a fairly higher rate than in case B. The second concept shows only a linear dependence on the velocity, whereas policy A gives a quadratic dependence intensified by a continuous decrease of the possible deceleration (friction) with increasing velocities (Figures 4 and 5).

**Reaction Time**

Generally, the driver's response or reaction time is referred to as the time for perception, intellection, emotion, and volition (PIEVT time).

In both concepts, A and B, the response time consists of the time to perceive the situation and the time to apply the brakes. The various studies conducted and the opinions among authors differ as to which time range can be considered valid. Most commonly, the total perception-reaction time ranges from 0.5 to 4.0 seconds. Design standards assume 2.5 sec. (AASHO) and 1.0 sec. (German specifications)

Matson, Smith, and Hurd (3) give an average brake reaction time of 0.82 sec. for conditions similar to concepts A and B, however, the perception time must be considered in addition. Normann (4) while studying braking distances from high speeds found reaction times between
0.4 and 1.7 seconds in initial test runs, but the 53 drivers were informed of the study objectives in advance. He observed an average of 0.73 seconds.

As far as this study is concerned a reaction time ranging from 0.7 to 2.0 seconds will be employed. This seems reasonable considering the fact that drivers adjust their attention and driving habits to the prevailing conditions. Thus, their attention will be higher with high velocities especially when following a car.

**Brake Application**

Since both concepts deal with emergency cases and panic reactions it can be assumed that brakes will be applied as hard and as fast as possible. Hence, the brake application is maximal, resulting in locked wheels.

**Vehicle Braking Capability and Deceleration Rate**

Maximum deceleration rates (5) of modern motor vehicles are as high as 0.8 g. But often, for lack of maintenance and adjustment, vehicle brakes in use do not maintain such high rates. In panic stops, however, the minimum stopping distance is obtained by locking all four wheels so that the available friction between tire and road surface will determine the stopping distance.
CHAPTER III

DECELERATION

A vehicle's capability to decelerate is one of the main features in avoiding a collision. In ordinary stopping maneuvers the vehicle is decelerated by both the tractive resistance and the braking deceleration.

The total tractive resistance is comprised of rolling, engine, and air resistance. Though tractive resistance only contributes a small portion to the total deceleration, it is necessary to determine its variations with speed, vehicle characteristics, and road characteristics.

The braking deceleration is contingent on the vehicle's braking capability and the friction between tire and road surface. It is very difficult to compute values of deceleration that would be representative of all existing road conditions and all driver and vehicle characteristics. An attempt has been made to approach this problem by referring to conditions most commonly found. The factors involved and their variations were represented by ranges. Thereby, particularly, the viewpoint of safety has been considered.

3.1 Tractive Resistance

The sum of rolling, engine (power train), and air resistance
comprise the tractive resistance.

**Rolling Resistance**

Mainly three factors cause the rolling resistance:

1. deformation of road and tire,
2. the suction effect between tire and road, and
3. sliding in the tire's contact area.

Recent investigations indicate that rolling resistance is a direct function of the load carried by the tire and is only slightly affected by speed (6).

Matson, Smith, and Hurd (3) described three components, namely, impact, surface, and internal resistance whereby only impact resistance increases with speed.

For most practical purposes, however, rolling resistance of 10 to 15 lbs/1000 lb vehicle weight can be considered valid, assuming average conditions and a smooth, hard surface of the road, as asphalt and concrete pavements (3, 7, 8). Then, the total rolling resistance is obtained as follows:

\[
\frac{R_R}{R} = c_R x W
\]  \hspace{1cm} (3-1)

where:

\[R_R = \text{rolling resistance, lb.}\]

\[c_R = \text{rolling coefficient 0.010 - 0.015}\]

\[W = \text{vehicle weight, lb.}\]

and the rate of deceleration can be derived:
\[ d_R = C_R \times g \]  \hspace{1cm} (3-2)

where:

- \( d_R \) = rate of deceleration caused by rolling resistance, \( \text{ft/sec}^2 \)
- \( g \) = acceleration of gravitation \( = 32.2 \text{ ft/sec}^2 \)

**Engine Resistance**

It is a well known fact that the engine itself retards a vehicle's forward motion when the throttle is closed. Though the relevance to the total tractive resistance has not been stressed in the past, the vehicle is decelerated quite considerably by the internal friction of the engine and the power train, and the pumping action of the motor with a closed throttle.

The literature review revealed that no recent literature is available on the subject. Moyer (9) and Beakey (10), 1934 and 1938 respectively, empirically studied the amount of engine deceleration. They measured the engine resistance as the difference between the free-wheeling and the high-gear deceleration. The values obtained represent overall decelerations from an initial speed to a full stop.

Moyer found 1.61 \( \text{ft/sec}^2 \) deceleration at 40 mph and 0.28 \( \text{ft/sec}^2 \) at 10 mph with a 1932 Studebaker Six Coupe as the test car. Beakey obtained a series of values for various speeds by test runs of a 1937 passenger car (Chevrolet, Dodge, Buick 60).

Though these investigations were conducted about 30 years ago, the values obtained can still be considered valid as far as their order of
magnitude is concerned. Two major American car manufacturers were not able or willing to provide recent figures. Thus, it can be expected that the vehicles presently used with reciprocating engines of similar design will have similar engine deceleration rates. Figure 1 shows Bekey's average engine deceleration rates of the three 1937 passenger cars.

Figure 1: Deceleration Caused by Engine Resistance from Initial Speeds (Bekey) (10)
Air Resistance

Air drag constitutes the major portion of the total tractive resistance at high velocities. Basically, three elements influence the air resistance of a vehicle (11):

1. speed,
2. size (cross sectional or frontal area), and
3. shape (aerodynamic characteristics of the car body).

Investigations have shown that air resistance varies directly as the square of the relative velocity between air (wind) and car, and increases directly with the cross sectional area of the vehicle (3, 6, 9). Finally, the shape of the car body or its streamlining design directly influences the air resistance.

The following formula has been found valid:

\[ R_A = \frac{\rho A \cdot c_D \cdot v^2}{2g} \]

where:

- \( R_A \) = air resistance, lb.
- \( v \) = speed, ft/sec
- \( \rho \) = air density at normal elevation, lb/ft\(^3\)
- \( c_D \) = air drag coefficient
- \( A \) = frontal area, ft\(^2\)
- \( g \) = acceleration of gravity = 32.2 ft/sec\(^2\)

In a simpler form (with the dimensions used above):

\[ R_A = 0.00257 \cdot c_D \cdot A \cdot v^2 \]  \hspace{1cm} (3-3)
where:

\[ V = \text{speed, mph.} \]

In recent studies (11) a drag coefficient of approximately 0.5 has been obtained for modern cars. The drag coefficient may generally be assumed to be in a range of 0.3 (streamlined) to 0.7 (truck). The rate of deceleration follows simply as

\[ d_A = \frac{R_A}{W} \times g \quad (3-4) \]

where:

\[ d_A = \text{deceleration caused by air resistance, ft/sec}^2 \]

\[ W = \text{weight of vehicle, lb.} \]

Figure 2 gives the effect of air resistance on speed, assuming a modern sedan compact car.

**Total Tractive Resistance**

From the preceding discussion it is quite obvious that the amount of total tractive resistance changes with speed. In Figure 3 the total average deceleration rates from initial speeds caused by tractive resistance have been plotted showing the three individual components. The deceleration values caused by engine and rolling resistance can be plotted directly, but the average rates caused by air resistance must be computed from integration of equations 3-3 and 3-4 or Figure 2 to find the actual overall retarding effect when stopping from initial speeds.

The following formula for the total tractive deceleration from
**Figure 2**: Deceleration caused by air resistance at various speeds.

Car: Modern Sedan Compact

- Weight: 3000 lb
- Frontal Area: 21.5 ft²
- Air Drag Coeff: 0.80

**DECELERATION**

[ft/sec²]
initial speeds can be easily derived:

\[ d_T = d_E + d_R + d_A \]  \hspace{1cm} (3-5)

where:

\[ d_T \] = total deceleration from an initial speed caused by tractive resistance

\[ d_T(v_i) = d_E(v_i) + c_R \times g + \frac{0.00257 c_D A g}{W v_i} \int_{0}^{v_i} v^2 \, dv \]  \hspace{1cm} (3-6)

where:

\[ v_i \] = initial speed, mph.

Applying representative values for the involved factors (modern sedan compact, hard surfaced roads) (Fig. 2), the total tractive deceleration is characterized by the governing effect of the engine resistance at most common speeds (20 to 90 mph). Air deceleration represents a main factor only when stopping from high speeds (90 mph and greater).

The diagram of Figure 3 depicts deceleration values of 0.7 ft/sec$^2$ at 10 mph and 2.13 ft/sec$^2$ at 80 mph. This increase is particularly important with regard to the decrease of braking (friction) deceleration with increasing speeds (Figure 5). Thus, choosing a mean coefficient of friction of 0.76 (or 24.5 ft/sec$^2$) at 10 mph and 0.54 (or 17.4 ft/sec$^2$) at 80 mph for dry pavement conditions, the tractive deceleration increases from 2.8 percent to 12.2 percent of the total deceleration.

This clearly shows the significance of the tractive resistance at decelerations from high speeds and explains the higher friction values obtained
by the stopping distance method (Figure 5).

3.2 Braking Deceleration

Braking or the rate of deceleration primarily depends on the kind and quality of the braking system, the amount of brake application, and the factor of adhesion between tires and road surface. The braking deceleration in an emergency stop is determined by the adhesion between tires and road surface, since the braking capability of motor vehicles frequently exceeds the tractive effort. The measure of this adhesion is the coefficient of friction, defined as the ratio of the frictional force to the vehicle weight. Thus, in a panic stop, the coefficient of friction - as obtained by locking all four wheels - is considered a realistic criterion in determining braking deceleration.

Factors Affecting Friction

The so-called skid or sliding coefficient decreases with increasing velocities and is affected by a variety of factors. Giles summarized the components affecting friction between tire and road surface. He differentiates primary from secondary factors:

<table>
<thead>
<tr>
<th>Primary Factors</th>
<th>Secondary Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>Wheel</strong></td>
<td>Vehicle Suspension and Riding</td>
</tr>
<tr>
<td>load size</td>
<td>Quality of Road</td>
</tr>
<tr>
<td>2. <strong>Tire</strong></td>
<td>construction</td>
</tr>
</tbody>
</table>
material
inflation pressure
tread

3. Tire Road
   Contact
   Condition
   contact time
   type of sliding
   rate of slip

4. Surface
   Condition
   dry
   wet
   snow
   
   Weather (and seasonal variation)
   age of surface
   traffic volume
   Wear

5. Surface
   Texture
   Materials and Methods of
   Construction

This multitude of influences explains why the coefficient of friction or the
skid resistance, and hence braking maneuvers, will vary considerably with
the prevailing conditions and the factors described above.

Measurements of Frictional Forces

Friction values can be measured by different testing methods, namely

1. the trailer method,
2. the stopping distance method,
3. the rate of deceleration or braking force method, and
4. the laboratory methods.

Correlation between skid tests conducted in Virginia (13) showed substantial
differences in the friction coefficients obtained by the different methods and
drivers. Even successive measurements of the same pavement using
the same test device were of a noticeable variety. No valid relationship
between trailer data and friction values obtained by the stopping distance
method could be established.

Basically, the stopping distance method gives an average coefficient
of friction that is available to stop a car from an initial speed, but includes
the retarding effect of the tractive resistance. The true coefficient of friction
at a certain speed, however, can be determined by the trailer method. The
deceleration test determines an overall friction value between initial and
final speed.

Laboratory test methods have been directed to evaluate the
effects of variables influencing the slid resistance, as for example properties
of pavement surfaces and materials (14). The resulting friction values,
however, do not give coefficients of friction that would actually be found in
car braking maneuvers.

Ranges of Coefficient of Friction

It follows from the foregoing that a range of friction values has
to be considered to represent the variations of friction and the variability of
its measurement methods.

Figures 4 and 5 show the relationships between velocities and
the coefficients of friction. Figure 4 includes about 75 percent of recent
literature data (13–19, 21–25) with a variety of conditions and trailer test
Figure 4-8: Effect of Speed on Traction Ranges
(Various Trailer Testing Methods)
Figure 51: Effect of speed on friction ranges (stopping distance method).
methods. Figure 5 presents data obtained by the stopping distance method. In setting up these ranges, care has been taken to determine the upper limits in order to give special attention to safety requirements.

Three references (18, 20, 25) that contradict the general tendency of decreasing friction values with increasing speeds were not included in these ranges, since the coefficients of friction in these studies were based either on small samples or extreme tire and surface conditions and, thus, made an inclusion of these results undesirable.

Deceleration Pattern

A typical deceleration-time record, as given in Figure 6, covers the whole range from rolling to sliding and shows two fairly pronounced peaks: one, shortly after the wheels are braked and one shortly before the car stops. The first peak deceleration corresponds to the maximum value of the braking-force coefficient, the second peak is due to an increased grip between tires and road surface at low speeds, just before the car is stopped.

These curves obtained by braking tests can be used to determine the average deceleration value which is available to stop a car. Starks and Lister (26) found an average deceleration of 0.63 g independent of speed, conducting test runs on dry aerodrome runways in England with 1950 car models.
FIGURE 6: TYPICAL DECELERATION-TIME CURVE (STARKS LISTER) STOP FROM 50 MPH
3.3 Total Deceleration

The most important factor in safety considerations of the car-following problem is the reliability of representative deceleration rates.

Deceleration rates obtained by the stopping distance method and shown as friction ranges in Figure 5, include the total tractive resistance and the friction between tires and road. They are average deceleration rates available to stop a car from initial speeds and represent braking conditions of panic stops, similar to the basic assumptions of the safety concepts of this study. However, the amount of data on which the ranges of Figure 5 have been based and their validity are restricted by the small number of investigations.

Data measured by the trailer test method give instantaneous coefficients of friction at certain velocities, but do not include the tractive resistance. The friction ranges of Figure 4 include coefficients of friction obtained by different test trailers and procedures which have been developed in the last 35 years. Thus the pertinent results on which Figure 4 has been based were collected in a multitude of investigations and by several tests of extreme skid conditions which cannot be considered as representative for average pavement conditions.

To compare trailer data with values obtained by the stopping distance method, the instantaneous trailer coefficients of friction at certain speeds have to be converted into average deceleration rates. This can be done by integrating the friction limits of Figure 4 and by adding the tractive
resistance:

\[ d_{\text{total}} = d_{\text{tractive}} + \frac{V_i}{V_i} \int_0^V f(v) \, dv \]  

(3-7)

where:

\[ d_{\text{total}} = \text{total average deceleration rate, ft/sec}^2 \]

\[ d_{\text{tractive}} = \text{deceleration caused by the tractive resistance, ft/sec}^2 \]

\[ f(v) = \text{coefficient of friction as function of velocity} \]

\[ V_i = \text{initial speed, mph} \]

\[ g = \text{acceleration of gravitation} = 32.2 \text{ ft/sec}^2 \]

By the help of the trapezoidal rule as a first approximation to the integration:

\[ \int_0^{V_i} f(v) \, dv = \int_a^b f(x) \, dx \approx \frac{h}{2} \left\{ f(a) + 2f(a + h) + 2f(a + 2h) + \ldots + 2f(a + (n - 1)h) + f(b) \right\} \]

where:

\[ a \leq x \leq b; \quad h = \frac{b - a}{n} \]

and:

\[ a = 0; \quad b = V_i; \quad h = \Delta V = 10 \text{ mph} \]

\[ f = f(v) = \text{coefficient of friction (Figure 4)} \]

Figure 7 illustrates the procedure for an initial speed of 80 mph and the upper limit of the friction range for dry pavement. For this example:

\[ d_{\text{total}} = d_{\text{tractive}} + \frac{80}{80} \int_0^{80} f(v) \, dv \]
Figure 7: Graphical Integration of Friction Values
Based on Trailer Method

With Figures 3 and 7:

\[ d_{\text{total}} = 2.13 + \frac{32.2}{80} \times 51.11 = 22.68 \text{ ft/sec}^2, \]

which is extremely high and exceeds the analogous deceleration rate computed from the stopping distance range about 21 percent.

The results of the two methods differ substantially (13),

namely between 5 and 20 percent of the total deceleration rate computed from
stopping distance tests. This is mainly due to the fact that the trailer
ranges of Figure 4 are based on data obtained by different test equipment
with inclusion of extreme test conditions.

The deceleration rates calculated from stopping distance tests
have been used in this study to compute minimum distances for safe spacing,
since they represent average deceleration rates from initial speeds and are
based on conditions of panic stops similar to the assumptions of the safety con-
cepts in car-following.
CHAPTER IV

MINIMUM DISTANCE FOR SAFE SPACING

4.1 Basic Approaches

Three different approaches – theoretical, experimental, and by the use of recommendations – shall be analyzed. These approaches result in minimum distances for safe spacing, namely

1. theoretical safe spacings determined from the absolute and marginal safety concepts and based on deceleration rate ranges (Figure 5) and reaction times between 0.7 and 2.0 seconds,

2. "experimental" safe spacings evaluated from Normann's(4) and Starks–Lister's (26) braking distance measurements plus the reaction time distances based on reaction times between 0.7 and 2.0 seconds,

3. recommended safe spacings computed from recommendations by different authorities.

A fourth possible approach, the use of the stopping distances given in the AASHO design standards (27) will not be considered here. These
distances set up for highway design purposes are based on low coefficients of friction and a rather high perception-reaction time of 2.5 seconds, and cannot be considered to be useful in computing realistic data on safe spacings.

4.2 Safe and Marginally Safe Spacings

The underlying concepts and the components involved have been analyzed in the preceding chapters. Two equations have been used to compute minimum distances for safe spacings:

Case A: minimum spacing for safe conditions

\[ s_A = 1.47 T V + \frac{V^2}{30f} \]

Case B: minimum spacing for marginally safe conditions

\[ s_B = 1.47 T V \]

Both concepts result in safe spacing ranges with different degrees of safety. Figures 8 and 9 show envelopes based on deceleration rates computed from stopping distance tests (Figure 5) and a reaction time ranging from 0.7 to 2.0 seconds. As discussed before, both sets display the variability of basically safe spacing parameters.

According to the above formula, the marginally safe spacing is characterized by a linear dependence on velocity. The spacing envelope encloses a continuously widening range with increasing speeds and requires exactly the same values for wet as well as dry pavement conditions.

Spacing of vehicles increases with \( V^2 \) in the absolute safety concept. For dry pavement, reaction time is the determining factor in
computing safe spacings. With wet pavement, the reduced coefficient of friction affects safe spacings more than long reaction times.

At 80 mph, the safe spacings of the absolute safety concept for dry pavement are up to 6 times greater than the marginally safe spacings and up to 10.7 times greater for wet pavement conditions.

4.3 Braking Distance Measurements

Braking distances, i.e., "stopping distances" less the portion covered during the reaction time, have frequently been used in skid prevention research and friction tests (see Chapter III). However, these investigations were conducted with specially equipped test cars to evaluate the relevant factors affecting friction and to establish means of determining slippery pavements. The actual braking distances as such were of secondary importance in these investigations.

Only two investigators, Normann (1953) and Starks and Lister (1954), comprehensively studied braking distances and performances of a larger sample of drivers and common car makes. Though these tests were conducted under ideal conditions, with no traffic interference, the collected data shed light on braking distances which may be expected under actual traffic conditions.

Normann (4) tested 53 vehicles representing 10 of the most common American motor vehicles. He conducted a series of tests on a dry concrete taxiway whereby each vehicle was driven by the person who normally operated the vehicle. Starks and Lister (26) (Road Research Laboratory)
FIGURE 10: EXPERIMENTAL BRAKING DISTANCES VERSUS SPEED
investigated braking distances of 1946/47 and 1950 British models. These experiments were carried out by laboratory drivers on an aerodrome runway having a dry "excellent" surface.

In both tests, the actual braking distances were obtained by locking the wheels as in panic stops. Reaction times were not considered, merely the distance covered from the beginning of the brake action (application of brake pedal) to the actual stop of the car was measured. The braking distances include the distance travelled within the brake response time and do not account for the use of the clutch pedal.

The authors represented their findings by the following formulae for the average braking distance in feet; where velocity V is measured in mph:

Normann: \[ D_b = 0.00101 V^{2.92} + 0.82 V \]

Starks, Lister: \[ D_b = 0.053 V^2 \]

Figure 10 is a graphical representation of the results of the two investigations. When comparing these results with the minimum distances for safe spacing used in the approaches of this study, reaction time distances have to be added.

4.4 Recommended Safe Spacings

The average driver needs some kind of rule of thumb as to what spacing he should maintain with regard to the leading car. Such a rough safe spacing guide would make him conscious of the level of risk or safety that he can expect. Though the driver is often forced to keep certain spacings in constrained traffic flow conditions, the safe spacing recommenda-
tions will help him to become aware of the degree of traffic safety when
following a car.

American safety associations and automobile clubs recommend
one car length for each 10 mph increment of speed as minimum spacing.
Figure 11 shows the minimum distances for safe spacing for car lengths
between 14 and 19 feet (5) with an average car length of about 17.5 feet.

Two different recommendations of safe spacing are known
in Europe:

1. \( s_R = V \)

2. \( s_R = \left( \frac{V}{10} \right)^2 \)

where:

\( s_R \) = recommended spacing, meter

\( V \) = velocity, km/hr

Hence at 60 km/hr (37.3 mph):

\[ s_{R_1} = 60 \text{ meter} = 197 \text{ ft.} \text{ and } s_{R_2} = \left( \frac{60}{10} \right)^2 \approx 36 \text{ meter} = 118 \text{ ft.} \]

Figure 11 depicts the resulting minimum distances of safe spacing for both
recommendations, i.e. linearly and quadratically increasing spacings,
respectively. The linear spacing recommendation gives higher distances up
to 64 mph.

Obviously, the results of both the American and the European
recommendations imply quite different degrees of safety. A comparison of the
plots of Figure 11 with the absolute and marginal safety concepts shows that
the American recommendation is based on the marginal safety criterion and
the second European proposal is similar to the absolute safety concept.
At 80 mph, the European spacings are up to 4 to 5 times more than the
spacings required by the American rules.

4.5 Comparative Analysis

Figure 12 compares the sets of minimum distances for safe
spacing obtained by the three approaches discussed previously. There is a
range of spacings for both the absolute and the marginal safety criterion.

A good correspondence between Normann's braking distances
(increased by reaction time distances) and the absolute safe spacings of
concept A (Figure 8) can be noted in the case of dry pavements. Up to
60 mph "Normann's spacings" are near the curves based on the upper friction
limit (with differences of 0.7 to 5.5 ft), from 60 mph to 80 mph they approach
the spacing sets calculated from the lower friction limit (with differences
of 1 to 14 ft).

Starks and Lister's measurements result in values too low
for speeds above 60 mph. This is certainly due to the extrapolation of the
original curve beyond 60 mph (Figure 10).

The quadratically increasing spacings calculated from the
European recommendation give approximate values for the entire absolute
safety range.

The marginally safe spacings may be compared with spacings
computed from the multiple car length recommendation, as can be seen from Figure 12.

Wet pavement conditions have not been considered in Figure 12, but it is quite obvious that the recommendations are not at all satisfactory for these conditions. The graphs of Figure 9 show the steep increase of spacing distances with rising speeds. Therefore, the risk taking of the drivers increases if drivers do not change their driving behavior when travelling on a wet pavement.
FIGURE 2.1 COMPARISON OF SAFE SPACING SETS
OBTAINED BY DIFFERENT APPROACHES
DRY PAVEMENT

NORMANN - 85%
T-26
STARKS-LISTER
EUROPEAN RECOMMENDATION
NORMANN - AVG
T-27
STARKS-LISTER

MARGINAL SAFETY
L-144 (AMERICAN REC.)
T=0.7

ABSOLUTE SAFETY
L-1591 (AMERICAN REC.)
T=0.0

--- UPPER LIMIT OF FRICTION RANGE (FIG. 5)---
--- LOWER ---
--- NORMANN OR STARKS-LISTER ---
CHAPTER V

TRAFFIC FLOW AND SAFE SPACINGS

5.1 Traffic Flow Models

Traffic flow is a unique phenomenon. Various studies have been undertaken and much research has been accomplished in order to describe its characteristics and complexities. Mathematical models have been developed to express vehicular flow by interrelationships of its fundamental parameters.

Basically, there are two different approaches: theoretical and empirical. Thus, the various models can be grouped as follows:

1. theoretical:

   deterministic: analogy models - Lighthill and Whitham (28), Greenberg (29) - and car following models - Herman et al (30),

   stochastic: probability models - Haight (31), Prigogine (32) - and models based on the queueing theory - Blunden (33),

2. empirical:

   - Greenshields (34), Normann (35), and other early researchers (36).
Each of these theories deal with interrelationships between speed, volume, and density. The approaches were either macroscopic or microscopic, that is, the models were either set up by investigating traffic flow as a whole (analogy model) or they were deduced from microscopic properties (car following models).

The deductions, limitations, and validity of the various models especially with regard to the five fundamental boundary conditions of traffic flow have been discussed elsewhere (10, 11, 12).

It is evident that the simple concepts of safe spacing cannot constitute a valid theory of traffic flow or valid measures of maximum volume or capacity, critical density, or speed as has been tried by early researchers(35, 36). However, though dependent on certain assumptions, the absolute and marginal safety concept comprise safety criteria based on realistic ranges of vehicle capabilities, road variables, and human elements, and thus, shed light on the traffic flow models and their inherent degrees of traffic safety.

All following considerations will refer to single lane traffic.

5.2 Speed-Flow Relationship

It shall be assumed that vehicles move at a uniform speed. They shall be separated from one another by headways (measured from front to front) which may be derived either from some theoretical relationship (concepts A and B) or may be based on empirical observations (36, 40).
Then:

\[
\text{flow} = \frac{\text{speed}}{\text{headway}}
\]

**Absolute Safety Concept**

By use of the safe headway:

\[
h_A = 1.47TV + \frac{V^2}{30f} + 1 \quad (5-1)
\]

where:

\[h_A = \text{safe headway based on absolute safety criterion, ft.}\]

\[l = \text{car-length, ft.}\]

The flow can be computed from

\[
q = \frac{5280 V}{1.47TV + \frac{V^2}{30f} + 1} \quad (5-2)
\]

or

\[
q = \frac{5280}{1.47T + \frac{V}{30f} + \frac{1}{V}} , \quad \text{where } q \text{ is obtained in veh/h.}
\]

Differentiating flow \( q \) as a function of speed \( V \), whereby the coefficient of friction is considered constant;

\[
\frac{dq}{dV} = \frac{5280 \left( -\frac{1}{30f} + \frac{1}{V^2} \right)}{(1.47T + \frac{V}{30f} + \frac{1}{V})^2}
\]

and setting \( \frac{dq}{dV} = 0 \),

the uniform speed at which maximum flow occurs can be calculated:
\[ V_{\text{opt}} = \sqrt{30 \, \text{lf}} \]  \hspace{1cm} (5-3)

where:

\[ V_{\text{opt}} = \text{optimum speed, mph.} \]

The maximum flow or volume follows by substituting \( V_{\text{opt}} \) in Eq. 5-2:

\[ q_{\text{max}} = \frac{3600}{T + \frac{2}{1.47} \sqrt{\frac{1}{30 \, \text{lf}}}} \]  \hspace{1cm} (5-4)

If for example the rate of deceleration \( d \) is constant = 0.63g (ft/sec\(^2\)) and thus, \( f = 0.63 \), and \( l = 17.5 \text{ ft} \):

\[ V_{\text{opt}} = \sqrt{30 \times 17.5 \times 0.63} = 18.1 \text{ mph.} \]

\[ \max q_T = 0.7 = \frac{3600}{0.7 + \frac{2}{1.47} \sqrt{\frac{17.5}{30 \times 0.63}}} = 1790 \text{ veh/hr.} \]

\[ \max q_T = 2.0 = 1085 \text{ veh/hr.} \]

However, the optimum speed and maximum flow computed above only indicate the order of magnitude and range in which optimum conditions can be expected, since the coefficient of friction varies with speed.

Figures 13 and 14 present speed-volume curves based on spacings of the absolute safety concept and on an average car length of 17.5 feet. From these graphs it may be noted that:

1. optimum speeds range between 16 and 20 mph depending on pavement conditions;

2. optimum speeds as well as maximum flows are higher for dry than for wet pavement conditions;
Figure 13: Speed-flow curves for dry pavement (Concrete A)

- Upper limit of friction range (Fig. 5)
- Lower limit of friction range (Fig. 5)
<table>
<thead>
<tr>
<th>Optimum Speeds</th>
<th>Maximum flows (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V(mph)</td>
<td>Pavement</td>
</tr>
<tr>
<td></td>
<td>Reaction time (sec)</td>
</tr>
<tr>
<td>20</td>
<td>1900</td>
</tr>
<tr>
<td>18</td>
<td>1830</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
</tr>
</tbody>
</table>

3. longer reaction times result in flatter curves
   and appreciably lower maximum lane volumes
   (up to 40% less),

4. the influence of the lower limits of the deceleration
   ranges is more pronounced in the case of wet
   pavements than in the case of dry pavement conditions.

Marginal Safety Concept

Based on the minimum headway providing marginal safety in the
car-following situation

\[ h_B = 1.47VT + 1 \]  \hspace{1cm} (5-5)

where:

\( l \) = car length, ft, and

\( h_B \) is measured in feet, the flow is obtained from

\[ q = \frac{5280V}{1.47VT + 1} \]  \hspace{1cm} (5-6)

or

\[ q = \frac{5280}{1.47T + 1/V} \]
where:

\[ q = \text{flow, veh/hr}. \]

An optimum speed cannot be derived since the flow curve steadily increases from \( V = 0, q = 0 \) to \( q = \frac{5280}{1.47 T} \) with \( V \) approaching infinity. Up to a certain speed, there is a steep increase in \( q \)-values depending on the reaction time, after which the curve flattens and shows only slightly increasing traffic flows.

The \( q \)-values are by far greater than the corresponding flows computed from the absolute safety concept. The characteristic curve does not accord with the actual decrease of traffic flow at speeds beyond certain optimum speeds.
5.3 Speed-Density Relationship

At uniform speed, density is related to velocity by

\[
\text{density} = \frac{1}{\text{headway}}
\]

where headway is a function of speed.

Absolute Safety Concept

Since the absolutely safe headway is given by

\[
h_A = 1.47 V T + \frac{V^2}{30 f} + 1,
\]

the density can be calculated from

\[
k_A = \frac{5280}{1.47 V T + \frac{V^2}{30 f} + 1}
\]  \hspace{1cm} (5-7)

where:

\[k_A\] is density for the absolute safety concept, veh/mile

Figures 16 and 17 present the resulting diagrams for dry as well as wet pavement conditions. Both graphs are quite similar. Densities at certain speeds decrease in accordance to changes

1. from dry to wet pavement conditions,
2. from high coefficients of friction (upper limits) to low coefficients (lower limits), and
3. from short to long reaction times.

The highest possible density \(k_j\) occurs when traffic is stopped \((V = 0)\) with no space between the vehicles:
FIGURE 16: SPEED-DENSITY CURVES FOR DRY PAVEMENT (CONCEPT A)

- Upper Limit of Friction Range
- Lower Limit of Friction Range
FIGURE 17: SPEED-DENSITY CURVES FOR WET PAVEMENT (CONCEPT A)
\[ k_j = \frac{5280}{1}, \text{and for } 1 = 17.5 \text{ ft:} \]
\[ k_j = \frac{5280}{17.5} = 302 \text{ veh/mile} \]

**Marginal Safety Concept**

In this case the valid equation for density is

\[ k_B = \frac{5280}{1.47 VT + 1} \quad (5-8) \]

where:

\[ k_B = \text{density for marginal safety concept, veh/mile} \]

The resulting speed-density curves are of hyperbolic shape and show increasing densities with decreasing speeds.

The density values for \( T = 20 \) sec. are appreciably lower than densities for \( T = 0.7 \) sec. As for the absolute safety concept, the theoretical jam density is given by \( k_j = 5280/1 \).
5.4 Volume-Density Relationship

Generally, the relationship between volume and density is referred to as the fundamental diagram of traffic flow. The flow-density curve is simply determined by the basic equation

\[ \text{volume} = \text{density} \times \text{speed}. \]

**Absolute Safety Concept**

For each uniform velocity, volume as well as density can be computed separately from the safe headway \( h_A \). The direct dependence of both fundamental parameters of traffic flow is mathematically given by

\[
\begin{align*}
(1) \quad q &= kV \\
(2) \quad k &= \frac{5280}{1.47VT + \frac{V^2}{30f} + 1}
\end{align*}
\]

Solving equation 2 for \( V \):

\[
V = \frac{30f}{2} (-1.47 \, T^+ \sqrt{1.47^2 T^2 - \frac{4}{30f} (1 - \frac{5280}{k})})
\]

and substituting \( V \) in equation 5 in equation 1

\[
q = b_0 k^+ \sqrt{b_1 k^2 + b_2 k}
\]

where:

\[
\begin{align*}
q &= \text{flow, veh/hr.}, \\
b_0 &= -\frac{1.47 \, T \times 30f}{2}, \\
b_1 &= \frac{30f}{4} (1.47^2 T^2 \times 30f - 161), \\
b_2 &= 5280 \, k \times 30f.
\end{align*}
\]
In calculating single values, however, it is more convenient to express flow and density by equations 5-2 and 5-7:

\[ q = \frac{5280 \cdot V}{1.47 \cdot V + V^2 + 1} \text{ and } \]

\[ k = \frac{5280}{1.47 \cdot V + V^2 + 1} \frac{30}{f} \]

These single volume and density values may then be related to the same uniform velocities.

The q-k curve increases from \( q = 0, k = 0 \) to the maximum flow

\[ q_{\text{max}} = \frac{3600}{T + \frac{2}{1.47} \frac{1.47}{\sqrt{30 \cdot f}}} \quad \text{for } f = \text{constant} \]

at

\[ V_{\text{opt}} = \sqrt{60 \cdot f} \]

as it has been derived on pages 44-45. Then, with \( k_{\text{opt}} = \frac{q_{\text{max}}}{V_{\text{opt}}} \)

\[ k_{\text{opt}} = \frac{3600}{2.1 \cdot \frac{1}{1.47} + T \sqrt{30 \cdot f}} \quad (5-10) \]

where:

\( k_{\text{opt}} = \text{density for optimal condition, veh/mile.} \)

For the example given on page 45, \((f=0.63, l=17.5 \text{ ft.})\) the optimum density is

\[ k_{T=0.7} = 99.2 \text{ veh/m} \quad k_{T=2.0} = 59.5 \text{ veh/m} \]

After passing optimum conditions, the flow curve slowly decreases with increasing densities and finally approaches jam conditions where the traffic
volume is equal to zero and the density is maximal ($k_j = 5280/1$).

These results are illustrated on Figures 19 and 20. Generally, there is a steep increase of traffic volumes between $k = 0$ and $k = 30$ veh/m ($T = 2.0$ sec) or $k = 60$ veh/m ($T = 0.7$ sec), a characteristic maximal portion with small changes in traffic flow between $k = 40$ and 80 veh/m, and $k = 70$ and 140 veh/m (for $T = 2.0$ and $T = 0.7$ sec), and a decrease of traffic flow to theoretical jam conditions at $k_j = 302$ veh/m and $q = 0$.

Basically, it is found that

1. optimum conditions occur between densities of 80 and 120 veh/m for $T = 0.7$ sec, and densities of 40 and 80 veh/m for $T = 2.0$ sec,

2. maximum flows are obtained between 1600-1900 veh/hr for $T = 0.7$ sec, and 1030-1130 veh/hr for $T = 2.0$ sec,

3. longer reaction times decrease the possible maximum flow and the associated optimum densities (up to 40% from $T = 0.7$ to $T = 2.0$ sec),

4. the lower deceleration limit noticeably decrease possible traffic volumes only in the case of wet pavement conditions,

5. maximum flows for dry pavements are up to about 14% higher than those for wet pavements,

6. optimum flow for wet pavement conditions occurs
Figure 10: Volume-Density Curves for Dry Pavement (Concerta)
at slightly higher density than that for dry pavement conditions (up to 5% or 7 vehicles/mile).

Marginal Safety Concept

The mathematical relationship for the q-k relationship can be derived from

\[ q = k \times V \text{ and } k = \frac{5280}{1.47V^2 + 1} \]

where:

\( k = \text{density, veh/mile.} \)

It is:

\[ q = \frac{5280}{1.47T} - \frac{k_1}{1.47T} \quad (5-11) \]

where:

\( q = \text{flow, veh/hr.} \)

This equation represents a linear relationship between \( q = 0 \) for jam conditions and \( q = \text{maximum} \) when \( k = 0 \). This function does not agree with the characteristic shape of the fundamental q-k curve of traffic flow and, thus, cannot be used to describe the actual flow-density relationship.

5.5 Consequences of Safe Driving for Traffic Flow Models

Capacity or, generally, traffic flow reflects the efficiency of a road to expedite vehicles as well as the policy of safe driving that drivers adopt. Thus, traffic flow models may be regarded either under the objective of optimal highway operation or under the purpose of testing the inherent
degree of traffic safety.

Principally, in studying traffic safety more from a theoretical and "macroscopic" point of view, traffic flow curves may be examined in the light of accident statistics or in the light of safe driving concepts. An attempt will be made in the following investigation to test the safety standards of traffic flow models and the significance of safe driving policies.

In comparing traffic models with the fundamental diagrams of the safe driving concepts (Figures 19 and 20), Greenshields' empirical model and Lighthill-Whitham's as well as Greenberg's analogy model will be discussed since these "classical" models have been generally considered valuable and have proven successful in describing certain traffic flow phenomena.

Compatibility of Fundamental Parameters

To achieve such a comparison, the fundamental parameters as used in the diagrams of the safety concepts and as applied in the various traffic flow models shall be considered to be analogous. It, however, should be noted that

1. the q, k, y diagrams of the safety concepts are based on parameters such as uniform velocity and consistent adoption of the same driving policy with regard to safe headways,

2. in theoretical traffic flow models average values
of q, k, and v are used which are derived by statistical means.

3. empirical traffic flow models (Greenshields') have been deducted from "average" conditions of q, k, and v,

4. car-following models, though derived from microscopic studies of traffic flow, require the use of average densities and velocities to obtain Greenberg's equation of the q-k relationship (29).

Thus, since the following comparisons shall theoretically study the inherent degree of safety of those models, the space-mean speed as well as average densities and flows shall be assumed compatible with uniform speeds, and densities and flows derived from uniform safe driving policies.

The following considerations are based on the absolute safety concept from which conclusions shall be drawn to the marginal safety criterion.

**Greenshield's Empirical Model**

Greenshields (34), in 1934, based his q-k equation on a straight line relationship between average density and average speed. The fundamental diagram of traffic flow was expressed by a parabolic equation:

\[ q = 2 \ c \ k \ (1 - k/k_f), \]  \hspace{1cm} (5-12)

where:

\[ q = \text{flow, vech/hr} \]
\[ c = V_{opt} = \text{optimum speed, mph,} \]

\[ k_j = \text{jam density, veh/mile.} \]

For a valid comparison of Greenshields' formula and his q-k curve with the q-k relationship derived from the absolute safety concept, the parameters \( c \) and \( k_j \) have to be determined. This is accomplished by choosing the optimum condition of the absolute safety criterion, \( v_{opt} \), \( k_{opt} \), and \( q_{max} \) as primary factors to compute \( k_j \).

Thus, \( k_j \) can be derived from equation 5-12, where

\[ q_{max} = 2 \frac{v_{opt} \cdot k_{opt} \cdot (1 - k_{opt}/k_j)}{k_j} \]

Since \( q_{max} = v_{opt} \cdot k_{opt} \),

\( k_j \) can be computed:

\[ q_{max} = v_{opt} \cdot k_{opt} = 2 v_{opt} \cdot k_{opt} \cdot (1 - k_{opt}/k_j) \]

and

\[ k_j = 2 k_{opt} \quad (5-13) \]

For dry pavement and \( T = 0.7 \text{ sec.} \),

\[ c \approx V_{opt} = 20 \text{ mph} \quad (\text{Figure 13}) \]

\[ k_{opt} = 95 \text{ veh/mile} \]

\[ k_j = 2 k_{opt} = 190 \text{ veh/mile} \]

The computation of \( k_j \) is not only meaningful to make a comparison of Greenshields' q-k curve and the q-k curve based on the absolute safety criterion, but also it gives a more realistic value far below the theoretical
jam density. Figure 21 shows the resulting "Greenshields" q-k curve for
the above values.

The Lighthill-Whitham Theory and Greenberg's Analogy Model

Lighthill and Whitham assumed an analogy between the method
of kinematic waves - suggested by theories of flow about supersonic projectiles
and of flood movement in rivers - and traffic flow. Employing an analogy
to the flow of a one dimensional fluid, Greenberg (29) obtained the following
flow-density relationship

\[ q = ck \ln \frac{k_j}{k} \quad (5-14) \]

where:

\[ q = \text{flow, veh/hr} \]
\[ c = V_{opt} = \text{optimum speed, mph} \]
\[ k_j = \text{jam density, veh/mile} \]

Herman and Potts (30) verified this equation by deriving a
similar relationship from the microscopic car-following law governing
the motion of two cars:

\[ q = \alpha_c k \ln \frac{k_j}{k} \quad (5-15) \]

where:

\[ \alpha_c = \text{"characteristic" speed defining the sensitivity for} \]
\[ \text{the reciprocal spacing car-following law,} \]

which corresponds to equation 5-14 by putting \( \alpha_c = c \).

Thus, again introducing optimum conditions as inputs for the de-
sired comparison of the absolute safety concept and Greenberg's q-k
relationship, a valid $k_j$ value can be derived from equation 5-14, where

$$q_{max} = v_{opt} k_{opt} \ln \frac{k_j}{k_{opt}}.$$  

Since

$$q_{max} = v_{opt} k_{opt},$$

$(1) = (2)$ $v_{opt} k_{opt} = v_{opt} k_{opt} \ln k_j/k$, and

$$l = \ln \frac{k_j}{k}.$$ 

Hence

$$k_j = e^{k_{opt}} \quad (5-16)$$

For the case of dry pavement and $T = 0.7$ sec.

$$k_j = e \times 95 = 258 \text{ veh/mile}$$

The resulting $q$-$k$ curve for Greenberg's equation of traffic flow is depicted in Figure 21.

Traffic Safety Expressed in Flow Models

Greenshields' empirical diagram, Lighthill-Whitham's and Greenberg's analogy $q$-$k$ curve, and the absolute safe spacing curve are illustrated in Figure 21. Optimum conditions with $k_{opt} = 90 \text{ veh/mile}$ and $v_{opt} \approx 20 \text{ mph}$ have been used to determine the relevant curves necessary for comparison.

It can be seen that those portions of the curves which refer to low traffic densities do not differ very much. However, within the range between optimum and jam density, the traffic flow models show considerably smaller volumes than the values derived from the safe spacing concept whereby
the difference increases with higher densities.

In the light of traffic safety, both curves which have been derived from traffic flow models indicate spacings which are larger than the spacings based on the absolute safety criterion and therefore provide an even higher degree of safety than the absolute safety concept. These curves depict a higher degree of safety than the marginal safety since the marginally safe spacings are smaller than the safe spacings based on the absolute safety criterion.

The validity and consequences of such a comparison and the correctness of the conclusions are further discussed under Chapter VIII.
Figure 21: Fundamental Diagrams of Models and Safe Spacing Concept.
CHAPTER VI

DATA COLLECTION AND ANALYSIS PROCEDURES

6.1 Objectives

Traffic safety research has mostly been directed to accident investigations considering highway, vehicle, and driver characteristics. A more positive approach to the traffic safety problem, however, is to analyze actual traffic movements within a framework of valid and reasonable safety criteria.

Thus, in the car-following situation, the safe spacing concepts derived earlier in this study may be used to determine the degree of safety in traffic flow from real world data.

The object of this study was to investigate car-following practices in freeway traffic and to determine the resulting degree of traffic safety. An attempt was made to obtain factual proof of the relative risk which drivers implicitly accept in the car-following situation and which has been considered to be the most important cause for the high percentage of rear-end collisions.

The more specific objectives were as follows:

1. to define safety for the comparison of spacings at
different velocities,

2. to analyze the variation of traffic safety as
found in car-following operations when vehicles
progress along the roadway both in space and
in time,

3. to determine the proportions of "safe" and
"unsafe" driving times in car-following,

4. to test the policies of safe driving on their actual
acceptance by the majority of drivers, and

5. to investigate the velocity - traffic safety
relationship in car-following.

6.2 Procedures

Data Acquisition by Photogrammetric Techniques

Car-following experiments conducted in the past have been
mainly designed to study interactions between two vehicles. However,
this essentially microscopic approach cannot result in any general conclusion
about traffic safety in car-following practices. Thus, photogrammetric
techniques are especially suitable to provide pertinent data both in space
and in time since they present a complete picture of traffic movement
and the actions of single vehicles travelling along a roadway.

The method used for data collection was developed by the
Transportation Engineering Center of the Ohio State University (42). Data
were reduced from the photographs with the help of an analytical stereoplotter. Headways and velocities were computed by transforming photo coordinates to ground coordinates and converting vehicles' ground coordinates into accumulative distances traveled by each vehicle in each photograph from an arbitrarily fixed starting point.

The computer output data could be directly used for the purposes of this study since they satisfy the data requirements of the study objectives, namely

1. the spacings between vehicles (computed from the individual headways by deducting the appropriate car length), and

2. the velocities of the vehicles, at each time interval respectively.

The change of both parameters, and, indirectly, the variation of traffic safety in car-following, can be illustrated most clearly by vehicle trajectories plotted on time-distance diagrams. Each line represents the time-distance trace of one vehicle and its movement both in space and in time. Spacings and velocities of each vehicle at any moment and at any point can be easily computed (Figure 22).

**Application of Safety Criteria**

According to the objectives of the study, the main task was to analyze measured car-following data in the light of traffic safety.
FIGURE 22: TIME DISTANCE DIAGRAM WITH VEHICLE TRAJECTORIES

\[
\text{VELOCITY} = 0.682 \frac{d}{t} \text{ (MPH)}
\]

\[
\text{SPACING} = h - l \text{ (FT)}, \text{ WHERE } l = \text{ CAR LENGTH}
\]
Therefore the envelopes of safe spacings (Chapter IV) were established as a base for this analysis. The velocity-spacing data measured by use of photogrammetric techniques could be directly compared with safe spacings at corresponding speeds.

Five safe spacing sets for dry pavement conditions were finally selected as the bases for the data analysis of this study, since they comprehensively describe the entire range of driver reaction times (0.7 - 2.0 seconds) and road friction conditions (total friction range, Figure 8) most commonly found in car-following practices:

Concept of Absolute Safety:

1. "A₁" - reaction time $T = 0.7$ sec., upper friction limit (Figure 5),
2. "A₂" - reaction time $T = 2.0$ sec., lower friction limit (Figure 5),

Concept of Marginal Safety:

3. "B₁" - reaction time $T = 0.7$ sec.,
4. "B₂" - reaction time $T = 2.0$ sec.,

"American" Safe Spacing Recommendation:
5. "R" - one car length per 10 mph velocity.

Safety Factor

To reduce the data in the light of traffic safety, it was necessary to introduce a new term by which the measured spacing-velocity data could
be analogously expressed and related to the five selected safe spacing sets at any car-following velocity. This was simply done by defining the "safety factor" as the quotient of the measured spacing and the safe spacing at corresponding velocities. Hence:

\[
\text{safety factor } \delta = \frac{\text{measured spacing}}{\text{safe spacing}}
\]

It is a dimensionless parameter which principally indicates

- a "safe" car-following situation, if \( \delta \geq 1 \), and
- an "unsafe" car-following situation, if \( \delta < 1 \).

If for example a spacing of 50 feet is measured at 25 mph, then the safety factors for the five safety criteria above with safe spacings of 53.5, 106.0, 25.7, 73.5, and 44.4 feet (car length = 17.75 ft) at 25 mph, may be computed as follows:

\[
\delta_{A_1} = \frac{50}{53.5} = 0.93; \quad \delta_{A_2} = \frac{50}{106} = 0.47;
\]

\[
\delta_{B_1} = \frac{50}{25.7} = 1.95; \quad \delta_{B_2} = \frac{50}{73.5} = 0.68;
\]

\[
\delta_R = \frac{50}{44.4} = 1.13.
\]

Hence, in cases \( A_1, A_2, \) and \( B_2 \) the car-following situation would be considered "unsafe", but should be interpreted as "safe" for criterion \( B_1 \), which assumes a reaction time distance for \( T = 0.7 \) sec. as required safe spacing. Finally, safety factor \( \delta_R \) indicates that the recommended spacing of \( 2.5 \times \) car length is met.

Principally, the safety factor merely denotes the proportion
of measured and safe spacing. Safety factors greater than 1.0 indicate the additional margin in car-following safety as a supplementary distance available in which to brake. Safety factors less than 1.0, however, are only meaningful when related to the initial car-following speed, since the factors with values less than 1.0, but of the same order of magnitude, demonstrate quite different "degrees of unsafety", or better still, "degrees of collision severities" with regard to the various car-following and eventual collision velocities.

To illustrate the interrelationship between safety factor, car-following, and collision velocities, collision speeds were plotted against car-following (initial braking) velocities at various safety factors (Figures 23 and 24) based on the following formulae:

**Concept of Absolute Safety**

\[
V_{\text{coll}} = \sqrt{\frac{V_{\text{cf}}^2 - 30f \left( \delta s_A - 1.47TV_{\text{cf}} \right)}{}} \tag{6-1}
\]

**Concept of Marginal Safety**

\[
V_{\text{coll}} = \sqrt{\frac{V_{\text{cf}}^2 - 30f \left( \delta s_M + \frac{V_{\text{cf}}^2}{30f} - 1.47TV_{\text{cf}} \right)}{}} \tag{6-2}
\]

where:

- \( V_{\text{coll}} \) = collision velocity, mph
- \( V_{\text{cf}} \) = car-following velocity, mph
- \( s_A, s_M \) = absolute or marginal safe spacing, at car-following velocities (Figure 8), ft.
- \( \delta \) = safety factor
T = reaction time, sec.

f = coefficient of friction

These equations denote the collision speed of the trailing car at which it will hit the front vehicle and are derived from the available braking distance. Thus, in the case of concept $A_1$, for a safety factor of 0.6 at a car-following velocity of 50 mph, the available braking distance may be computed from:

$$b = \delta s_A - 1.47 TV_{cf} \quad (s_{A1} \text{ from Figure 8})$$

$$= 0.6 \times 178.9 - 1.47 \times 0.7 \times 50$$

$$= 55.9 \text{ ft.}$$

The collision speed, then, is

$$V_{\text{coll}} = \sqrt{V_{cf}^2 - (b \times 30f)}$$

With $f = 0.655$ at 50 mph (Figure 5)

$$V_{\text{coll}} = \sqrt{50^2 - (55.9 \times 30 \times 0.655)}$$

$$V_{\text{coll}} = 37.5 \text{ mph (see Figure 23).}$$

Figures 23 and 24 illustrate for both the absolute and marginal safety concepts that collision velocities increase with:

1. decreasing safety factors,
2. increasing car-following speeds,
3. increasing reaction times, and
4. decreasing road friction.

However, when expressed as percentages of car-following speeds, collision
Figure 23: Collision velocities for various safety factors below 1.0 (absolute safety concept), dry pavement conditions.
Figure 24: Collision velocities for various safety factors below 1.0 (marginal safety concept). Dry pavement conditions.
velocities decrease with increasing car-following speeds. In other words through collision velocities increase absolutely with increasing car-following velocities, their relative values for each of the various safety factors decrease.

In summary, safety factors with values less than 1.0 should be principally interpreted in connection with their respective velocity values.

6.3 Study Site Characteristics

Study Location

This study was based on data obtained by photogrammetric techniques during the summer of 1964. Photographs were taken of the evening peak traffic flow on a 6800 feet urban section of Interstate Highway 71 between Fifth Avenue and Morse Road, Columbus, Ohio. The speed limit on this section was 60 mph.

The study was confined to the analysis of vehicle movements on the 12 feet wide inside lane of the six lane divided highway. The pavement of the studied highway section was concrete with dry surface conditions.

Vehicle Trajectories

The photographs cover a time range of 130 seconds. The movements of 48 passenger cars were recorded for a total observation or driving time of 3765 seconds (1 hour 2.6 minutes). The average observation time per vehicle was about 78 seconds.
The total traffic flow was graphically depicted by individual vehicle trajectories (Figure 25), showing the car-following situations at time intervals of one second.

**Traffic Flow Characteristics**

The sample taken over a time period of 130 seconds represents a typical traffic flow condition during the evening peak. For the first 40 seconds, Figure 25 shows vehicle movements at 30-40 mph velocity. Then it illustrates a traffic breakdown with a kinematic wave progressing upstream after which the traffic flow builds up again and moves at 25-45 mph velocity.

The pertinent traffic flow parameters, volume and density, can be simply computed by sectioning the time-distance diagram (Figure 25) horizontally and vertically, and by relating the number of trajectories to the corresponding time or distance intervals, respectively. Thus the following ranges for both parameters were found:

**Volume:**

1750-2250 veh/hr for an observation time of about 60 sec.

**Density:**

75-95 veh/mile for an average distance of about 2000 ft.

The speed limit of the studied section was 60 mph, car-following speeds ranged between 0 and 54 mph.
Figure 25: Vehicle Trajectories, Inside Lane
CHAPTER VII

STATISTICAL ANALYSIS AND RESULTS

7.1 Data Reduction for Statistical Analysis

The computer output data were available for each one second interval. To obtain an overall picture of traffic safety in a car-following situation, spacing and velocity data were analyzed for each three second interval.

The spacings of vehicles for time intervals of three seconds were computed from the available headway data by deducting the car length of the leading vehicle. The associated velocity values were used to determine the safe spacings with regard to the five selected safety criteria. These safe spacings were related to the actual spacings by calculating the respective safety factors. Table 1 shows the data reduction for a sample of vehicle 222.

Altogether, about 1300 different spacing-velocity data were reduced, representing 48 vehicles with observation or driving times between 5 and 130 seconds. All further analyses were based on these initial computations.
<table>
<thead>
<tr>
<th>Time Interval (sec.)</th>
<th>Velocity (mph.)</th>
<th>Headway (ft.)</th>
<th>Spacing (ft.)</th>
<th>Safe Spacing and Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A₁ s  A₂ s  A₂ s  B₁ s  B₂ s  R s</td>
</tr>
<tr>
<td>22</td>
<td>41.63</td>
<td>70.50</td>
<td>52.75</td>
<td>123.2 0.41 218.7 0.24 42.8 1.23 122.5 0.42 70.5 0.75</td>
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<tr>
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<td>67.25</td>
<td>49.50</td>
<td>40.7 1.21 83.5 0.59 21.5 2.30 61.5 0.81 35.4 1.40</td>
</tr>
</tbody>
</table>

s = safe spacing, ft.

Table 1: Example of Data Reduction for Vehicle No. 222
(car length of preceding vehicle = 17.75 ft.)
7.2 Variations of the Safety Factor

The initial step to illustrate the different degrees of safety in the car-following situation for individual vehicles, was to plot the computed safety factors at three second time intervals for each of the five basic safety criteria.

Figure 26 shows a typical safety factor diagram of a vehicle progressing along the studied section for 38 seconds. To represent the relationship of the degree of safety to the car-following velocity, the associated speed values were plotted on the same graph. The safety factor for each of the five safety criteria varied with every change of spacing or velocity.

From Figure 26 the following may be noted:

1. At any velocity the safety criteria $A_2$ and $B_1$ resulted in the lowest and highest safety factors, respectively.

2. For the speed range between 40 and 50 mph, safety factors gradually increased in the following sequence: $A_2$, $A_1$, $B_2$, and $B_1$.

3. For the speed range below 40 mph, safety factor values increased in the sequence $A_2$, $B_2$, $A_1$, and $B_1$.

4. The recommended multiple car length criterion R was characterized by safety factors between concepts $B_1$ and $B_2$ (see also Figure 11).
5. At low velocities, safety factors showed high values (generally far above 1.0).

7.3 Unsafe Driving Time

The unsafe driving time for each individual vehicle could be easily determined from the reduced data shown in Table 1. Since a safety factor with a value less than 1.0 indicates an unsafe car-following situation, the time intervals with $S < 1.0$ were added in order to compute the unsafe driving time for each single vehicle:

$$t_{\text{unsafe}} = \frac{\sum (\Delta t)_{S<1.0}}{t_{\text{total}}} \times 100$$

(7-1)

where:

- $t_{\text{unsafe}} = $ unsafe driving time, in percent of total observation time
- $(\Delta t)_{S<1.0} = $ period of time with safety factor $S < 1.0$, secs.
- $t_{\text{total}} = $ total observation time, secs.

This was carried out for each of the five safety criteria. An average unsafe driving time was calculated by weighting the individual observation times of the 48 vehicles. (Appendix, Table 5) The following results were obtained:

<table>
<thead>
<tr>
<th>Safety Criterion</th>
<th>Average Unsafe Driving Time (in % of Total Observation Time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>69.81</td>
</tr>
</tbody>
</table>
Thus the absolutely safe condition $A_1$ (reaction time 0.7 second and higher friction limit) was satisfied for 30.19% of the observation time. The safety criterion $A_2$ was only met 9.11% of the observation time. The reaction time distance for 0.7 seconds was maintained 89% of the observation time.

 Principally, it was found that safety criteria based on longer reaction times were considerably less satisfied than criteria derived from short reaction times. The influence of the reaction time is pronounced resulting in low safety factors if low reaction times are assumed.

 In Figure 27 the cumulative distribution curves of unsafe driving times as a percentage of the total time are given. More information on the data from which these curves were constructed is presented in Table 5 of the appendix. The curves of Figure 27 denote the total percentage of unsafe drivers travelling at or above the indicated percentage of unsafe driving time. Thus, for example for criterion $A_2$, 85 percent of the "unsafe" drivers progressed unsafely at or above 88 percent of their total driving time. Table 2 shows figures for the 50 as well as 85 percentile:
Table 2: Percent of Unsafe Driving Time

<table>
<thead>
<tr>
<th>% of unsafe drivers travelling at or above $T_{p=x}$</th>
<th>% of unsafe driving time $P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 A2 B1 B2 R</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>67  98  20  95  44</td>
</tr>
<tr>
<td>85</td>
<td>34  88  17.5  67  20</td>
</tr>
</tbody>
</table>

In summary, criterion $B_1$, was best met by the majority of drivers; this is apparent from the low average unsafe driving time of 11 percent of the total observation time as well as from the low 50 and 85 percentiles of Figure 27. Next to $B_1$, the recommended car-following policy of multiple car-lengths $R$ showed the highest average safe driving time of 63 percent. The sequence $A_2$, $B_2$, $A_1$, $R$, and $B_1$, again, characterized the gradually increasing degree of acceptance of these criteria by drivers as well as the increase in traffic safety with regard to these criteria.

7.4 Average Safety Factors

The car-following safety of each vehicle for the associated observation time was evaluated by computing the average safety factor. The obtained average safety factors (Appendix, Table 6) were divided into ranges and the cumulative distribution curves were plotted by weighting each safety factor with regard to its respective observation time. Figure 28
illustrates:

1. For criterion $B_1$ 86 percent of the drivers had an average safety factor of $\delta > 1.0$, indicating that the majority of drivers implicitly accept this criterion as their minimum safe spacing policy.

2. Only 4 percent of the vehicles can be considered "safe" with regard to $A_2$.

3. 60 percent of the vehicles moved safely when interpreted in the light of the multiple car length policy.

4. The sequence $A_2$, $B_2$, $A_1$, $R$, and $B_1$ characterized an increase in car-following safety when related to the respective criteria.

The pertinent results are listed in Table 3:

Table 3: Average Safety Factor

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Range of Av.</th>
<th>% of drivers</th>
<th>Av. Safety Factor for Safety Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>travelling with $\delta \leq 1.0$ Median 85-Perc.</td>
</tr>
<tr>
<td>$A_1$</td>
<td>$0.56 - 2.71$</td>
<td>60</td>
<td>0.90</td>
</tr>
<tr>
<td>$A_2$</td>
<td>$0.25 - 1.30$</td>
<td>96</td>
<td>0.43</td>
</tr>
<tr>
<td>$B_1$</td>
<td>$1.00 - 5.17$</td>
<td>14</td>
<td>1.72</td>
</tr>
<tr>
<td>$B_2$</td>
<td>$0.35 - 1.81$</td>
<td>.83</td>
<td>0.60</td>
</tr>
<tr>
<td>$R$</td>
<td>$0.59 - 3.53$</td>
<td>40</td>
<td>1.09</td>
</tr>
</tbody>
</table>
Figure 28: Cumulative distribution curves of average safety factor.

PERCENT OF DRIVERS TRAVELLING WITH $\pm \Delta V$

AVERAGE SAFETY FACTOR $\bar{S}_{AV}$
The maximum values of the average safety factors were caused by vehicle 231, the head of a platoon, which had a large - and thus "very safe" - spacing to the preceding car.

7.5 Relationship between Velocity and Traffic Safety

Velocity data and the corresponding safety factors computed for each car-following situation (Table 1) were analyzed to determine the principal relationship between velocity and traffic safety and to evaluate the speed range having the lowest degree of traffic safety in car-following.

Ten 5 mph velocity ranges were set up and the computed individual safety factors were arranged with the corresponding velocity classes. For each velocity range and each safety criterion, statistical tests were made, and the mean safety factor and standard deviation were computed (Table 4).

Figure 29 shows the average safety factors plotted against the midpoints of the 5 mph speed ranges.

The ten 5 mph velocity classes covered the pertinent range of speeds between 2.5 and 52.5 mph. Velocities below 2.5 mph were not considered since these speeds were measured during the breakdown of traffic flow for the time intervals between 45 and 85 seconds at distances between 3400 and 4000 feet where vehicles practically stopped. This situation was no longer considered to present a car-following situation.

Table 4 and Figure 29 illustrate the following results:
1. Mean safety factors sharply increased for velocities below approximately 15 mph (with the exception of $A_1$) and increased again for velocities above 40 to 45 mph.

2. A distinct minimum safety range was obtained for velocities between 30 to 40 mph considering criteria $B_1$, $B_2$, and $R$, and between 30 to 40 mph and 35 to 45 mph for criteria $A_2$ and $A_1$, respectively.

3. For any velocity the criteria $B_1$ and $A_2$ denoted the highest and the lowest mean safety factors, respectively. Criterion $R$ represented a value ranging between $B_1$ and $B_2$.

4. The safe spacing criteria $R$ and $B_1$ resulted in mean safety factors above 1.0 for all velocities. $A_1$ gave mean safety factors above 1.0 for velocities below 20 to 25 mph.

A discontinuity in the general tendency of the mean safety factor was observed for the velocity range of 32.5 to 37.49 mph. This was not considered in the curves of Figure 29 since, again, it was caused by vehicle No. 231 maintaining an extremely large spacing in the 32.5 to 37.49 mph speed range.

For the velocity class 47.50 to 52.49 mph only 11 vehicles
were observed. No reliable conclusion can be obtained from the small sample.
Figure 29: Relationship between mean safety factor and velocity.
<table>
<thead>
<tr>
<th>Velocity Class (mph)</th>
<th>Midpoint (mph)</th>
<th>Number of Indiv. Safety Factors</th>
<th>Mean Safety Factor for Vel. Class</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5-7.49</td>
<td>5</td>
<td>30</td>
<td>3.55 1.18 3.60 1.20 2.10</td>
<td>2.350 0.730 2.340 0.770 1.340</td>
</tr>
<tr>
<td>7.5-12.49</td>
<td>10</td>
<td>57</td>
<td>1.74 0.74 2.40 0.82 1.47</td>
<td>0.709 0.343 1.076 0.406 0.710</td>
</tr>
<tr>
<td>12.5-17.49</td>
<td>15</td>
<td>150</td>
<td>1.41 0.69 2.18 0.76 1.33</td>
<td>0.684 0.299 1.088 0.385 0.674</td>
</tr>
<tr>
<td>17.5-22.49</td>
<td>20</td>
<td>327</td>
<td>1.12 0.54 2.09 0.72 1.30</td>
<td>0.643 0.311 1.190 0.408 0.753</td>
</tr>
<tr>
<td>22.5-27.49</td>
<td>25</td>
<td>302</td>
<td>0.99 0.54 2.02 0.72 1.31</td>
<td>0.564 0.315 1.154 0.408 0.755</td>
</tr>
<tr>
<td>27.5-32.49</td>
<td>30</td>
<td>207</td>
<td>0.82 0.45 1.92 0.71 1.27</td>
<td>0.463 0.273 1.059 0.361 0.691</td>
</tr>
<tr>
<td>32.5-37.49</td>
<td>35</td>
<td>69</td>
<td>0.85 0.46 2.17 0.76 1.41</td>
<td>0.452 0.249 1.250 0.427 0.810</td>
</tr>
<tr>
<td>37.5-42.49</td>
<td>40</td>
<td>87</td>
<td>0.66 0.38 1.92 0.67 1.19</td>
<td>0.385 0.196 1.106 0.389 0.683</td>
</tr>
<tr>
<td>42.5-47.49</td>
<td>45</td>
<td>40</td>
<td>0.71 0.43 2.12 0.78 1.45</td>
<td>0.339 0.210 1.275 0.381 0.825</td>
</tr>
<tr>
<td>47.5-52.49</td>
<td>50</td>
<td>11</td>
<td>0.73 0.46 2.55 0.85 1.68</td>
<td>0.508 0.336 1.850 0.845 0.978</td>
</tr>
</tbody>
</table>

Table 4: Relationship Between Velocity and Safety Factor
CHAPTER VIII

DISCUSSION AND CONCLUSIONS

Rear-end collisions are a serious problem on expressways and freeways. The high percentage of this type of accident has been mostly considered to be related to the pattern of driving and the relative risk accepted by the majority of drivers in car-following situations. Therefore, an attempt was made in the foregoing study to evaluate the degree of traffic safety in car-following by testing real world data against safe spacing criteria.

8.1 Safe Spacing Concepts and Recommendations

Basic Assumptions

Two different criteria of safe spacing were introduced to provide a measure for analyzing traffic safety in car-following. Assumptions had to be made to simplify the complex car-following problem and to give reasonable approximations of most existing conditions for the car-following situation.

Both the absolute and marginal safety concept were based on the assumption of one lane traffic with no possibility to switch lanes.
Even on multilane expressways with dense traffic, these conditions are quite common as discussed by Herman (30) in an investigation of the car-following model. Principally, however, the possibility to avoid a rear-end collision by changing the lane is dependent on the traffic density in the adjacent lanes. As depicted in Figure 25, only 5 out of 43 vehicles switched on to the inside lane investigated in this study.

The following assumptions, of a car-following model with only two cars following each other under uniform conditions were used in this investigation:

1. Both vehicles travel at about the same velocity.
2. Road conditions are identical for both vehicles.
3. Deceleration patterns are similar for both vehicles.

Though the car-following model has been proven to provide a valid description of traffic flow, it seems to be questionable whether traffic safety in car-following can be comprehensively analyzed by safe spacing criteria based on a simple two-car model.

The variance in human responses, road conditions, and vehicle capabilities, are important factors in rear-end collisions. Traffic dynamics and the propagations of disturbances in heavy traffic are considered to be determining factors in chain collisions. Most frequently in chain collisions, the first vehicle stopped in an emergency is not involved in a collision with the immediately following car, but the third and fourth vehicle
are implicated.

However, though both concepts of absolute and of marginal safety do not consider the degree of variance in real life conditions, they can be considered to establish valid boundaries for the comparison by which the relative degree of safety in car-following situations can be tested.

Theoretical Safe Spacing

The absolute as well as marginal safety criterion of this study resulted in a continuously widening envelope of safe spacing with increasing velocities (Figures 8, 9, and 11). The concepts were based on ranges of coefficients of friction obtained by the stopping distance method and reaction times between 0.7 and 2.0 seconds.

The literature review revealed that the methods and results of friction measurements differ quite considerably. It was found that the field of skid-prevention research is characterized by a multitude of different testing equipment and methods and by little effort to coordinate the measurements of the various researchers, and to establish standards for testing methods. For the purposes of this study, it was necessary to set up friction ranges in relation to velocity and to account for the variety of factors most commonly found to influence the stopping capability of vehicles.

No valid correlation between friction ranges obtained by the trailer method and friction values based on the stopping distance method
has been established. The frictional data obtained by the stopping distance method were used to compute safe spacings, since this method - similar to the absolute safety concept of this study - most clearly represents the conditions of panic stops with locked wheels.

Figure 12 shows that the spacings calculated for safe conditions and dry pavement agree with the stopping distances by Normann (4) and Starks and Lister (26) whereby Stark-Lister's distances are only valid up to 60 mph. The comparative analysis indicated that Normann's average experimental distances (for a sample of 53 drivers) approach the safe spacings based on the lower limit of the friction range (Figure 5) at velocities over 60 mph. Normann's 85-percentile curve (Figure 10) presented braking distances which are by far higher than the stopping distances computed from the friction ranges of Figure 5, especially for velocities above 60 mph. Thus it is concluded that Figure 5 denotes too high friction values as to be representative for actual braking decelerations of 85 percent of the drivers.

Figure 9 illustrates that the influence of wet pavement conditions is very pronounced. Drivers should maintain spacings which are about 1.5 times the distances required for dry road surfaces. Wet pavement conditions affect the required safe spacing more distinctly than an increase of reaction times from 0.7 to 2.0 seconds.

In the case of marginally safe conditions, all vehicles are
assumed to produce the same rate of deceleration. The concept of marginal safety results in linearly increasing spacings with increasing velocities since speed enters the equation for marginally safe spacing as a linear factor. Spacings are the same for dry as well as wet pavement conditions.

Thus, conditions assumed for the absolute safety concept require the consideration of the friction between tire and surface and of the influence of velocity. The marginal safety criterion requires spacings mainly depending on the reaction time of drivers and the time lag in propagating disturbances.

Recommended Safe Spacing.

As shown in Figure 11, there is no simple rule of thumb which can be considered to be valid for safe spacing or for all conditions in car-following situations.

The American recommendation of one car length per 10 mph increment in velocity is represented by curves similar to the marginally safe concept. The reaction time of drivers, however, is not considered a determining factor. The European rule of 10 meters per 10 km/h increment in velocity results in distances which are larger for velocities below 50 mph than the required spacing for the concept of absolute safety and too small for velocities in excess of 50 mph. The second European recommendation, similar to the absolute safety concept, presents mean
values of the absolute safety concept. This recommendation, however, does not provide a simple rule for the American driver since it is based on the metric system of measurement.

8.2 Traffic Flow and Traffic Safety

A major problem of today’s traffic condition is how to increase traffic flow and how to improve traffic safety at the same time. An attempt was made in Chapter V of this study to determine the consequences of the safe spacing criteria on the fundamental parameters of traffic flow.

Relationships of the Fundamental Flow Parameters

The deduction of the relationships between volume, density and velocity from headway models or safe spacing concepts is not new (36). The basic difference between the q-k-v relationships of this study (Figures 13–20) and the flow diagrams of early researchers (Highway Capacity Manual, 1950) is the inclusion of a variety of factors affecting traffic safety in car-following by the use of safe and marginally safe headways which were based on realistic ranges of reaction times and coefficients of friction.

Maximum flows between 1000 and 1900 veh/h/lane were found for

1. velocities between 16 and 20 mph, and
2. densities between 40 and 120 veh/mile
depending on the reaction time and the coefficients of friction.

Traffic volumes deduced from headways based on low coefficients of friction, prevailing with wet pavement conditions, are lower than volumes for higher friction values with dry pavements. This explains the fact that traffic flow is more likely to break down when the pavement is wet and volumes experienced with dry pavement conditions cannot be maintained at similar velocities.

For the safe as well as marginally safe condition, traffic flows are strongly dependent on the reaction times of drivers: The shorter the reaction time, the higher the volumes. For the concept of marginal safety and most common car-following velocities (up to 60 mph), the flows based on uniform reaction times of 0.7 seconds are 2.5 times higher than the traffic volumes possible for reaction times of 2.0 seconds. Even the absolute safety concept results in an increase of traffic flow of 30 to 70 percent with reaction times reduced from 2.0 to 0.7 seconds. Hence, on an automatically controlled highway, traffic flow could be considerably increased by eliminating the retarding effect of driver reaction times.

Traffic Flow Models and Safe Spacing Criteria

The traffic flow models of Greenshields and Greenberg have been compared in Figure 21 with the volume-density relationship deduced from the absolute safety concept. The comparison was based on the
assumption that the fundamental parameters of the models expressed by average statistical q, k, v values can be considered as uniform parameters as introduced by the absolute safety criterion. This assumption appears to be justified when regarding traffic flow from a macroscopic viewpoint. There is no difference between the attempt to describe the sum of individual vehicle movements, known as traffic flow, by average flow parameters, and the approach to describe traffic flow by assigning uniform velocities and headways to the individual vehicles and their movements.

Both models indicated spacings which were larger than the spacings required by the absolute safety concept. Since it has been established from the data of this study that vehicles do not generally maintain these large spacings, but are travelling in platoons with long distances between these platoons, the problem of improving traffic safety in the car-following situation without decreasing traffic flow is reduced to the problem of "distributing" vehicles along the highway with sufficient "safe" spacings in between.

8.3 Degree of Safety in Car-following

Five safe spacing sets for dry pavement conditions were selected to analyze car-following data obtained by photogrammetric techniques on the northbound inside lane of an 6800 foot urban section of Interstate Highway 71 in Columbus, Ohio:
Absolute Safety Concept:

\[ A_1 \text{ and } A_2 : \text{ reaction times } 0.7 \text{ and } 2.0 \text{ seconds, upper and lower friction limit (Figure 5).} \]

Marginal Safety Concept:

\[ B_1 \text{ and } B_2 : \text{ reaction times } 0.7 \text{ and } 2.0 \text{ seconds} \]

American Safe Spacing Recommendation:

\[ R : \text{ one car length per each } 10 \text{ mph.} \]

The pertinent results have been listed in Chapter VIII. It can be concluded that

1. about 90% of the drivers consider criterion \( B_1 \) as the minimum safety criterion in car-following,

2. about 60% of the drivers implicitly accept the recommendation \( R \) for safe spacing,

3. safe spacings based on the absolute safety criteria \( A_1 \text{ and } A_2 \), are maintained for 10 and 30%, respectively, of the driving time and are travelled by 40 and 4 percent of the drivers, respectively,

4. there is a distinct minimum safety range for velocities between 30 and 40 mph.

Only the fourth conclusion can be compared with data from the literature since the approach of this study is new and since it was the first time that car-following data both in space and in time were available for
a whole platoon of cars travelling along a freeway. Solomon (43) investigated traffic accidents as related to travel speed from accident reports (Figure 30). He found the lowest involvement rate for velocities between 60 and 70 mph and steeply increasing accident rates for velocities below 40 mph. Thus, the number of accident-involved drivers per 100 million vehicle miles increases about 2.3 times from 50 mph to 40 mph velocity, and about 8 times from 50 mph to 30 mph travel speed.

Solomon's results agree with the findings of this study as depicted in Figure 29. The minimum safety range between 30 and 40 mph depending on the safety criterion corresponds to the steep increase of accidents below 40 mph as shown in Solomon's figure. The increase of safety factors for velocities above 45 mph accords with decreasing involvement rates for velocities over 40 mph reaching a minimum at about 65 mph.

Velocities over 60 mph were not covered by this study, and more studies will be necessary. A speed limit of 60 mph has been imposed on the investigated urban section of I 71 where, close to the downtown area of Columbus, high traffic densities occur. Therefore, insufficient data were obtained in the speed range exceeding 50 mph.

8.4 Recommendations

Further research is recommended to verify the findings of this study which in this form have been obtained for the first time. It is therefore suggested:
Figure 30: Accident Involvement Rate by Travel Speed, Daylight (Solomon (43))
1. to extend car-following studies to other highways,

2. to extend investigations on traffic safety as related to velocities in excess of 50 mph.

3. to explore the "degree of unsafety" or the severity of possible rear-end collisions in car-following situations with special regard to safety factors below 1.0.
REFERENCES


APPENDIX FOR "SAFETY CRITERIA IN CAR-FOLLOWING
SITUATIONS FOR FREEWAY TRAFFIC"
Table 5: Unsafe Driving Time of Individual Vehicles

<table>
<thead>
<tr>
<th>Vehicle No.</th>
<th>Total Observation Time (sec.)</th>
<th>Unsafe Driving Time (% of Total Observation Time)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( A_1 )</td>
</tr>
<tr>
<td>207</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>208</td>
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Table 5 (Continued)

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<tr>
<th>Vehicle No.</th>
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<th>Unsafe Driving Time (in % of Total Observation Time)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$A_1$      $A_2$      $B_1$      $B_2$      $R$</td>
</tr>
<tr>
<td>233</td>
<td>130</td>
<td>11.9       85.6       0          26.2       0</td>
</tr>
<tr>
<td>234</td>
<td>130</td>
<td>38.1       97.6       0          88.1       2.4</td>
</tr>
<tr>
<td>235</td>
<td>129</td>
<td>83.3       97.6       16.6       97.6       76.1</td>
</tr>
<tr>
<td>236</td>
<td>130</td>
<td>100.0      100.0      11.9       100.0      75.1</td>
</tr>
<tr>
<td>238</td>
<td>125</td>
<td>47.5       95.0       0          81.0       21.4</td>
</tr>
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<td>125</td>
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</tr>
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Average:

78  71.23  90.89  10.97  80.28  37.08
Table 6: Average Safety Factor for Individual Vehicles

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<th>B₁</th>
<th>B₂</th>
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Table 6 (Continued)

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