INVESTIGATION OF TRAFFIC DYNAMICS BY AERIAL
PHOTOGRAMMETRY TECHNIQUES

by the
Research Staff
Transportation Research Center
Department of Civil Engineering

INTERIM REPORT
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ABSTRACT

This report documents the progress made during the first year of a three year research program aimed at improving and simplifying an aerial photogrammetry technique for practical applications in traffic operations and accident prevention. A new data reduction system for removing data from photographs and transferring it to punched card output is described. Preliminary findings of a pilot study of urban freeway operations are given. Two specific studies of traffic dynamics relating to the characteristics of the traffic stream in the vicinity of a traffic bottleneck and the potential of traffic energy as a parameter of traffic flow are discussed.
PREFACE

This report summarizes the work performed on Research Project EES 278, "Investigation of Traffic Dynamics by Aerial Photogrammetry Techniques", since June, 1969. This research project is sponsored by the Ohio Department of Highways in cooperation with the U. S. Bureau of Public Roads. The work was conducted by the Research Staff of the Transportation Engineer Center under the direction of Dr. Joseph Treimerer, Professor of Civil Engineering. Principal contributors to this report include:

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Recognition is also given to Mrs. Helen Payne and Joe Erion for their efforts in the preparation of the report.

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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CHAPTER ONE

INTRODUCTION

Background

In order to meaningfully study the dynamics of traffic flow along a roadway, a large amount of information concerning the movement of that traffic must be collected. In recent years a technique for collecting such data through the utilization of aerial survey methods has been developed at the Transportation Research Center. Application of this technique provides continuous data for measuring such attributes of the traffic stream as traffic density, acceleration and deceleration, velocity, weaving movements, headways and spacings. The influence of various design features on traffic flow may also be determined and the efficiency of operational control measured through detailed data analysis and evaluation.

The aerial survey technique is thought to represent a valuable tool for both the researcher concerned with the dynamics of traffic flow and the practitioner faced with the responsibility of designing and operating the highway system. Many problems associated with aerial traffic studies, however, have yet to be solved. The research program described in this report was designed to treat these problems and to then apply the improved technique to the solution of practical problems in the highway transportation field. The results presented represent the progress made in the first year of a three year program.
Objectives of the Research

The objectives of the research program are fourfold:

1. To explore practical applications of the aerial photogrammetry technique and to conduct pilot studies in cooperation with the Ohio Department of Highways.

2. To apply the results of the research program to improve traffic flow and increase safety.

3. To conduct further studies of traffic dynamics utilizing aerial photography with emphasis on research in the theory of traffic flow.

4. To develop better methods for the reduction and analysis of aerial photography data.

Scope of Research Undertaken During Fiscal Year 1970

Primary emphasis during the first year of the research program was placed on Objectives 1 and 4. During recent years the data reduction process has been a major bottleneck in the overall research effort. Since the availability of accurate data is a prerequisite to the achievement of the first three objectives of the research program, the development of an efficient and reliable data reduction system (Objective 4) was considered to be of the highest priority. At the same time, the exploration of ways in which the aerial survey technique can be applied to aid in the investigation of practical problems of highway design and operation (Objective 1) is of great interest to
the Ohio Department of Highways. Thus, immediate and concentrated effort in this area was also considered desirable.

Specific studies of the dynamics of traffic flow (Objective 3) were conducted as a secondary priority. The results from these studies are expected to provide a valuable theoretical foundation for the investigation of approaches for improving traffic flow and increasing safety on the highway network (Objective 2).

Summary of the Contents of this Report

The progress made during the first year of the research program is documented in Chapters Two through Five of this report. A brief description of the contents of each of these chapters is presented below.

Chapter Two is devoted to a description of a new data reduction system capable of extracting data from aerial photographs and converting it to a readily usable form for the computer (punched-card output). The system consists of three basic components: a Mann Type 829D Comparator, a Mann Type 1945 Data Logger and an IBM 026 Printing Card Punch. These components have been modified to fit the data reduction requirements of the subject research program. With the new system, all the necessary information including both control point coordinates and vehicle coordinates can be lifted from a typical aerial photograph and punched onto IBM cards in approximately 30 minutes. This represents about one-third of the time required using the old system of reading photo coordinates using a Nistri AP/C Analytical Plotter and punching the data onto cards manually. Data can now
be reduced at a rate equal to or greater than the rate at which it can be analyzed and evaluated. Hence, data reduction no longer represents a major bottleneck to the research effort.

Chapters Three and Four document the results of two studies conducted with the intent of increasing the understanding of the dynamics of traffic movement. Chapter Three summarized an investigation of the characteristics of the traffic stream in the vicinity of a traffic bottleneck. In this investigation the progress of several platoons of vehicles is followed as they travel through the bottleneck. Continuous records of traffic density, velocity, vehicular spacing and headways, and traffic energy are obtained for each platoon. These data are classified into three groups depending upon whether the platoons were approaching the bottleneck, within the bottleneck or leaving the bottleneck. Each group of data is then analyzed to investigate in detail the variations exhibited by the traffic parameters mentioned above. The results of the analysis are presented in graphical form.

The findings of this investigation may be summarized as follows:

1. The relationship between speed and density for each platoon may be divided into two distinct regions. The data for the "before-within" condition can be accurately represented by a three regime linear relationship with breakpoints defined at densities of 55 and 95 vehicles per mile. The "within-after" condition is best fit by a two regime linear relationship with a breakpoint at approximately 95 vehicles per mile.
2. When a platoon is released from the point of maximum density, the resulting values of speed, volume and kinetic energy are retarded as compared to the "before" condition at respective densities.

3. The existence of this retardation phenomenon is independent of the maximum density attained during compression.

4. Before a platoon can return to stable flow conditions, it has to be subjected to a region (density = 55-70 vpm, speed > 25 mph) where density remains fairly constant and speed, volume, and kinetic energy increase tremendously.

5. In the lower density regions, the drivers of the vehicles in a platoon have a relatively free choice of spacing or headway. As the density of the platoon increases to about 30 vehicles per mile, the drivers adopt a headway in the range of 1.8 to 2.2 seconds. The behavior of the drivers remains influenced by time headway until a density of 95 vehicles per mile is attained. While in the high density region (density > 95 vpm), driver behavior is controlled mainly by spacing.

6. Separations greater than those required by the absolute safety concept of car following are exhibited by platoons when they are near the state of maximum compression.

7. Before a platoon subjected to compressed flow can return to its original stable condition, it must pass through a region where the chance of danger of collision is much greater than that accepted during stable flow conditions.
Consideration of these results yields the following practical recommendation for efficient and safe highway operation. Traffic densities should not be allowed to rise above 55 vehicles per mile because once a platoon of vehicles leaves the stable flow condition defined by this density the status of the platoon will degenerate to retarded and unsafe levels before stable flow can be reattained. This recommendation serves as an input to Chapter Five which describes a practical problem solving study of highway operation.

Chapter Four is devoted to a detailed investigation of the potential of traffic energy as a measure of the characteristics of a traffic stream. The energy concept as applied to traffic is a relatively new approach in the search for parameters to describe the dynamics of road traffic flow. Drew introduced the concept by considering the traffic stream to be analogous to a compressible fluid flowing in a constant area duct. He suggested that traffic possesses a certain amount of total energy consisting of two types: energy of movement (kinetic energy) and a transitory energy (internal energy). He defined kinetic energy to be a function of the density of the traffic stream and the square of its average velocity and proposed that the parameter "acceleration noise" calculated as the standard deviation of an individual vehicle's acceleration distribution be used as a measure of internal energy. He further suggested that the principle of conservation of energy could be applied to the traffic stream and that, hence, the total energy possessed by the stream remains constant.
The investigation documented in Chapter Four is based on the premise that the internal energy of a traffic stream is related to the interaction among vehicles within the stream. Any parameter intended to measure internal energy, therefore, should have a zero value when no traffic is on the road (zero density) and should have a maximum value when a maximum number of vehicles are on the road (jam density). Evaluation of the existing energy concept from this premise reveals that the principle of conservation of energy does not hold for a traffic stream as long as kinetic energy is taken as a function of density. In addition, "acceleration noise" does not represent a good measure of internal energy because it does not fulfill the boundary condition that internal energy is a maximum at maximum density.

In order to overcome this latter shortcoming, a search was undertaken to find a parameter which does provide a suitable indication of internal energy. Two platoons of vehicles were studied and several alternative parameters were evaluated. Included among these parameters were:

a. Standard deviation of the acceleration distribution of a platoon.

b. Average of the absolute value of acceleration of the vehicles in a platoon.

c. Standard deviation of the platoon speed distribution.

d. Coefficient of variation of the platoon speed distribution.
Of these alternatives, only the coefficient of variation of the platoon speed
distribution fulfilled all the requirements postulated for the desired parameter
including the boundary conditions. It is recommended, therefore, for consid-
eration as a suitable indicator of internal energy. The energy concept
modified to include this new parameter is thought to represent a valuable
contribution to the understanding of the dynamics of traffic flow.

Chapter Five describes the progress made to date in a pilot study
aimed at applying the aerial survey technique to solve practical problems of
highway design and operation. This study is being conducted in cooperation
with the Bureau of Traffic of the Ohio Department of Highways and the City
of Columbus Traffic Engineering Division. Initial efforts have been devoted
to an investigation of the operational problems associated with urban freeways.
A section of Interstate 71 on the north side of Columbus, Ohio, extending from
the Fort Hayes Interchange north to the interchange with Interstate 270, has
been selected as the study site.

The study has been organized to proceed in five steps:

**Step 1.** Conduct several general survey flights along the study corridor
in an attempt to pinpoint the location of operational problem areas.

**Step 2.** Compare the location of the critical sections identified using
aerial photography with those identified by the Franklin County Regional Plan-
ing Commission.
In order to confirm the observations made from the aerial photography, a group of selected field studies were conducted on the freeway itself. Initial efforts have been concentrated on the morning peak period. A series of travel time studies and a density trap study have been completed. These studies tend to support the aerial photography studies and indicate the existence of a region of severe congestion between the East North Broadway overpass and the Hudson Street overpass.

A series of intensive aerial surveys of this section is presently being conducted. The results of these surveys will be analyzed in an attempt to determine what characteristics of this region combine to cause this extreme congestion. It is thought that the information gained through the studies of traffic dynamics described in Chapters Three and Four will be valuable inputs to this analysis.
CHAPTER TWO

DATA ACQUISITION BY AERIAL PHOTOGRAPHY

Introduction

In the last Interim Report (EES 278-2) a technique was described with which accurate traffic surveys can be conducted using aerial photogrammetric methods. The basic procedure consists of taking aerial photographs of the selected study area at fixed time intervals from a helicopter, reducing these data to provide accurate ground positions of vehicles within the study area at consecutive points in time and calculating the desired information. Such information as traffic volume, traffic density, space headways, velocities and accelerations may be obtained in this manner. In addition, the propagation of traffic disturbances (kinematic waves) may also be observed. This information allows the researcher or practitioner to obtain a complete record of the movement of vehicles as they progress along a roadway or through a system of roadways.

In previous phases of the research, the data collection portion of the aerial survey technique has been developed to function very well. The collection device is a KA-62A aerial reconnaissance camera manufactured by Chicago Aerial Industries, Inc. This camera is placed in a specially designed mount in the helicopter to allow accurate aiming of the camera and to attenuate the vibrations inherent in helicopter flight. Details regarding the characteristics of the camera and the design of the mount were reported in Interim Report EES 278-2. The data evaluation procedure for converting
the data once it is removed from the photographs to the desired traffic
information has likewise been developed to function reliably. This procedure
involves the use of a battery of computer programs which were specially
developed for the subject research project. Through utilization of these
programs accurate results may be obtained in a reasonable period of time
and at a moderate cost. For these reasons, no significant additional effort
has been devoted to either the data collection or the data evaluation procedure
during the current research program. The only alteration made has been to
convert the computer programs from the somewhat outdated SCATRAN com-
puter language to the more advanced FORTRAN IV G language. This change
has resulted in some saving of both computer time and money and has also
made these programs more readily adaptable for use by institutions and
agencies other than The Ohio State University.

The data reduction process required to extract data from aerial photo-
graphs and transfer it to a readily usable form for the computer, however,
has proved to be a major problem in the past. This process includes reading
the photo-coordinates of each vehicle and each control point on the photographs
using the Nistri AP/C Analytical Plotter of the Ohio Department of Highways.
The output from the AP/C is in the form of typed printout from the instru-
ment's electric typewriter. All photo-coordinates must then be transferred
manually to punch cards for further reduction of the photo-data to ground-
data by an electronic computer. Depending upon the number of vehicles
found on each photograph this entire process, photo-coordinate reading and
manual card punching, could be expected to take between 1-1/2 hours to 2 hours per photograph. Given that an average traffic data film may contain anywhere from 300 to 500 usable photographs, the magnitude of time required for the completion of the reduction process can easily be seen. In addition to the time requirements inherent to this process, further data reduction delays resulted because the AP/C is the property of the Ohio Department of Highways and thus could be used for the research program only when not in use by Highway Department personnel.

In an attempt to relieve the data reduction bottleneck, one of the primary goals of the research during the current year has been the development of an efficient, accurate and reliable data reduction system. Although the preferred system would be one which would allow data reduction to be performed automatically without requiring human operator control, preliminary studies have indicated that no reasonably priced automatic system has yet been developed. Since it was desired to have a system available for use as soon as possible, without suffering the time loss which would be required for a lengthy development program and because a system was desired which could be installed at a moderate cost, effort was concentrated on the development of a simple operator-controlled data reduction center.

**Basic Data Reduction System**

The data reduction system ultimately devised consists of three basic components. Each component is a standard production item available upon order from the appropriate manufacturer. The system includes:
1. Mann Type 829D Comparator
2. Mann Type 1945 Data Logger
3. IBM 026 Printing Card Punch

These three components are shown pictorially in Figure 2.1. A description of the function of each of the components is provided below.

Mann Type 829D Comparator

The Mann Type 829D Comparator is a precision screw instrument designed specifically for high precision measurements of distances on photographic film or plates giving direct reading of .001 mm. The photographic measurements are made in Cartesian coordinates by movement of a plate or film carrying stage beneath a viewing system along accurately machined ways. The Y coordinate stage ways are integral with the X coordinate stage, and will provide a Y coordinate stage motion at right angles to the X coordinate motion to within 10 seconds of arc. The comparator will accurately measure over a distance of 150 mm in the X coordinate and 100 mm in the Y coordinate.

The top element of the Y coordinate stage can be pivoted through ± 2 degrees to bring the fiducial marks on the photograph being measured parallel to the motion of the stage along the ways. Once aligned, the film is held in place by a top pressure platen secured by four spring fingers attached to the stage.

Film viewing is performed through a front surface projection type viewing system utilizing a 6 inch by 6 inch white viewing screen enclosed in a hood to allow usage in normal room light. A 10X projection lens system
Figure 2.1 Basic Data Reduction Equipment
mounted in a lens tube is located above the film stage and directs the photographic image to the screen through a right angle prism assembly. The projection system may be focused by simply sliding the lens tube vertically in its mount until proper focus is achieved. Illumination is provided by a high intensity light source located at the rear of the comparator unit which directs light up through the film stage from below through a second prism assembly. The light source is blower cooled and the condensing system has sufficient heat absorbing properties so that the ambient temperature rise at the photograph being measured is but a few degrees.

The recticle required for making coordinate measurements is an integral part of the viewing screen. The recticle can be made to appear either light or dark by varying the illumination at the rear of the screen in order to achieve the best contrast between the recticle and the film being viewed. Provision is made for rotating the projection screen through a small arc so that the recticle can be adjusted to "track" parallel to the ways of the film stage.

Readout of film coordinates is accomplished through readout dials located on both the X and Y coordinate screws. Each dial has 1000 divisions with each division equivalent to one micron of stage motion. Accumulated turns of the screws are obtained from a counter scale attached to the front of the instrument base adjacent to the readout dials. Each division of the counter scale represents 1.0 mm of stage motion. In addition, provision is made to attach an electronic readout device to the coordinate screws to
provide automatic readout and display of film coordinates.

Exclusive of the quality of the image being read and human error, the overall accuracy of the instrument is such that the actual stage position at any millimeter interval in its travel in the measuring direction shall not deviate from the position indicated by the readout dials by more than .001 mm or .001% of the travel, whichever is greater (the measuring direction of the instrument being with the stage traveling toward the readout dials).

Mann Type 1945 Data Logger

The Mann Type 1945 Data Logger is specially designed for use with Mann Company measuring comparators to provide digital display and tabulation of coordinate values and identifying data. The data logger system consists of two pulse generator type reading heads which are attached to the X and Y lead screws of the comparator, the data logger unit and cables for connection to the output devices.

The output data available from the data logger consists of six distinct entities or "words":

X coordinate: Sign, six digits, space.

Y coordinate: Sign, six digits, space.

Frame count: three digits, space.

"A" switch register: eight digits, maximum

"B" switch register: eight digits, maximum

Space: one digit.
A plug-in circuit board is provided so that the output data may be extracted in any desired order. This circuit board permits printing or punching of an output message consisting of as many as fifteen "words" which may originate in the data logger or in an auxiliary unit.

The displays for the X and Y coordinates, each consisting of six digits plus sign, correspond to the coordinate value in microns. The coordinate may be displayed in either signed or complement counting display modes. The positive counting sense for the coordinates with respect to stage motion may be chosen in either direction. The frame count is continuously displayed as a three digit number. The X, Y and Frame counters are provided with zero-reset switches as well as with individual pre-set pushbutton switches for each digit. The signs may be pre-set by means of two position momentary toggle switches.

Two banks of register switches allow the insertion of constants or identity data into the output format. These registers can be used for output information such as film numbers, lane numbers, flight numbers, control point numbers; etc. A space function is available in the register to separate the register digits into groups to facilitate interpretation.

Transfer of data from the data logger to the output device (IBM 026 Printing Card Punch) is accomplished with either a foot or hand actuated readout switch. Readout proceeds at a rate of ten characters per second. A set of buffer registers are included in the data logger to hold coordinate values until the readout cycle is completed so that the comparator stage
can be moved on as soon as the cycle is initiated. This feature greatly speeds the rate at which coordinate values can be taken from the film.

IBM 026 Printing Card Punch

The output element of the data reduction system is an IBM 026 Printing Card Punch. This machine is connected on line with the data logger and allows the photo-coordinate values, the switch register values and the frame count to be transferred directly to punched card output. In this manner the need for punching data onto cards manually, a requirement which represented a significant time delay in the Nistri AP/C data reduction system, has been completely eliminated.

The complete data reduction system as described above was installed in the laboratory of the Traffic Research Group. A calibration check was made and an average deviation of the measured values from the true value, including reading errors, of $\pm .002$ mm was found. As photography taken for the subject research project is normally taken from an altitude of about 3000 feet above ground, resulting in a photo to ground scale of approximately 1:12,000, this deviation amounts to only about $\pm 1$ inch on the ground. This accuracy is well within the limits necessary to meet the data reduction requirements of the subject research project.

System Modifications

Further system testing revealed that although light density photography could be easily reduced with the present equipment, some difficulty was
experienced in reducing medium and heavy density films. In order to correct this problem a series of slight system modifications were performed to allow the reduction of a broad range of different film densities with a high degree of accuracy and a minimum of strain upon the eyes of the operator. These modifications are documented below.

1. Light Intensity

The light intensity provided by the projection viewing system supplied with the comparator was found to be insufficient to illuminate any but the very light density films. Since many data films can be expected to fall in the medium to heavy density range, this proved to be a serious limitation. To correct this problem the existing 150w light source was replaced with a variety of different lamps ranging in wattage from 200w to 500w. A 300w lamp provided enough illumination for reduction of all but the very dense films and could be used without modification of the existing cooling system. A 500w lamp provided somewhat more illumination but would require additional forced air cooling if used continuously. To avoid the necessity of modifying the cooling system it was decided to use the 300w lamp.

2. Magnification

It was thought that the reading accuracy of the comparator could be increased by supplementing the supplied 10X lens system to provide a greater degree of magnification. For this reason a tube was constructed containing a 50 mm lens which could be slipped over the outside of the existing lens tube and adjusted up or down to achieve the proper focus. By
adjustment of the position of the additional lens the magnification of the system can be varied from 10 times to approximately 25 times magnification. A magnification of about 20 times proved to be the most useful. This magnification allows the operator to identify the exact position of control points and vehicles on the photograph with greater accuracy and with far less strain on his eyes without encountering the added problem of picking up film grain and film imperfections which can be seen at higher magnifications.

3. Projection Screen and Recticle

The cross-hair system etched into the projection screen supplied by the manufacturer proved to be too coarse to permit the reading of control point and vehicle coordinates with the degree of accuracy desired. Hence, a new recticle plate was constructed featuring a small illuminated dot which could be placed with a greater degree of accuracy than the cross-hairs. This new recticle, in combination with the increased magnification described above, allows the operator to pinpoint the coordinates of the control points and the front-center of the individual vehicles.

Performance of the System

The modified data reduction system was placed in service and subjected to operational testing. It was found that on the average approximately 16 photographs could be completely reduced and all data punched on IBM cards during an 8 hour work day. This works out to a data reduction rate of about 30 minutes per photograph which compares quite favorably to the 1-1/2 to 2 hours per photograph required using the Nistri AP/C to read the photo-
coordinates and punching the data onto cards manually. In addition, the entire data reduction system is available for use on a round-the-clock 24 hour per day basis. Thus, there are no hold-ups due to unavailability of equipment. Since the system is simple in design it is also expected that there will be limited downtime because of equipment malfunction.

This expectation has been proved out by six month of nearly continuous operation with no downtime except that required for routine lubrication of the comparator and replacement of the projection lamp. Although strain on the eyes of the operator remains rather severe, the system is easy to use and, therefore, new personnel can be trained and added to the data reduction team in a minimum of time and without sacrificing the desired level of accuracy in reading photo coordinates. In this manner, the system can be kept in continuous operation with each operator required to work only an hour or two at a time.

Utilizing the new data reduction system as modified, a typical aerial survey film containing 300 usable frames can be completely reduced with all pertinent data transferred to punched card output in about 150 hours. Although this is still a significant amount of time it has been reduced to the point that data can be lifted from the photographs at a rate equal to or greater than the rate at which it can be analyzed and evaluated. Hence, the data reduction process no longer represents a major bottleneck to the research program.
CHAPTER THREE

A STUDY OF THE CHARACTERISTICS OF FREEWAY CONGESTION

Introduction

A widespread urban freeway problem is that of the overcrowding or congestion which results from the peak traffic demands. Work traffic is customarily associated with peak demand so that for a short time each weekday morning and afternoon many urban freeway sections offer a poor level of service to the motorists.

In the general traffic stream equation, \( q = kv \), \( q \) is the flow (or volume) in vehicles per unit of time, \( v \) is the arithmetic mean speed of the vehicles in the traffic stream in distance per unit of time, and \( k \) is the concentration (or density) of vehicles in a length of roadway in vehicles per unit of length. If any two of these three traffic stream elements are known, the third is uniquely determined. There is however, no single dependent element but only a relationship between the elements.

Congestion is a qualitative term which is used in traffic engineering to indicate a condition of traffic and traffic movement. Density is the quantitative measure of congestion and, thus, should be a desirable element to use in freeway operation control. High volumes of traffic or high average speeds are not objectionable from an operational standpoint. Actually, high volumes and speeds are desirable in themselves, but it is known that sustained high volumes can lead to lower speeds and, hence, high densities or concentrations of vehicles on the roadway, which are undesirable.
Volumes and speeds have been measured for many years by a variety of means. However, heretofore, continuous densities have not been directly measurable.

The scope of this chapter is to investigate freeway congestion using aerial photography data which yields, among other parameters, continuous densities. This is done in an attempt to investigate in more detail the variations in traffic parameters in the vicinity of an observed bottleneck. The results are mostly in the form of graphs of the variables in terms of each other, and the resulting traces obtained are compared with previous studies.

**Definition of Terms**

**Bottleneck:** A section of roadway which exhibits highly congested and unstable conditions resulting in regions of low speed-high density flow that greatly reduce the volumes that can be transported. Such circumstances may be attributed to certain physical or control features of the system, however, experience suggests that a breakdown may also be caused by traffic conditions alone, such as states of high density. It is this latter case of "traffic bottleneck" which may be associated with the data used in this chapter.

**Concentration, k:** Often called density; the number of vehicles on a fixed length of roadway at a given time; expressed in terms of vehicles per mile, vpm.
Flow, q: Often called volume; the number of vehicles passing a fixed point within a given period of time; expressed in terms of vehicles per hour, vph.

Speed, v: The arithmetic mean speed of all the vehicles on a given length of roadway at a given time; expressed in terms of feet per second, fps. The speed may also be represented by the variable u which has the units of miles per hour, mph.

Spacing, s: The distance (front bumper to front bumper) between successive vehicles at any instant; expressed in feet.

Headway, h: The time spacing between successive vehicles at any instant obtained by dividing the velocity of the second vehicle into the spacing between the vehicles; expressed in seconds.

Separation, l: The distance (rear bumper to front bumper) between successive vehicles at any instant; expressed in feet.

Data Collection and Reduction

Data Acquisition by Aerial Photography

Traditional means of collecting traffic data have been from fixed positions on the road or to a lesser extent by the moving vehicle method, i.e., by observers traveling in a vehicle. None of these methods can provide continuous information on traffic movement with regard to the changing conditions of speed, volume, density, acceleration, headways in space and time, and the propagation of disturbances. The aerial survey
technique developed at the Transporation Engineering Center at The Ohio State University provides the above information by following a platoon of vehicles in a helicopter and recording the progress of each vehicle in the platoon at consecutive time intervals.

Reduction of data is performed by determining the photo coordinates of each vehicle in each photograph together with the photo coordinates of identifiable fixed points on the ground for orientation. The photographic data is then transferred to punch cards for further reduction of the photo-data to ground-data by the computer. Using these data, computer-plotted time-distance diagrams for each lane of traffic can be obtained.

Development of Data

The data may be developed and processed in five distinct steps.

Step 1: The hollerith card deck produced by the photo reduction procedure is processed on the IBM 7094 computer. The SCATRAN program used changes the photo coordinates of each vehicle to ground coordinates and then further reduces these data by computing the accumulative distance, spacing, headway, and velocity of each vehicle. This program has as its output a hollerith card deck which contains on each card the lane number, vehicle number, film and section number, and photograph number, along with the computed values listed above.
Step 2: By observing the vehicle trajectories for the data, various platoons of vehicles may be selected for further analysis. The hollerith cards corresponding to the desired platoons are then extracted from the total deck produced in step 1. The resulting platoon data deck are duplicated thereby allowing the original cards to be replaced so that other platoons may be formed.

Step 3. The platoon data deck established in step 2 is processed on the IBM 7094 computer using a SCATRAN program. A short example follows to indicate the general procedures used in this program. The following data is available as output from the step 1 program.

Photo 61 - Lane 1

<table>
<thead>
<tr>
<th>i</th>
<th>Vehicle</th>
<th>Distance d, ft</th>
<th>Spacing s, ft</th>
<th>Headway h, sec</th>
<th>Velocity v, fps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>175</td>
<td>1072.09</td>
<td>376.98</td>
<td>4.63</td>
<td>81.47</td>
</tr>
<tr>
<td>2</td>
<td>176</td>
<td>1449.07</td>
<td>384.45</td>
<td>4.05</td>
<td>95.01</td>
</tr>
<tr>
<td>3</td>
<td>177</td>
<td>1883.52</td>
<td>205.00</td>
<td>2.06</td>
<td>99.33</td>
</tr>
<tr>
<td>4</td>
<td>178</td>
<td>2083.52</td>
<td>146.58</td>
<td>1.43</td>
<td>102.21</td>
</tr>
<tr>
<td>5</td>
<td>179</td>
<td>2185.10</td>
<td>292.32</td>
<td>2.88</td>
<td>101.65</td>
</tr>
<tr>
<td>6</td>
<td>180</td>
<td>2477.42</td>
<td>510.98</td>
<td>4.57</td>
<td>111.88</td>
</tr>
</tbody>
</table>

Direction of Travel

![Diagram of vehicle positions and spacings]
Using this data, the following information can be calculated.

\[ X = d_6 - d_1 = 2477.42 - 1072.09 = 1405.33' \]

\[ n = 5 \text{ vehicles} \]

\[ \Sigma s_i = 1405.33 \text{ ft.} \]

\[ \Sigma v_i = 479.67 \text{ fps} \]

\[ v = \frac{\Sigma v_i}{n} = \frac{479.67}{5} = 95.93 \text{ fps} \]

\[ s = \frac{\Sigma s_i}{n} = \frac{1405.33}{5} = 281.07 \text{ ft.} \]

\[ k = \frac{n}{X} = \frac{5}{1405.33} = 0.00356 \text{ veh./ft.} = 18.79 \text{ vpm} \]

\[ q = kv = 0.00356 (95.93) = 0.341 \text{ veh./sec.} = 1227.6 \text{ vph} \]

It should be noted that the platoon data deck contained six vehicles for the given photograph, however, the platoon size is actually five vehicles.

The step 3 program has as its output a hollerith card deck containing one card for each photograph processed. Each card contains the following platoon data for each photograph processed: density, volume, average velocity, standard deviation of velocity, average spacing, standard deviation of spacing, average headway (\( \Sigma h_i/n \)), standard deviation of headway, average headway (s/v), and the number of vehicles in the platoon.

**Step 4:** The OMNITAB programming system was used exclusively in this step since OMNITAB has the facility of producing plots on the online printer. The version of the program used at The Ohio State University was adapted for use on the IBM 360/75 by the Statistical Laboratory of Iowa State University.

Using the data deck produced in step 3, the following plots are produced:
volume, average speed, standard deviation of speed, average spacing,
standard deviation of spacing, average headway, standard deviation of
headway, coefficient of variation of speeds, kinetic energy (q \cdot u) \quad \bullet \quad \bullet
each versus density; average speed versus volume; and average speed versus
kinetic energy. These graphs were obtained for three conditions of the
platoon, namely, upstream and within the disturbance, within and after the
disturbance, and, finally, the entire situation. The maximum observed
density was used as a breakpoint.

Step 5: During recent years, a number of hypotheses concerning the
interrelationship among basic characteristics of vehicular traffic flow, such
as volume, speed, and density, have been proposed. Some researchers have
relied almost completely on the statistical analysis of data for developing
functions, while others have begun with a purely theoretical concept, from
which relations were derived and later tested.

It was the purpose of step 5 to provide for preliminary assessment of
the "before-within" and "within-after" conditions of each platoon keeping in
mind the currently available hypotheses. The approach selected was the
regression of speed against density and flow against density. Linear re-
gression analysis techniques were chosen since they are both simpler and
more highly developed than those of non-linear analysis. The "before-
within" and "within-after" conditions of each platoon were fitted with succes-
sive powers of density from zero to degree five with a multiple linear
regression being performed on these variables. Also, exponential and transposed exponential curves were fitted to the speed-density data using the same procedures.

Again, OMNITAB was used exclusively in this step since OMNITAB has been provided with a very good multiple linear regression sub-routine. Although the results of this step are not directly included in this chapter, the findings definitely provided a foundation for further analyses. The more valuable outcomes are integrated with the commentary of the following sections.

Platoons Selected for Investigation

The data for this analysis were extracted from the aerial traffic survey which was carried out on July 4, 1967. The survey yielded photographs of a specific group of vehicles which were southbound on Interstate Highway 71 during the morning peak hour (around 7:45 a.m.). The photographs were taken from a helicopter at time intervals of one second.

Many platoons of vehicles were chosen from the resulting trajectories of which eight were processed and analyzed. These platoons are shown in Figures 3.1 - 3.4. Although the reasons for choosing these platoons vary, each was selected for a specific purpose. The rationale may be summarized as follows: platoon 122 contained a group of vehicles which proceeded from low density, high speed conditions through a disturbance and into rather stable conditions; platoon 123 was a unique group which had no vehicles
Figure 3.1  Identification of Platoon 122 (Enclosed Area)
Figure 3.2  Identification of Platoon 123 (Enclosed Area)
Figure 3.3 Identification of Platoons 126 and 127 (Enclosed Areas)
Figure 3.4 Identification of Platoons 141, 142, 143 and 144 (Enclosed Areas)
entering or leaving the platoon; platoon 126 was subjected to a large range of density in a rather short period of time; platoon 127 included the maximum observed density; and Platoons 141-144 were selected since they were mutually exclusive groups of vehicles (derived by using the largest continuous spacings as dividers) which encompassed the majority of the vehicles observed.

The total results for each platoon are not included in this chapter, instead only the relevant and representative diagrams will be presented. Discussion will be limited to the patterns and results obtained from the analyses of Platoon 142, since it adequately represents the entire study. The remainder of the results for the other seven platoons have been included as an appendix to this report.

**Speed-Density Relationship**

**Presentation of Hypotheses**

Based on the observation that the average speed of a platoon of vehicles is a function of the density of that platoon, a number of different hypotheses to describe this relationship have been proposed. Six of these speed-density relationships were selected for examination. These hypotheses are illustrated in Figure 3.5.

**Test of Hypotheses**

The basis purpose of this portion of the research was to make decisions regarding the relative merits of the six speed-density hypotheses as applied to the study data. The objective was not to discredit or disprove any hypothesis,
Figure 3.5  Proposed Speed - Density Relationships
but to determine the hypothesis which best represented the study data such that further analyses could be unified and based upon the same foundation.

Since each of the given hypotheses can be transformed into linear functions, the techniques of linear regression analysis were quite applicable. These techniques are highly developed and can be found in most books on applied statistics, therefore, only the relevant and necessary equations will be presented here.

The linear, first-order regression model may be written as

\[ Y = \beta_0 + \beta_1 X + \epsilon \]

Since \( \beta_0 \) and \( \beta_1 \) cannot be determined exactly without examining all possible occurrences of \( Y \) and \( X \), observed data for the relationship in question may be used to give estimates \( b_0 \) and \( b_1 \) of \( \beta_0 \) and \( \beta_1 \); thus it can be written

\[ \hat{Y} = b_0 + b_1 X \]

where \( \hat{Y} \) denotes the predicted value of \( Y \) for a given \( X \), when \( b_0 \) and \( b_1 \) are determined.

The estimation procedure will be that of least squares. Suppose there are \( n \) sets of observations, then

\[ Y_i = \beta_0 + \beta_1 X_i + \epsilon_i \]

and the sum of the squares of deviations from the true line is

\[ S = \sum_{i=1}^{n} \epsilon_i^2 = \sum_{i=1}^{n} (Y_i - \beta_0 - \beta_1 X_i)^2 \]

The values of the estimates \( b_0 \) and \( b_1 \) will be chosen such that, when substituted for \( \beta_0 \) and \( \beta_1 \), the least possible value of \( S \) will be produced.
The final solution yields the following equations for the least squares estimates.

\[ b_1 = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sum (X_i - \bar{X})^2} \]

\[ b_0 = \bar{Y} - b_1 \bar{X} \]

Substituting this value for \( b_0 \) into the equation for \( \hat{Y} \) gives the estimated regression equation

\[ \hat{Y} = \bar{Y} + b_1 (X - \bar{X}) \]

where \( b_1 \) is as given above. Using this procedure, the regression curve (s) for each hypothesis was attained.

**Statistical Tests.** In order to test the significance of the estimates, the F test was applied. If the calculated F value exceeded the appropriate critical value, the null hypothesis, \( H_0: \beta_1 = 0 \), had to be rejected. All hypotheses were highly significant.

In a further attempt to determine the "goodness" of the prediction, the standard error of estimate and the sample correlation coefficient were calculated. The standard error of estimate, \( SE \), is an estimate of \( \sigma^2 \) and is usually estimated in terms of the vertical deviations of the sample points from the least-square line.

These standard statistics did not provide meaningful comparative information. Since the objective of this phase of the study was to determine the hypothesis which best represented the study data, other parameters and analysis criteria had to be established.
Comparative Parameter. Because the regression curves provide the best fit with respect to the sum of squares of deviations, it was felt that the various hypotheses could be compared by using the deviations or residuals as a basis. As a final result, the total sum of the squared residuals was selected as the value to be used to compare the hypotheses. This parameter is given by

\[ TB = \sum_{i=1}^{k} (y_i - \hat{y}_i)^2 \]

Breakpoint Analysis. Another stage of the analysis was the establishment of the breakpoints for the three discontinuous hypotheses. For the two hypotheses which required only one breakpoint, separate regression analyses were performed for each of the possible ways in which the observations could be broken into two groups, using a separation of 5 vpm between alternative breakpoints within the range of 40 vpm to 130 vpm. The optimal breakpoint was determined by selecting the condition with the least sum of the squares value.

The location of the optimal breakpoints for the third discontinuous hypothesis (three linear regimes) was accomplished in the same manner except that two breakpoints had to be established. Separate regression analyses were performed for each of the possible ways in which the observations could be broken into three groups. The breakpoints were varied in 5 vpm increments - - - the lower breakpoint in the range of 40-80 vpm and the upper breakpoint in the vicinity of 85-130 vpm.
Comparative Analysis and Results

The least value of the sum of the squares of the residuals constituted the criterion for selecting the optimal condition of each discontinuous hypothesis. Again, using the least value of TB as the decisive criterion, the hypothesis which best represented the sample data could also be selected. In all cases, the hypothesis of three linear regimes provided the "best fit" for the "before-within" condition of all eight platoons considered.

The two breakpoints of the three-regime hypothesis divide the study data into low, medium, and high regions of density. Therefore, the best two-regime situation was chosen to represent the "within-after" condition of each platoon since none of the platoons return to the low density region. The study data and the "best fit" speed-density curves for platoon 142 are shown in Figure 3.6.

Further analysis was undertaken in order to determine the three-regime relationship which best represented all eight platoons. The sum of the squares of the deviations was calculated for each possible combination of breakpoints for each platoon (excluding platoon 144 since region III did not exist). The total sums of squares matrix establishes the breakpoints at 55 and 95 vpm for the optimum overall situation.

To test the hypothesis that there is essentially no difference between the "best fit" equation and the "adapted" equation, the t statistic was applied.
Figure 3.6  "Best Fit" Speed-Density Curves for Platoon 142
The t statistic is given by
\[ t = \frac{\bar{X}_1 - \bar{X}_2}{\sigma \left( \frac{1}{N_1} + \frac{1}{N_2} \right)^{1/2}} \]

In this study, the t test was applied to the deviations or residuals such that \( X_1 \) was equal to the average residual value for the adapted case and \( X_2 \) was equal to the best fit mean residual value.

The t statistic allows the null hypothesis to be tested. On the basis of a two-tailed test at a 0.01 level of significance, the null hypothesis that there is essentially no difference between the equations would be rejected if \( t \) were outside the range \(-t_{0.995} \) to \( t_{0.995} \) for \( (N_1 + N_2 - 2) \) degrees of freedom.

All calculated values of \( t \) fall well within the corresponding critical range. Therefore, the breakpoints of 55 and 95 vpm for the three-regime linear hypothesis determined from considering all the data are acceptable for the study data of each platoon taken individually. It is this condition which will provide the foundation for the analyses which will be presented in the future sections.

Variations in Flow, Density and Speed

In these analyses the three linear regime speed-density hypothesis with breakpoints at 55 and 95 vpm will be employed exclusively. With respect to the three resulting regions of density, the following terminology will be used:
Density, \( k, \text{ vpm} \)

The stable flow region may also be referred to as the low density zone while medium density corresponds to the disturbed flow section.

The general theoretical relationships between the traffic variables and parameters are shown in Figure 3.7. These relations will be explained in future sections.

**Speed, Volume, Density Relationships**

The graphs of speed versus density, volume versus density, and speed versus volume for platoon 142 are shown in Figure 3.8 - 3.10. In these sketches the solid line indicates the situation before and within the disturbance (up to maximum observed density) while the broken line represents the within-after disturbance condition.

**Speed-Density.** The regression curves of speed on density for platoon 142 are indicated in Figure 3.8. The platoon begins with a low density-high speed condition. As density increases, the space mean speed of the platoon decreases. This relationship holds true until the platoon reaches its point of maximum density within the congested area. At and beyond this
Relationship Between Fundamental Traffic Variables and Parameters

Figure 3.7
Figure 3.8 Speed-Density Relationship for Platoon 142
point it no longer applies, in fact, the opposite occurs. As the platoon is released from the maximum density condition and as the density decreases, the space mean speed increases. This pattern continues until a specific region of speed and density is encountered at which the platoon tends to act as a very solid unit. This region is defined by speeds above 25 mph and density in the 55-70 vpm range. It is interesting to note that the average speed of 25 mph was the explicit cut-off point for all the platoons. Observe, also, that as the platoon is released from the maximum density condition, the speeds are retarded.

The platoon remains in this 55-70 vpm density region for a relatively long period of time (over one minute for platoon 142). The density does not further decrease appreciably until the speeds reach 35-40 mph.

**Volume-Density.** The curvilinear relationships between flow and density are shown in Figure 3.9. These curves were derived from the corresponding regression curves of speed on density.

According to the Highway Capacity Manual, as the density increases from zero, speed decreases and the relationship between flow and density becomes curvilinear. As the point of critical density is passed there is a decrease in flow despite the continued increase in density. The curvilinear flow-density relationship appears common to both uninterrupted and interrupted flows.

As platoon 142 passes from free flow, through disturbed flow, and into compressed flow the volume-density curve follows the generally accepted
Figure 3.9 Derived Volume-Density Relationship for Platoon 142
pattern. However, as the platoon is released from the maximum density condition, the "after" curve does not follow the same path, in fact, the volume is considerably retarded when compared to the "before" condition at respective densities. This situation holds until the platoon encounters the speed-density region defined in the previous section. Since the speeds increase in this region while the density remains fairly constant, the volume must also increase. Platoon 142 reaches a volume of 2700 vph (as compared to 2000 vph for the "before" condition at the same density) before the density decreases enough to allow the platoon to return to the original stable flow state.

As can be seen, the roadway is carrying a much larger volume than would normally be expected in this density region. By allowing the average speeds to increase to the level that produces these volumes, the drivers have also permitted the average headway to reduce to 1.3 seconds. As will be pointed out later, this state of affairs more than doubles the probability of danger of collision.

**Speed-Volume.** The Highway Capacity Manual states the fundamental speed-flow relationship for a given population of drivers as follows: As traffic flow increases, the space mean speed of traffic decreases. This relationship holds true throughout the range of free flow and impending congestion, up to the point of critical density, or the density at maximum flow. At and beyond this point, however, it no longer applies; both the rate of flow and the space mean speed then decrease with an increase in density.
Investigations conducted on an extensive scale have shown that a straight line reasonably represents the speed-flow relationship in the range below critical density, for uninterrupted flow conditions on all ordinary multilane highways without access control, as well as on most four-lane freeways.

Previous studies of the speed-volume relationship have been limited generally to the uninterrupted flow condition. The main reason for this is that the speed-flow relationship is difficult to isolate under interrupted flow conditions. However, with the use of aerial photography, the condition of interrupted flow has been observed and the results are illustrated in Figure 3.10.

This figure reflects the commentary of the previous two sections, namely, that both speed and volume are retarded when a platoon of vehicles passes through a bottleneck. Before the platoon can return to free flow conditions, it must be subjected to a region of density (55–70 vpm) where the speeds, and therefore volumes, are increased to a relatively unsafe level. This fact very sharply illustrates the need to keep platoons of vehicles within the stable flow state thereby not allowing the degenerate case to occur.

Variations in Speed

Standard deviation is a measure of absolute variation, that is, a measure of the actual amount of variation present in a set of data. The variance (square of standard deviation) of n observations \( u_1, u_2, \ldots, u_n \)
Figure 3.10  Derived Speed-Volume Relationship for Platoon 142
measures essentially the average of their squared deviations from the
mean $\bar{u}$. Figure 3.11 contains the graph of standard deviation of speed
versus density for platoon 142.

In the lower density regions, the speed distribution appears to be
independent of density. As density increases, a maximum value of $\sigma_u$ is
rapidly attained then, as density increases further, the dispersion of speeds
decreases to a region where the platoon acts as a unit and each vehicle in
the platoon moves at approximately the same speed. As density continues
to increase and as the status of the platoon becomes unstable, the dispersion
of speeds increases instead of decreasing. Eventually, $\sigma_u$ drops again
because the individual drivers do not have a free choice of speed or room
to maneuver due to the high density. Since the platoon does not completely
stop, $\sigma_u$ does not go to zero, instead, the standard deviation of speed
steadily increases as the platoon is released from the point of maximum
density. This pattern continues until the density eventually reduces to a
region where the platoon again acts as a unit and each vehicle in the platoon
moves at approximately the same speed.

In order to compare the variation in several sets of data, it is
generally desirable to use measures of relative variation; for this purpose
the coefficient of variation is used, where $CV_u = (\sigma_u / \bar{u}) \cdot 100$. Note that
this measure, which gives the standard deviation as a percentage of the mean,
is independent of the scale of measurement. Figure 3.11 also indicates the
Figure 3.11 Variations in Speed of Platoon 142
relationship between the coefficient of variation of speeds and density for
the example platoon.

It should be noted from the handfitted curves that in the lower density
regions the pattern is essentially the same as that exhibited by the standard
deviation of speed, however, in the higher density regions, the patterns
are not similar. As density increases and as the platoon approaches max-
imum density the coefficient of variation of speeds increases. When the
platoon is released from the maximum compressed state, $CV_u$ decreases
as density decreases until the platoon encounters the same region of density
as explained above.

Application of the Energy Concept

In his energy-momentum approach to level of service, Drew relates
that a single stream of traffic offers a striking analog to the flow of a com-
pressible gas in a constant-area duct. Both consist of discrete particles:
individual molecules in the case of a fluid and individual vehicles in the
case of the traffic stream.

The kinetic energy of a traffic stream is defined as $aku^2$, where $a$
is a dimensionless constant. This corresponds to $\rho v^2/2$ which is the
kinetic energy in a hydrodynamic system. Kinetic energy $aku^2$ is the
energy of motion of the traffic stream. If in fact there is an internal energy
associated with a traffic stream, it should manifest itself as either lost or
crratic motion because of adverse geometrics and traffic interaction.
The conservation of energy for the traffic stream over a section of road \( x \) is simply a case of the total energy (kinetic energy plus the internal energy of the traffic stream) being equal to a constant. It may appear that a traffic stream can encounter a loss of energy due to the effects of friction in the system, however, energy is not really lost; it is simply converted from one of the mechanical forms (kinetic energy) to internal energy, a thermal form of energy. Referring to the second law of thermodynamics, mechanical forms of energy, such as kinetic energy, are more valuable than an equivalent amount of thermal energy or internal energy. This is certainly true in the case of traffic flow. Thus, one can say that the forces of friction (traffic interaction) tend to convert the desirable forms of energy (traffic motion) into less valuable forms (traffic interaction).

The platoons considered in this study tend to validate the above theory. The graphs of kinetic energy versus density and speed versus kinetic energy are given in Figure 3.12 for platoon 142. The kinetic energy of the platoon is taken to be equal to \( k \cdot u^2 \) or \( q \cdot u \) (thereby making \( \alpha = 1 \)). As density increases from zero, kinetic energy increases, reaches a maximum, and then decreases until the point of maximum density is encountered. As the platoon is released from this point and as density decreases, the kinetic energy increases again. The kinetic energy of the platoon after maximum density is less than that observed before compression at respective densities. The platoon eventually reaches that region where density remains fairly constant while speed and volume increase. In this
Figure 3.12  Energy versus Density and Speed versus Energy for Platoon 142
region, therefore, kinetic energy increases tremendously. Then, when
density finally decreases, the kinetic energy remains unaltered until the
original stable flow condition is re-established.

The affiliation between speed and kinetic energy combines the speed-
density and kinetic energy–density associations. As a platoon approaches
a bottleneck and as the density of the platoon increases, both speed and
kinetic energy decrease. These decreases take place rapidly at first
then as the platoon approaches the point of maximum density, this change
tapers off. When the platoon is released from the jam the reverse takes
place and as density decreases, both speed and kinetic energy increase —
gradually at first then at a more rapid rate.

Spacing and Headway Considerations

Spacing versus Density

Spacing is equal to the reciprocal of density. This association is given
by \( k = n / \Sigma s_i \). It follows that \( \Sigma s_i / n = 1/k \) or \( s = 1/k \). A representative
curve of spacing versus density for a platoon is given in Figure 3.13.
Although the curve of average spacing versus density is quite smooth,
distinct variations in spacing are taking place as the platoon is subjected
to changes in density. These patterns in variance will be shown in Figure
3.14 in conjunction with time headways.

It should be remembered that the spacing of a vehicle is defined as the
distance from the front of the given vehicle to the front of the vehicle pre-
ceeding it. Since no buses, cars with trailers, or semi-trucks were included
Figure 3.13  Representative Curve of Spacing versus Density
Figure 3.14 Variations of Spacing and Time Headway versus Density for Platoon 142
in any of the platoons investigated, the distance (separation) between two vehicles may be taken as the corresponding spacing minimum 17.5 feet (the generally accepted average car length).

Time Headway versus Density

The average headway of a platoon at a specific instant of time may be calculated by taking the average spacing and dividing by the average velocity or be dividing the volume (veh/hr) into 3600 (sec/hr). Figure 3.14 contains the graph of time headway versus density for platoon 142.

In the lower density regions, the drivers of the vehicles have a relatively free choice of spacing or headway. As the density of the platoon increases to about 30 vpm, where the average spacing is 175 feet, the drivers adopt a headway in the range of 1.8 to 2.2 seconds. This time headway remains constant as the density increases further until a density of 95 vpm (s = 56 feet) is attained (note this corresponds to the upper breakpoint of the speed-density relationship). At this point, the driver's behavior seems to become influenced by the distance headway or spacing. As the density increases even further and as the average spacing decreases, the platoon acts as a unit and each vehicle in the platoon maintains approximately the same spacing -- as evidenced by the small values of the standard deviation of spacing in Figure 3.14. In the same density region, the headways increase quite rapidly and attain a maximum near the point of maximum density.
The platoon remains as a unit with little variation in spacing within the group as it is released and the density decreases. Driver behavior remains influenced by spacing until time headways reduce to less than 2.2 seconds. At this time, headway once again becomes the governing factor. It was at this point (k ≈ 70 vpm) that platoon 142 reached a state of increasing speed and constant spacing and remained in this condition for over a minute. During this time, the drivers allowed the average time headway to reduce to 1.3 seconds.

Perhaps a question of safety might be raised here regarding the danger posed by a headway of 1.3 seconds. An attempt to answer this question will be presented in the next section. However, it can be deduced that driver behavior in a platoon of vehicles of medium density is controlled primarily by time headways while driver behavior in a platoon approaching the maximum compressed state is influenced mainly by spacing.

Recommended Safe Separations

In order to investigate the separation patterns exhibited by the platoons, three concepts were employed, namely,

1. the concept of absolute safety,
2. the concept of marginal safety, and
3. the concept of following distances and danger.

Explanation of these concepts follows.

**Absolute Safety Concept.** 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). 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 separation 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 traveled during the reaction time of the driver and the braking distance:

\[ S_A = 1.47UT + \frac{U^2}{30f} \]

where, \( U = \) speed, mph

\( T = \) reaction time of the driver, seconds

\( f = \) coefficient of friction or 1/100 (percent of braking)

**Marginal Safety Concept.** This 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 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 separation since the basic assumptions imply that both cars travel at about the same speed and are subject to the
same deceleration pattern. This separation is determined by the distance
taveled during the reaction time of the driver. Thus,

\[ S_B = 1.47 \text{ UT} \]

using the same variables as presented earlier.

Both concepts result in minimum safe separation ranges with dif-
ferent degrees of safety. Figure 3.15 indicates the envelopes based on
deceleration rates computed from stopping distance tests (insert) and
a reaction time ranging from 0.7 to 2.0 seconds. As discussed before,
both sets display the variability of basically safe separation parameters.

Following Distances and Danger. If all the drivers of a platoon allow a
given separation, \( s \), and all have the same reaction time, \( T \), then it is
possible to compute the probability of danger of collision when the sepa-
ration is insufficient for complete safety. It is necessary to say probability
of danger of collision, not probability of collision, because in many cases
the collision may be avoided by steering instead of by simply using the
brakes.

If the braking efficiencies of vehicles are distributed at random the
probability of danger of collision, when a vehicle brakes to its maximum,
depends on the value of the quantity \( 2(1-VT)/V^2 \), which is denoted by \( \phi \)
The probability is given as a function of \( \phi \) in Figure 3.16 for cars follow-
ing cars.

Figure 3.16 may be used in various ways. To find, for example,
the separation that would give a chance of 0.05 for danger of collision,
Figure 3.15  Safe and Marginally Safe Separation Envelopes  
(Dry Pavement)
\[ V = \text{velocity, fps} \]
\[ T = \text{reaction time, seconds} \]
\[ I = \text{safe separation, feet} \]

\[ \phi = \frac{2}{V^2} (1 - VT) \]

Figure 3.16  Probability of Danger of Collisions as a Function of \(2 \ (1 - VT)/V^2\)
the appropriate value of $\phi$ may be obtained from the curve: for cars following cars it is about 0.04. Equating this to $2(1-VT)/V^2$ and taking various values of $T$ the separations given in Table 3.1 are obtained. If within a platoon these separations were adopted by the drivers with the corresponding reaction times there would be danger of collision in 5 out of every 100 times a car within the platoon braked to its greatest extent.

Safe Separations Applied to Speed and Density

The safe separation concepts may be related to density by applying the relationship

$$k = \frac{1}{s}$$

Therefore,

$$k_A = \frac{5280}{1.47UT + U^2 + L}$$

and

$$k_B = \frac{5280}{1.47UT + L}$$

where $k_A$ and $k_B$ represent the density for absolute and marginal safety, respectively. The density for the probability concept is given by

$$k_p = \frac{5280}{\phi \frac{V^2}{2} + VT + L}$$

In all equations, $L$ was taken to be equal to 17.5 feet.
Table 3.1  Separations Which Should be Observed by all Vehicles to Give an Overall 5% Chance of Danger of Collision When Vehicle Ahead Brakes to Maximum Extent.

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>T = 0.5</th>
<th>T = 1.0</th>
<th>T = 1.5</th>
<th>T = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12</td>
<td>19</td>
<td>26</td>
<td>34</td>
</tr>
<tr>
<td>20</td>
<td>33</td>
<td>47</td>
<td>62</td>
<td>77</td>
</tr>
<tr>
<td>30</td>
<td>61</td>
<td>83</td>
<td>105</td>
<td>127</td>
</tr>
<tr>
<td>40</td>
<td>98</td>
<td>128</td>
<td>157</td>
<td>187</td>
</tr>
<tr>
<td>50</td>
<td>144</td>
<td>181</td>
<td>218</td>
<td>255</td>
</tr>
<tr>
<td>60</td>
<td>199</td>
<td>243</td>
<td>288</td>
<td>332</td>
</tr>
<tr>
<td>70</td>
<td>263</td>
<td>315</td>
<td>366</td>
<td>418</td>
</tr>
<tr>
<td>80</td>
<td>335</td>
<td>394</td>
<td>453</td>
<td>512</td>
</tr>
</tbody>
</table>
Figure 3.17 shows the safe separation concepts as applied to the speed-density plots of platoon 142. It should be noted that a platoon exhibited safe separations if its speed-density value at that instant was below and to the left of the selected curve. It can be seen that platoon 142 always exhibits average separations which are much greater than the minimum required for the marginally safe condition, however, the platoon does not enter the absolute safety envelope unless the speeds are less than 25 or 30 mph. When the group of vehicles is near the state of maximum compression, the separations are always greater than that which is required by the worst condition (T = 2.0) of the absolute safety criterion.

In order to compare the observed data with the probability concept, the shortest realistic average reaction time of 0.5 seconds was selected. The resulting required separations for probabilities of 0.05, 0.10, and 0.15 are also plotted in Figure 3.17. The chance of danger of collision reduces to less than 5 percent when the density increases to 55 vpm as the platoon approaches the maximum compressed state. The probability remains less than 0.05 as the platoon compresses and then expands again until the density decreases to 55-70 vpm. In this region the density remains fairly constant while the speeds increase and the time headways decrease. As indicated previously, these average headways actually reduced to 1.3 seconds. When the platoon is in this condition, the chance of danger of collision increases to the 15% level, which is 2 or 3 times
greater than the pre-jam condition. Eventually, the density decreases enough and the platoon returns to the original situation.

**Discussion and Conclusions**

Attempts have been made in this chapter to correlate and evaluate the basic parameters of traffic flow when applied to freeway congestion. Although all the platoons of vehicles investigated were extracted from one set of vehicle trajectories, it is felt that some valid patterns were established. The results may be summarized as follows:

1) Six proposed speed-density relationships were selected for examination. The purpose was to select the hypothesis which best represented the study data such that a unifying foundation for further analysis could be established. Regression of speed against flow was applied. The least value of the total sum of the squared deviations was used as the criterion for selecting, first, the best representative hypothesis and, second, the corresponding breakpoints. In all cases, the hypothesis of three linear regimes provided the "best fit" for the "before-within" condition of all eight platoons considered. Breakpoints at 55 and 95 vpm provided the optimum overall situation.

2) As a platoon progresses from stable flow, through disturbed flow, and into compressed flow, the relationships between the traffic flow parameters may be described by the generally accepted curves of Figure 3.7. The only alteration would be the existence of three distinct regions for each
graph due to the nature of the three-regime linear speed-density hypothesis (see Figure 3.18).

3) When a platoon is released from the point of maximum density or compression, the resulting values of speed, volume, and kinetic energy are retarded as compared to the "before" condition at respective densities. Thus, if the corresponding curves of speed, volume and kinetic energy versus density, are plotted together for both the "before" and "after" conditions, a loop may be identified in the plot similar to the hysteresis loop characteristic to certain phenomena in the field of physics.

4) The existence of the hysteresis phenomenon is independent of the maximum density attained during compression.

5) Before a platoon can return to stable flow conditions, it has to be subjected to a region \((k = 55-70 \text{ vpm, } u > 25 \text{ mph})\) where density remains fairly constant and speed, volume, and kinetic energy increase tremendously.

6) In the lower density regions, the drivers of the vehicles in a platoon have a relatively free choice of spacing or headway. As the density of the platoon increases to about 30 vpm, the drivers adopt a headway in the range of 1.8 to 2.2 seconds. The behavior of the drivers remains influenced by time headway until a density of 95 vpm is attained. While in the compressed flow region, driver behavior is controlled mainly by spacing.

7) Separations greater than those required for absolute safety are exhibited by platoons when they are near the state of maximum compression.
Figure 3.18
Derived Relationship Between Fundamental Traffic Variables and Parameters (Three Regime Linear)
8) Before a platoon can return to its original or desired condition, it must be subjected to a region where the chance of danger of collision is much greater than that accepted during stable flow conditions.

It is felt that the above phenomenon will be exhibited by all platoons of vehicles which are allowed to progress through the complete compression and expansion cycle.

Consideration of the above results yields the following conclusion and recommendation. If a platoon of vehicles leaves the stable flow condition, the status of the platoon will degenerate to retarded and unsafe levels before it can return to the desired stable condition. Therefore, it is suggested that densities not be allowed to rise above the 55 vpm level. This value may be classified as the critical or terminal density.
CHAPTER FOUR

A STUDY OF TRAFFIC ENERGY

Introduction

General Background

In the previous chapter the concept of traffic flow energy was briefly discussed. This concept is a relatively new approach in the search for parameters with which to describe the dynamics of road traffic flow. Although this approach seems to hold much promise for increasing our understanding of traffic flow, little research has been conducted to date in this area. This chapter is devoted, therefore, to an investigation of the potential of traffic energy as a measure of the characteristics of a traffic stream.

Drew introduced the energy concept into traffic flow analysis by considering the traffic stream to be analogous to the flow of a compressible fluid in a constant-area duct. He suggested that a kinetic energy term of the order $\alpha ku^2$ might be used to describe certain properties of a traffic stream since a similar term, $1/2 \rho v^2$, is defined in fluid mechanics as the kinetic energy of a compressible fluid. In the traffic case, $\alpha$ is a dimensionless constant, $\rho$ is the density of the traffic stream, and $u$ is the average speed of the stream. Then, by applying the well-known principle of conservation of energy, Drew further suggested that an internal energy term be added to the system to yield an expression for total traffic energy. The proposed relationship may be written as:
\[ T = E + I \]  

where: \( T \) = Total energy of a traffic stream (constant)  
\( E \) = Kinetic energy of the traffic stream (\( a \, ku^2 \))  
\( I \) = Internal energy of the traffic stream  

Assuming a linear speed-density relationship, this energy system is shown graphically in Figure 4.1. 

In most cases, the kinetic energy of a traffic stream can be easily obtained by measuring the density and average velocity of the stream. The internal energy, however, is thought to be related to the interactions among vehicles in the stream and it is very difficult to define. Drew has proposed that the parameter "acceleration noise" be used as a measure of internal energy. His proposal was based on two observations. First, the acceleration noise obtained by finding the standard deviation of the acceleration distribution of one vehicle traveling along a stretch of roadway has the same dimensions as kinetic energy. Second, a plot of acceleration noise and \( a \, ku^2 \) versus density revealed that the acceleration noise values are generally low when the kinetic energy values are high, thus yielding a near constant value for total energy. 

Using acceleration noise as a measure of internal energy Equation 1 can be rewritten as:  
\[ T = a \, ku^2 + \sigma_t = \text{constant} \]  

where \( \sigma_t \) is the derived acceleration noise parameter.  

Although this expression represents a significant concept for studying
Figure 4.1 Energy System Proposed by Drew, Assuming a Linear Speed-Density Relationship
traffic characteristics, it appears to have certain shortcomings. These shortcomings are discussed in the following section.

Analysis of the Existing Hypothesis

If the expression \( aku^2 + \sigma_t = \text{constant} \) is applied at the boundary conditions of a traffic stream, certain discrepancies become apparent. Consider first the internal energy term \( \sigma_t \). According to Drew, \( \sigma_t \) is derived from \( \sigma - \sigma_n \) where \( \sigma \) is the measured acceleration noise of a vehicle and \( \sigma_n \) is defined as the natural acceleration noise displayed by the same vehicle subjected to no traffic interference.

For the boundary condition where the density is zero \( (k = 0) \), the acceleration noise value \( \sigma \) has to equal \( \sigma_n \) by definition. Therefore, \( \sigma_t = \sigma - \sigma_n \) would reduce to \( \sigma_n - \sigma_n \) or zero. Since there are no vehicles on the road at zero density, the kinetic energy at this point would also be equal to zero. Consequently, the total energy of the traffic stream when \( k = 0 \) would be \( T = E + I = 0 \). At the other end of the density domain, jam density \( (k = k_j) \), all vehicles on the roadway are stopped. Since there is no movement \( \sigma \) would necessarily be zero. Also, since the idea of a natural acceleration noise makes no sense for such extremely high density conditions, \( \sigma_n \) is undefined at \( k_j \). Thus, no meaningful value for total energy can be found for the jammed condition using the proposed definition of internal energy. If the principle of conservation of energy holds true for a traffic stream, \( \sigma_t \) does not seem to represent a good measure of internal energy.
Intuitively, the internal energy of a traffic stream should express the degree to which vehicle interactions exist in the stream. From this point of view, the internal energy should be equal to zero when there are no vehicles on the road and should reach its maximum value when the density is a maximum since the greatest amount of vehicle interaction can be expected to occur at this point. A parameter is required which fulfills these boundary conditions. If it is assumed that such a parameter, call it I, exists; then the condition for the conservation of energy would be written as:

\[ T = aku^2 + I = \text{constant} \quad (3) \]

where \( I = 0 \) at \( k = 0 \) and \( I = I_{\text{max}} \) at \( k = k_j \).

During the entire analysis to this point, it has been assumed that the principle of conservation of energy can be applied to a traffic stream. If Equation 3 is evaluated at the appropriate boundary conditions, however, the following results are obtained:

\[ k = 0 \rightarrow E = aku^2 = 0 \text{ and } I = 0 \]
\[ \therefore T = E + I = 0 \]

\[ k = k_j \rightarrow E = aku^2 = 0 \text{ since } u = 0 \text{ and } I = I_{\text{max}} \]
\[ \therefore T = E + I = I_{\text{max}}. \]

Since \( I_{\text{max}} \) must be greater than 0, the conservation of energy as expressed in Equation 3 does not hold.

From the analysis documented above, two general conclusions can be drawn.
1. Acceleration noise is not an adequate parameter for representing the internal energy of a traffic stream if the internal energy is defined in terms of vehicular interaction.

2. If the kinetic energy of the traffic stream is defined as $aku^2$ and the internal energy is defined in terms of vehicular interaction, which is zero at zero density and a maximum at jam density, the principle of conservation of energy does not apply.

From these conclusions, it is apparent that some modifications must be made in the energy concept if it is to be utilized in traffic flow analysis. The next section is devoted to this purpose.

Theoretical Investigations

The Energy System of a Traffic Stream

Consider a stream of $n$ vehicles. At time $t_0$, assume these vehicles are spread along a section of roadway at a low density $k_0$ and are moving at an average speed $u_0$. Due to a disturbance of some sort, the first vehicle slows down and the vehicles start packing up. At time $t_1$ the average speed has dropped to $u_1$ and the density has increased to $k_1$. If the cause of the disturbance continues to prevail, a complete stoppage of the platoon will eventually occur. At this time a bumper to bumper situation will exist and the density will have reached its maximum value of $k_j$. This sequence of occurrences is illustrated in Figure 4.2.
Figure 4.2  Representation of a traffic platoon at varying densities
The above conditions can be considered analogous to the system shown in Figure 4.3. In this system, a bulk of compressible fluid with mass \( m \) is moving through a frictionless pipe with unit cross-section. The initial conditions are that at time \( t_0 \) this bulk of fluid is moving at a velocity \( v_0 \) with density \( \rho_0 \), and has length \( l_0 \). This condition is shown schematically in Figure 4.3 (a). A varying resistant force is now introduced into the system. Due to the resistance, the movement of the fluid mass is retarded and the fluid slows, eventually coming to a stop. At the same time, due to the compressive action of the variable force, the density of the fluid increases reaching a maximum density \( \rho_j \) when the stoppage occurs.

Now suppose the fluid mass was completely stopped at time \( t_j \) and that the average resistant force from time \( t_0 \) to \( t_j \) was measured as \( F_j \). Also assume that the length of the mass at \( t_j \) was \( l_j \). The final condition is shown in Figure 4.3 (c). An intermediate condition at time \( t_i \) is shown in Figure 4.3 (b). In this condition, the mass is moving at a velocity \( v_i \), the density is \( \rho_i \), the length of the mass has been reduced from \( l_0 \) by an amount \( \Delta l_i \) to \( l_i \), and the average resistant force from time \( t_0 \) to \( t_i \) is represented as \( F_i \).

Consider the condition shown in Figure 4.3(a). There is no external force in the system and the total energy involved is simply equal to the kinetic energy of the moving mass, \( \frac{1}{2} mv_0^2 \). After the resistance is applied to the system, the speed of the mass is reduced and part of the kinetic energy is lost and is transferred to another form of energy. In this
Figure 4.3  Representation of a mass of compressible fluid at varying densities
confined system the only other form of energy possible is that stored in the fluid itself due to the work done by the compressive action of the resistant force. At time \( t_1 \) the kinetic energy of the fluid has been reduced to \( 1/2 m v_1^2 \). The work done to this time by the resistance is equal to the average compressive force \( P \) times the distance by which the fluid was compressed \( \Delta l_i \). The total energy at time \( t_1 \) is then:

\[
1/2 m v_1^2 + P \Delta l_i = T
\]  

(4)

When the fluid mass is stopped at time \( t_j \) there is no kinetic energy in the system. The stored energy at this time is equal to \( P \Delta l_j \) where \( \Delta l_j = l_0 - l_j \). Hence the total energy would be:

\[
P_j \Delta l_j = T
\]  

(5)

Since the system is confined and no other forces or energy are involved, the principle of conservation of energy states that the total energy of the fluid for all three points in time must be equal.

\[
1/2 m v_0^2 = 1/2 m v_1^2 + P_i \Delta l_i = P_j \Delta l_j
\]  

(6)

Now, taking the intermediate condition as a reference, the following general expression can be written

\[
1/2 m v_i^2 + P_i \Delta l_i = C \text{ (constant)}
\]  

(7)

Dividing both sides of Equation 7 by \( l_i \) Equation 8 is obtained.

\[
1/2 \frac{m}{l_i} v_i^2 + \frac{P_i \Delta l_i}{l_i} = C/l_i
\]  

(8)

Since \( l_i \) is a variable, it follows that \( C/l_i \) is also a variable and the total energy of the system written in the form of Equation 8 is not a constant.
Now $m/l_i$ is the density of the fluid mass at time $t_i$ ($\rho_i$) and the term $P_i \Delta l_i$ is simply the energy stored in a unit section ($l_i$). Thus another form of Equation 8 is:

$$1/2 \rho_i v_i^2 + l_i = C/l_i$$  \hspace{1cm} \text{(9)}$$

The conclusion extracted from this analysis is that if the kinetic energy of a compressible fluid is expressed as $1/2 \rho_i v_i^2$ and the internal energy is expressed as the energy stored in a unit section of the fluid, then the principle of conservation of energy does not hold. From the analogous point of view, if the kinetic energy of a traffic stream is expressed as $\alpha ku^2$ then the energy of the stream will not be conserved, no matter how the internal energy is defined. This conclusion agrees with the observation made in the previous section from examination of the traffic stream boundary conditions.

The Internal Energy of a Traffic Stream

Although it has been demonstrated in the preceding section that the principle of conservation of energy does not hold for a traffic stream when kinetic energy is defined as $\alpha ku^2$, it is thought nevertheless that the concepts of kinetic and internal traffic stream energy are valuable contributions to the understanding of the dynamics of traffic flow. In order to apply these concepts, however, a parameter must be found which accurately reflects internal energy. This parameter must satisfy the boundary conditions for internal energy which were discussed previously and should in general exhibit a pattern such that high points of internal energy are associated with low points of kinetic energy and vice versa.
Consider the compressible fluid discussed previously. The internal energy in general can be expressed as $P_i \Delta l_i$. Since $\Delta l_i = l_o - l_1$ and $m = \rho_o l_o = \rho_1 l_1$ then $\Delta l_i$ can be written as $m/\rho_o - m/\rho_1 = m(1/\rho_o - 1/\rho_1)$.

Thus, the internal energy term becomes $P_i \rho_i (1/\rho_o - 1/\rho_1)$. The traffic stream analog of this term would be $P_i k_i (1/k_o - 1/k_1)$ where $P_i$ is the average of an imaginary resistant force acting on the traffic stream from time $t_o$ to time $t_i$.

If this resistant force were constant (call it $P_c$), then the term $P_i k_i (1/k_o - 1/k_1)$ could be written as a linear function of $k_i$, that is, as $P_c (k_i/k_o - 1)$. A graphical presentation of this force is shown in Figure 4.4.

It can be seen that the greater the density $k_i$ becomes the greater the internal energy and when $k_i \to k_o \to 0$ the internal energy also approaches zero. This behavior satisfies the boundary conditions previously postulated for the internal energy of a traffic stream.

The relationship shown in Figure 4.4 was based on the assumption that the resistant force was constant. When a traffic stream is considered, however, this force is invisible and might be imagined to be a function of the internal friction inherent in traffic flow. From our general knowledge of traffic behavior, it seems more logical to assume a variable force in these circumstances than a constant force. In mechanics a force $F$ is related to the mass of an object $m$ and its acceleration $a$ by Newton's Second Law of Motion, $F = ma$. Since $m$ is a constant it can be written that the force is simply a function of acceleration: $F = f(a)$. 
Figure 4.4  Density versus $P_c \left( \frac{k_i}{k_o} - 1 \right)$
Suppose that the imaginary force which acts on a traffic stream is indeed a function of the acceleration distribution of the stream with mean value \( \ddot{u} \). It is generally accepted that the velocity of traffic flow is a function of traffic density: \( u = f'(k) \). If we differentiate this expression with respect to time the following relationship is obtained:

\[
\ddot{u} = f'(k) \frac{dk}{dt} \quad \text{where} \quad f'(k) = \frac{df}{dk} \quad (10)
\]

This implies that the imaginary resistant force \( P \) is a function of \( f'(k) \frac{dk}{dt} \). In this expression, \( f'(k) \) would be a known function if the relationship between speed and density were defined. The relationship between \( \frac{dk}{dt} \) and density, however, is not easily determined. For this reason, no exact expression for the variation of internal energy with density can be obtained.

The insights gained into the nature of internal energy variation as a result of the analysis of this section, however, provide a valuable guide in the search for a suitable internal energy parameter.

**Experimental Investigation**

Methodology

Based on the background information provided by the theory of the previous section, a search was undertaken for an acceptable indicator of internal energy. An empirical approach was used utilizing data on traffic movement collected by the aerial photogrammetry technique. Two groups of vehicles were chosen for study. They are designated as Group A and Group B. The identification of these two groups of vehicles is shown on the trajectories presented in Figures 4.5 and 4.6 respectively.
Figure 4.5  Identification of Group A Vehicles (shaded area)
Figure 4.6  Identification of Group B Vehicles (shaded area)
Variations of the Imaginary Resistant Force for the Studied Platoons

The imaginary resistant force discussed from a theoretical point of view earlier was determined to play an important role in shaping the variational pattern of internal energy. Thus, it is logical to begin the investigation of the selected platoons by determining the pattern exhibited by this force in each platoon.

In order to calculate the force, the platoons are treated as confined masses of compressible fluid. The arithmetic mean speed of a given platoon is taken as the speed of the fluid mass and the force is considered to be a function of the time rate of change of the average speed (acceleration). Figures 4.7 and 4.8 show the relationships between average acceleration and density for the Group A and Group B vehicles. Disregarding scale differences, the average imaginary force would have the same variational pattern with density as does the average acceleration.

Recalling that the expression for internal energy of the traffic stream is $P_1 \left( \frac{k_i}{k_o} - 1 \right)$ and that $\frac{k_i}{k_o} - 1$ is an increasing linear function of density, the variation of internal energy with density can now be specified. The internal energy will be a generally increasing function of density with a hump at that value of density where the average resistance is at a maximum as shown in Figures 4.7 and 4.8.

This pattern will hold true only if the analogy between traffic flow and compressible fluid flow is valid. Since this analogy is not strictly
Figure 4.7  Average Acceleration versus Density for Group A Vehicles
accurate throughout the density domain, the term $P_i \left( \frac{k_i}{k_o} - 1 \right)$ cannot be used as a direct measure of internal energy in itself. It does provide, however, a good approximation of the true internal energy pattern.

**Alternative Internal Energy Parameters**

With the theoretical pattern for the variation of internal energy with density determined for the selected platoons, it is now possible to investigate the applicability of several possible internal energy parameters. Four different parameters have been considered to date. These are:

1. Standard deviation of the acceleration distribution of a platoon ($\sigma_a$). This is in contrast to the acceleration noise value discussed earlier which considers only one vehicle.

2. Average of the absolute value of acceleration of the vehicles in a platoon ($|\bar{a}|$).

3. Standard deviation of the platoon speed distribution ($\sigma_s$).

4. Coefficient of variation of the platoon speed distribution defined as the standard deviation of speed divided by the arithmetic mean speed ($CV_s$).

The results of this investigation are discussed below.

**Standard deviation of acceleration.** The relationships between the standard deviation of acceleration and density for the two platoons are shown in Figures 4.9 and 4.10. No recognizable pattern similar to the one desired for internal energy can be identified. In addition, this
Figure 4.9  Standard Deviation of Acceleration versus Density for Group A Vehicles
Figure 4.10 Standard Deviation of Acceleration versus Density for Group B Vehicles
parameter does not satisfy the boundary condition which requires that it be a maximum at the maximum density.

**Average absolute acceleration.** Figure 4.11 presents a plot of the average absolute acceleration versus density for the Group A vehicles. The pattern attained is similar to that attained for the standard deviation of acceleration and is of no value as a representative of internal energy.

**Standard deviation of speed.** Investigation of the standard deviation of the platoon speed distributions yielded much more encouraging results than the acceleration-oriented studies. Figures 4.12 and 4.13 show the variation of the standard deviation of speed with density for the Group A and Group B vehicles. Obvious variational patterns are present in both cases. It is observed that in the low density regions the two groups of vehicles exhibit different σ_s patterns implying that the nature of the speed distribution is independent of density in this area. When density increases, however, it is seen that the two groups of vehicles present similar variational patterns in speed distribution. The dispersion of speed decreases as density increases until a region is reached where almost all the vehicles in the platoon are moving at about the same speed. As density continues to increase, the dispersion of speeds begins to increase as well. This phenomenon can be explained by the realization that traffic flow at high densities tends to be unstable and there can exist a large variance among the speeds of the individual vehicles in such a disturbed flow situation. With still further increase in density, the dispersion of speed once again drops
Figure 4.11  Average Absolute Acceleration versus Density for Group A Vehicles
Figure 4.12  Standard Deviation of Speed versus Density for Group A Vehicles
Figure 4.13
Standard Deviation of Speed versus Density for Group B Vehicles

Density, vpm

Standard Deviation of Speeds, mph
because the space available to each vehicle for maneuvering has become severely limited. Finally, when jam density is reached $\sigma_s$ falls to zero since all movement on the roadway has ceased.

This parameter seems to be a good choice as an indicator of internal energy as far as being representative of prevailing vehicle interactions. It presents a consistent and recognizable pattern with density and is simple to calculate. It does not, however, satisfy the boundary condition that internal energy is a maximum at jam density.

**Coefficient of variation of speed.** In order to correct the boundary condition shortcoming displayed by $\sigma_s$ described above, a modified parameter was formed by dividing the standard deviation of the speed distribution by the arithmetic mean speed at each density level. This parameter, $CV_u$, is referred to in statistical terms as the coefficient of variation of speed and provides a measure of the relative dispersion of the speed values as a percentage of the mean speed. A plot of $CV_u$ versus density is given in Figures 4.14 and 4.15 for Group A and Group B vehicles.

It is noted that this parameter displays almost the same pattern as $\sigma_s$ at the low and medium density levels but increases rapidly to a maximum at jam density. Thus, this parameter displays all the desirable attributes of $\sigma_s$ and satisfies the necessary boundary conditions as well. Comparing the patterns exhibited in Figures 4.14 and 4.15 with those derived earlier from a theoretical approach, the coefficient of variation appears to be an excellent choice for an internal energy parameter.
Conclusions

From the analyses relating to traffic energy presented in this chapter, the following general conclusions may be drawn:

1. If the kinetic energy of a traffic stream is defined as $akv^2$ and the internal energy is defined in terms of vehicular interactions, the principle of conservation of energy does not hold. In fact, it will not hold regardless of how internal energy is defined as long as kinetic energy is taken to be $akv^2$.

2. In spite of the inapplicability of the principle of conservation of energy, the concepts of the kinetic energy and internal energy of a traffic stream are thought to be important contributions to the understanding of traffic dynamics.

3. Acceleration noise does not represent a good indication of internal energy throughout the entire density domain.

4. If traffic flow is taken to be exactly analogous to compressible fluid flow, internal energy can be expressed as $P_i \left( \frac{k_i}{k_o} - 1 \right)$ for the $i$th traffic state. If the analogy is only approximately correct, as seems logical, the term $P_i \left( \frac{k_i}{k_o} - 1 \right)$ serves as an approximation of the true internal energy.

5. Of the four alternative internal energy parameters studied (standard deviation of acceleration, average absolute acceleration, standard deviation of speed, and coefficient of variation of speed), only the coefficient of variation of speed fulfilled all the requirements postulated for the desired parameter. It is, therefore, proposed as a suitable measure of the internal
energy of a traffic stream.

It is thought that the material contained in this chapter represents a further step towards the attainment of an understanding of the dynamics involved in traffic movement. Such an understanding is a necessary prerequisite to the establishment of a safe and efficient highway system and forms a basis for determining control strategies for that system. For this reason, the material contained in this and the preceding chapter serves as an input to the practical investigation of freeway operation documented in Chapter V.
CHAPTER FIVE

A PRACTICAL STUDY OF FREEWAY OPERATION

Introduction

Investigations by Professor Smeed of the London University College have shown that many cities in the United States are approaching the point where increasing traffic demands can no longer be satisfied by the presently employed means of traffic control. In an attempt to overcome this problem certain cities have begun extensive programs of new freeway construction and have undertaken the improvement of critical arterial routes to the CBD. The benefit which can be attained by the construction of new freeways, however, is limited by the overall capacity of the CBD street system. Once this capacity is reached no further traffic can be moved into or out of the CBD no matter what volumes can be handled by the freeway system. Under these conditions the operational characteristics of the on and off ramps providing transition between the freeways and the CBD distribution system play a large role in determining the amount of traffic that the entire traffic network can support.

Entrance and exit ramps can limit system capacity in two ways:

1. Ramp capacity is insufficient, thus reducing the benefit for the CBD which can be obtained from an urban freeway.

2. Ramp traffic interferes with traffic on the freeway with a resulting breakdown of freeway traffic flow.
It should be understood that in this context the ramp system comprises not only the ramp itself and the acceleration or deceleration lanes, but the whole corridor along the freeway where traffic conditions rely extensively on the efficiency of the freeway access system.

Many different solutions have been proposed for alleviating traffic flow problems on urban freeways. These solutions range from simple ramp metering techniques to completely automated highway systems. Before any of these solutions can be seriously considered, however, more knowledge of the operational aspects of the freeway–street network is necessary and new research tools must be developed to supply the required information. Aerial survey methods have demonstrated their tremendous possibilities for collecting accurate data on traffic systems for the determination of such traffic flow measures as traffic density, velocity, acceleration and deceleration, lane changes, spacing and headways. The influence of various design features on traffic flow and the efficiency of operational control can also be determined. It is thought that the aerial survey technique could prove a valuable tool in finding the solution to many of the problems plaguing our urban freeways. In order to test this hypothesis, a pilot study of freeway operation was undertaken in cooperation with the Ohio Department of Highways. The progress made on the study is described below.

**Description of the Pilot Study**

**Selection of the Study Site**

A meeting was held on July 29, 1969, with representatives of the
Ohio Department of Highways and the City of Columbus Traffic Engineering Department to discuss the specific problem areas that these organizations feel should be studied as part of the "practical applications" phase of the subject research project. At this time, both organizations expressed interest in a general study of the operational problems associated with urban freeways. A section of Interstate 71 extending from the Fort Hayes Interchange north to the interchange with Interstate 270 was mentioned as a suggested data collection corridor. This section of highway would seem to offer a good site for study for two reasons. First, it is heavily traveled and is often highly congested during peak periods. Second, it has recently been expanded from two to three lanes between East North Broadway and I-270, thus offering a unique opportunity to assess the value of the improvement through before and after aerial survey. The location of the selected study site is shown in Figure 5.1.

The following procedure was suggested for the "practical applications" study:

**Step 1.** Conduct several general survey flights along the study corridor in an attempt to pinpoint the location of operational problem areas.

**Step 2.** Compare the location of the critical sections identified using the aerial survey method with those identified in the Franklin County Regional Planning Commission Study.
Figure 5.1 Location of the Selected Study Site on Interstate 71
Step 3. Conduct a series of more intensive aerial surveys of the identified problem areas in an attempt to determine the following information:

i) Specific nature of the problem

ii) Parameters which can be used to describe the traffic situation at the problem location

iii) Causative factors leading to flow breakdowns and congestion at the problem location.

Step 4. Inform city and state of findings and supply available data for their analysis. Based on their analysis of aerial survey data the city may perform control changes or other improvements designed to alleviate identified problem areas.

Step 5. Conduct a series of "after" aerial surveys to determine the effectiveness of improvements on the operational efficiency of the study section and supply the city with available data for their analysis.

Preparation of the Study Site

Accurate ground control points are a necessity to the study of traffic dynamics by aerial survey methods. Two different types of control points have been used on the I-71 study section depending on the nature of the roadway median.

The southern section of the study area from the Fort Hayes Interchange to East North Broadway has a concrete median ranging in width from 4 feet
to about 6 feet. Along this section, it was decided that white plastic lane
marking tape placed in 12 inch wide strips at 1000 foot intervals completely
across the median would provide control points which could be easily estab-
lished and would provide the necessary accuracy.

The northern section of the study area from just north of East North
Broadway to Interstate 270 has a grass median and contains a sufficient
number of natural control points, such as median drains, guardrail ends
and sign posts, as to make the use of "artificial" type control points
unnecessary.

Survey and Data Collection Flights

A series of six general survey data collection flights were made
between October 22 and November 13, 1969. Two flights were flown during
the morning peak period (7:15 - 8:15 A.M.) and four during the evening peak
(4:45 - 5:45 P.M.) in an attempt to pinpoint the location of specific opera-
tional problem areas within the I-71 study corridor. The flights were flown
at an altitude of approximately 3000 feet above ground, allowing for a longi-
tudinal coverage per photograph of nearly one mile. Photography was taken
at a range of exposure intervals varying from a minimum of 0.2 seconds to
a maximum of 1 second.

In the course of each flight approximately three runs were made along
the study corridor and photography was taken beginning with the first sign
of restricted traffic flow and continuing until free flow was reestablished.
In general, the congested area for southbound traffic was found to extend from midway between Morse and Cooke Roads to just south of the southbound on-ramp at Hudson Street. The congested area for northbound traffic was found to extend from midway between Fifth and Eleventh Avenues to just north of the East North Broadway overpass. Especially high concentrations were observed near the on-ramps at East North Broadway, Weber Road and Hudson Street during the morning peak.

During each run approximately 85 feet of film (200 frames) was taken of the congested areas giving a total of 1500 feet of film (3600 frames) for the six flights. These films were developed and a preliminary analysis completed to determine which films offered the most promise for immediate data reduction on the basis of traffic volume recorded and overall film quality. The selected films were then prepared for reduction. These films are presently being reduced. In order to provide additional data, more data collection flights are to be flown in the near future.

The above flights form Step 1 in the procedure suggested for the "practical applications" study. In Step 2 of the procedure, an attempt has been made to identify those areas that are critical bottleneck sections of the freeway. Initial efforts have been concentrated on the morning peak period.

The observer in the helicopter reported areas of traffic congestion on Interstate 71, i.e., sections of the freeway exhibiting the greatest density of traffic. As explained previously, these areas were found to extend from approximately midway between Morse and Cooke Roads to just south of the
southbound on-ramp at Hudson Street. The location of this section can be found in Figure 5.1. Within the areas of traffic congestion, regions of stop and go driving characteristically associated with the passage of a kinematic wave through the traffic stream were observed. A kinematic wave is a knot of extremely high density flow which can occur in even relatively free flowing, light density traffic. The driver caught in a series of such waves would experience delay because he would have to slow down, possibly to a standstill, each time a wave passes through that section of the traffic stream in which he is traveling.

Figure 5.2 shows the trajectories of vehicles traveling in the southbound shoulder lane during the morning peak. Observation of these trajectories illustrates how small kinematic waves can form due to:

i) traffic entering the freeway at on-ramps, and

ii) individual vehicle behavior.

The kinematic wave, marked 1, was caused by Vehicle 515 entering the freeway via the Cooke Road interchange on-ramp, and the resulting slowing down of the vehicle on the freeway immediately behind the entering vehicle. The wave in this case was slight and was soon dissipated because there were no further disturbances to the traffic stream. The wave marked 2 was caused in a similar manner. Wave 3, however, was caused by the erratic behavior of Vehicle 478. This vehicle slowed down at the entrance to the Cooke Road interchange off-ramp. One can infer from this that having had some doubt as to whether he should leave the freeway at this point the
Figure 5.2 Typical Vehicle Trajectories
driver slows down and then, deciding not to leave the freeway, he speeds up again to the average speed of the freeway traffic, as shown by the trajectory. This hesitation on the driver’s part and the slight drop of speed was sufficient to cause a small breakdown of steady traffic flow, i.e., Kinematic Wave 3.

It is hypothesized that a number of such small disturbances, occurring in a relatively short section of freeway, will initiate a kinematic wave of such a large magnitude that the wave will be propagated back through the traffic stream to freeway sections far beyond the point of origin and result in a complete breakdown of traffic flow. These minor disturbances will naturally have less chance of dissipating when traffic density increases.

Intensive Survey Flights and Related Field Studies

As indicated previously the next step in the procedure for the "practical applications" study is to conduct a series of more intensive aerial surveys of the identified problem areas (Step 3). This step is presently in progress.

One of the difficulties encountered is that the helicopter used for the survey flights is unable to hover at a fixed altitude for extended periods of time. It is impossible, therefore, to take a continuous series of photographs at one location and hence record continuously the traffic movements during the peak flow. To overcome this difficulty a sweep-sampling study using aerial photography whereby a five second burst of photographs is taken at specific locations as the helicopter proceeds rapidly down the freeway corridor will be conducted. The helicopter will fly from north to south over the freeway
and after covering the critical section will return to the north of the section and repeat the procedure again. These flights over the critical region will be repeated regularly throughout the peak period. By taking a systematic sample of the critical section in this manner it is hoped to approximate the data which would be obtained by continuous filming.

Related Field Studies:

To further substantiate observations from the aerial photographs and general survey flights, it was decided that a number of measurements and observations should be conducted on the freeway proper. The studies included the following:

i) Travel time studies

ii) Density Patterns on the Freeway

iii) The Effect of Ramps on Freeway Density

i) Travel time studies. Those sections of freeway which exhibit slow vehicle velocities are possible problem areas, which could have an adverse effect on the operation of the entire freeway. In an attempt to help pinpoint these problem areas, a travel time study was conducted on the morning of Thursday, February 5, 1970, between the on-ramp of Morse Road Interchange and the off-ramp of 17th Avenue Interchange during the morning peak.

A team of three cars was used, each car having a driver and an observer. The driver was instructed to remain in the center lane and to travel at the approximate average speed of the traffic in that lane.
A test vehicle traveling in the middle lane should approximate the average travel time of the majority of vehicles on the freeway. Such a vehicle in the shoulder lane would experience too much interference from merging and diverging vehicles from entrance and exit ramps, and hence, would have a longer than average travel time. Similarly, the median lane travel times might be too short to be representative. However, irrespective of the different travel times in each lane, since all test vehicles traveled in the same lane, comparison of travel times is possible.

The observer recorded the times at which his vehicle passed certain points on the freeway (e.g., overpass bridges, overhead signs) and was instructed to indicate where any complete stoppages were and to give some reason for these stoppages, if this were possible. All the stopwatches used were synchronized before the runs were started. The first car was on the freeway at Morse Road by about 7:10 A.M. with the other two cars following at approximately 5 minute intervals. As soon as 17th Avenue was reached, the cars returned to Morse Road and repeated the procedure. The final run was started at approximately 7:58 A.M. and ended at 8:06 A.M., which resulted in a coverage of some 56 minutes of freeway operation during the morning peak. The positions at which travel time readings were recorded were well defined and corresponding distances were calculated from signing-plans of the freeway. Average velocities were then calculated and the values plotted. Another travel time study was conducted on Tuesday, March 24, 1970, the procedure followed being similar to that described above.
Results of the travel time studies. The February 5 study yielded the following results. As time progressed the travel times increased, then decreased, with the travel times ranging from 6 minutes, 53 seconds to a maximum of 16 minutes, 58 seconds. Figure 5.3 shows the velocity patterns exhibited during the nine runs and Figure 5.4 shows how the travel time varied. The maximum travel time occurred when the test vehicle entered the freeway stream at approximately 7:33 A.M. The lowest velocities occurred between East North Broadway and Hudson Street. Trip 7 was continued past 17th Avenue. It was noticed that traffic flow improved considerably beyond this point and velocity increased. It is clearly shown on Figure 5.3 that once Hudson Street is passed, traffic velocities tend to increase throughout the whole peak period.

The study conducted on March 24, 1970 showed generally lower travel times. However, when congestion did begin to occur, the lowest speeds were again found between East North Broadway and Hudson Street and the longest overall travel time was again at approximately 7:30 A.M.

Data has been obtained from the Division of Traffic Engineering, City of Columbus, concerning speed-delay runs that they have conducted. Upon comparing our data and their data it was found that the lowest speeds occurred in the same locations on the freeway in both cases.

The most congested area would appear to extend from just north of the East North Broadway overpass to the Weber Road overpass. The average velocity of the 9 runs indicates that the lowest velocity lies in this region.
Figure 5.3  Variation of Velocity with Distance during the Morning Peak Period
Figure 5.4 Variation of Travel Time during the Morning Peak Period
The spacing of the two interchanges in this section is the shortest of all interchanges between Morse Road Interchange and 17th Avenue Interchange. The weaving length is correspondingly short and it is logical to assume that weaving friction would influence the traffic, as would the merging of the traffic from the two on-ramps of East North Broadway and Weber Road.

The Regional Planning Commission of Franklin County in a preliminary report for project T-1002, has studied the Interstate 71 and used a volume-to-capacity approach to define the regions that they believe are critical from an operations point of view. It was found that ramps north of East North Broadway operate at, or better than, level of service "C". Entrance ramps south of and including the East North Broadway on-ramp operate at unstable and forced flow conditions until traffic entering from Hudson Street acts to cause freeway flow to exceed capacity. This is then said to initiate forced flow conditions upstream of the Hudson Street Interchange southbound off-ramp. The report also states that the southbound entrance ramps load the freeway until the section of roadway between East North Broadway and Hudson Street is under forced flow conditions. Traffic entering from Seventeenth Avenue causes upstream flow to break down, therefore southbound travel is stop-and-go between Eleventh Avenue and East North Broadway, with low operating speeds and significant congestion. The report states that an obvious recommendation for operational improvements would be to meter or control entering traffic onto the freeway.
ii) Density patterns on the freeway. Density is a parameter which is often used as a basis for the operational control of a freeway system. In order to get an idea of the variation of density on I-71 during the peak hour, four teams of observers took vehicular counts during the morning peak of Wednesday, February 18, 1970. The day was chosen so as to be fairly representative of the normal morning-peak, being in the middle of the week with dry pavements and normal light conditions.

Vehicles were counted every 10 seconds in the median lane. This lane was chosen as it was felt that there would be the least weaving of all the lanes in that lane. This is desirable since weaving maneuvers tend to decrease the accuracy of a density study of this type.

The teams were situated on Hudson Street, Weber Road and East North Broadway overpasses, and just off the shoulder of the freeway, approximately half-way between Cooke Road and East North Broadway, next to the "East North Broadway Right Lane" sign. The results of the trap between the sign and East North Broadway are recorded on Figure 5.5. The volume passing both these stations checked very closely in the hour of observations. Traffic entering the freeway at East North Broadway and Weber Road, and weaving into the median lane, however, resulted in more cars leaving the last density trap than appeared to be entering the trap. The trap between Weber Road and Hudson Street was therefore adjusted by removing the extra vehicles in a uniform manner. Thus, the results plotted on Figure 5.6 will not be the actual densities but should give a realistic density pattern.
Average density = 52.4 vpm
Average velocity = 28.6 mph

Average Density between "East North Broadway Right Lane" sign and East North Broadway Overpass

Figure 5.5 Density Variation with Time - East North Broadway Right Lane Sign to East North Broadway Overpass
Average Density Pattern Between Weber Road and Hudson Street Overpasses

Figure 5.6 Density Variation with Time - Weber Road Overpass to Hudson Street Overpass
The results of the density study. It would appear that a high density peak formed on the freeway in the south between Weber Road and Hudson Street at about 7:10 A.M. during the morning peak hour the day of the observations. It was not until approximately 7:20 A.M. that a similar density peak started forming north of East North Broadway Interchange.

This suggests that the peak density builds up initially in the southern end of our study area and then slowly progresses northwards as the vehicles that enter from the north meet the high density area and are forced to slow down and join the crawling traffic. As vehicles move south they pass through the density peak, increase their velocity, and move into a more free flowing, lower density type of flow.

The velocity-distance waves of Figure 5.3 substantiate this observation as the approximate minimum velocity of the individual curves moves northwards as one progresses through the peak hour. However, as the section of high density begins to decrease, the sections of minimum velocity once more move southwards to between East North Broadway and Weber Road interchanges.

iii) The effect of ramps on freeway density. It is logical to assume that merging traffic will affect the through traffic on a freeway. A film from one of our flights was used to see if this assumption was in fact true for I-71. The freeway was divided into sections of about 550 feet (i.e. approximately one-half inch on the film negatives) and the total traffic, on all three lanes of the freeway, was counted in each section. The values were
converted to "Total density for three lanes, vehicles per mile" and recorded on Figure 5.7. Even though only one flight was considered, it can be seen from the graph that the densities increase quite clearly in the vicinity of interchange on-ramps. These high density areas would be less able to absorb any disturbances, such as those illustrated in Figure 5.2, than if the traffic were flowing under open highway free flow conditions.

Preliminary Findings

It is emphasized that insufficient data has been collected and analyzed to allow definitive statements concerning the location of operational problem areas on the Interstate 71 study section and the causative factors associated with these problem areas to be made at this time. The investigations to date do point, however, to the section between the East North Broadway and Hudson Street interchanges as the critical region during the morning peak period. This observation agrees in general with the findings of the Franklin County Regional Planning Commission published in the Preliminary Report for Project T-1002 dated May, 1969. The Commission is of the opinion, however, that traffic entering from Seventeenth Avenue causes the flow breakdown which eventually propagates upstream to the section described above. At present, our investigations have not indicated this and it is felt that the main problem area is north of the Hudson Street on-ramp. Further studies to be carried out during the next year will hopefully qualify these differences.
Figure 5.7 Density versus Distance Along Freeway during Morning Peak

Feet (x1000)

Total Density for 3 Lanes Veh./mile
REFERENCES


Transportation Research Center of The Ohio State University, "Investigation of Traffic Dynamics by Aerial Photogrammetry Techniques," EES 278-2 Interim Report, June, 1969.

APPENDIX

Introduction

In Chapter Three of this report it was stated that data from eight different platoons were analyzed in the study of the characteristics of the traffic stream in the vicinity of a bottleneck. Results from the analysis of only one of these platoons was presented in that Chapter, however, as it was thought that the entire study was adequately represented by that platoon. The results for all of the platoons are included herein for the reader earnestly interested in the details of the study.

Presentation of Results

The results are presented in graphical form. Plots of speed versus density, speed versus volume, and volume versus density are provided for seven of the eight platoons. No plots are provided for platoon 144 since it was not subjected to the entire cycle of compression and expansion. In these figures the solid line indicates the situation before and within the disturbance (up to maximum observed density) while the broken line represents the within-after condition. No further commentary is provided with the plots as that in Chapter Three is considered sufficient to describe the patterns observed.

In addition, four contour maps are included illustrating the variational patterns of speed, density, volume and kinetic energy in time and space for
the entire set of vehicle trajectories. Just as conventional land contours connect points of equal elevation, speed contours, for example, connect points of equal speed. Observation of these contours allows the location and time duration of regions of disturbed and compressed flow to be determined.
Figure A.1 Observed Speed-Volume-Density Relationships
Figure A.1 Continued
Figure A.1 Continued
Figure A.1 Continued
Figure A.1 Continued
Figure A.1 Concluded
Figure A.2  Contour Map Showing Levels of Equal Average Speed, mph
Figure A.3  Contour Map Showing Levels of Equal Average Concentration, vpm
Figure A.4  Contour Map Showing Levels of Equal Average Flow Rate, vph
Figure A.5  Contour Map Showing Levels of Equal Average Kinetic Energy, veh-mi/hr²