NEMETH, Zoltan Anthony, 1931-
THE DEVELOPMENT OF A NEW INTERSECTION
STUDY TECHNIQUE.

The Ohio State University, Ph.D., 1968
Engineering, civil

University Microfilms, Inc., Ann Arbor, Michigan
THE DEVELOPMENT OF A NEW INTERSECTION

STUDY TECHNIQUE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Zoltan Anthony Nemeth, Dipl. Ing., M.Sc.

* * * * * * *

The Ohio State University
1968

Approved by

[Signature]
Adviser
Department of
Civil Engineering
PLEASE NOTE: Appendix pages are not original copy. Print is indistinct on many pages. Filmed in the best possible way.

UNIVERSITY MICROFILMS.
PREFACE

Personal mobility provided by the use of private automobiles is a prized element in the quality of living in America. The increasing rate of urbanization of the nation, however, tends to concentrate traffic demands and thus accelerate the problems of roadway transportation. Difficulties are compounded at intersections. To meet the increasing needs for capacity more efficient means must be found to operate the intersection. In recent years, much effort has been directed toward research in this field. Unfortunately, a gap exists between theoretical work and applicable solutions. This dissertation is aimed at narrowing this gap by proposing a tool that combines a new field study method with modern simulation techniques. The study was undertaken as part of research project EES-274, entitled "Development of New Intersection Study Techniques," sponsored by the Ohio Department of Highways in cooperation with the U.S. Bureau of Public Roads. The writer is indebted to the sponsors for the financial support which made this research possible.

A word of thanks is due Dr. Johannes F. Schwar who provided the writer with the basic traffic engineering education that was necessary to conduct this research program.

Deep appreciation is expressed to Dr. Joseph Treiterer who, as adviser and research supervisor of the project, provided through many hours of discussion, close guidance throughout the study.
VITA

April 27, 1931 Born - Sopron, Hungary

1954 . . . Diploma in Civil Engineering, Technical University of Budapest, Hungary


1957-1961 . . Design Engineer, Montreal, Canada

1961-1968 . . Research Associate, The Ohio State University, Columbus, Ohio

1963 . . . M.Sc., The Ohio State University, Columbus, Ohio

PUBLICATIONS


"Investigation of Use of Turn Signals." The Ohio State University, Engineering Experiment Station, Sensing and Communication Between Vehicles, Report No. EES 227-1, April, 1964.

"Investigation and Measurement of Traffic Dynamics." Co-author with Dr. Joseph Treiterer et al. The Ohio State University, Engineering Experiment Station, Report No. EES202C-1, October, 1965.

FIELD OF STUDY

Major Field: Engineering

Studies in Traffic Engineering. Professor Johannes F. Schwar

Studies in Transportation Engineering. Professors Emmett H. Karrer and Joseph Treiterer
Studies in City Planning. Professor Israel Stollman

Studies in Operation Research. Professor Robert F. Miller
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREFACE</td>
<td>ii</td>
</tr>
<tr>
<td>VITA</td>
<td>iii</td>
</tr>
<tr>
<td>CHAPTER ONE</td>
<td></td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Problem Description</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Intersection Study Techniques</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Research Objectives and General Approach</td>
<td>5</td>
</tr>
<tr>
<td>References</td>
<td>6</td>
</tr>
<tr>
<td>CHAPTER TWO</td>
<td></td>
</tr>
<tr>
<td>The New Field Study Technique</td>
<td>7</td>
</tr>
<tr>
<td>2.1 Photographic Methods in Intersection Studies. Historical Background</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Time-lapse Photography Principle of Operation</td>
<td>8</td>
</tr>
<tr>
<td>2.3 Problems Involved in the Installation of the Camera</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Main Features of the Rotating Camera</td>
<td>14</td>
</tr>
<tr>
<td>2.5 Main Features of the Split-image Camera</td>
<td>18</td>
</tr>
<tr>
<td>2.6 Field Installation of the Equipment</td>
<td>19</td>
</tr>
<tr>
<td>2.7 Problems Involved in Data Reduction</td>
<td>22</td>
</tr>
<tr>
<td>2.8 The Rear Projection Console</td>
<td>24</td>
</tr>
</tbody>
</table>
CHAPTER THREE
The Digital Simulation Model of Signalized Intersections
3.1 Introduction
3.2 Purpose of the Model
3.3 The Structure of the Model
3.4 Representation of the Intersection
3.5 Representation of the Vehicles
3.6 The Car-following Procedure
3.7 Description of the Intersection Model
3.8 Comparison of Five Intersection Models
Notations Used in the Computer Program
References

CHAPTER FOUR
Testing of the New Technique
4.1 Scope of the Test
4.2 Results of the Test
References

CHAPTER FIVE
Summary
5.1 Summary of the Results
5.2 Significance of the Results
References

APPENDIX A
Advantages of the Photographic Technique
References

APPENDIX B
Current Signal Timing Practices in Ohio
References
| APPENDIX C       | Sample Calculations for the Grid System          | 120 |
| APPENDIX D      | Flow Charts                                      | 123 |
| APPENDIX E      | Listing of the Computer Program                 | 141 |
| BIBLIOGRAPHY    | Simulation of the Isolated Intersection          | 164 |
|                 | Analytical Investigation of the Isolated Intersection | 168 |
|                 | Traffic Characteristics at Intersections         | 171 |
|                 | Intersection Control                             | 177 |
|                 | Coordinated Traffic Signals                      | 186 |
|                 | Signalized Network                               | 188 |

vii
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sample Computer Output</td>
<td>66</td>
</tr>
<tr>
<td>2. Comparison of the Components of Five Intersection Simulation Models</td>
<td>69</td>
</tr>
<tr>
<td>3. Results of Simulation Compared with Data Film D3A - 446 Seconds</td>
<td>84</td>
</tr>
<tr>
<td>4. Results of Simulation Compared with Data Film D3D - 521 Seconds</td>
<td>85</td>
</tr>
<tr>
<td>5. Results of Simulation Compared with Data Combined Films D3A and D3D - 16 Minutes and 7 Seconds</td>
<td>86</td>
</tr>
<tr>
<td>6. Effect of Major Roadway Minimum Green on Traffic Delay Data: Film D3D - 521 Seconds</td>
<td>89</td>
</tr>
<tr>
<td>7. Effect of Unit Extension Time on Traffic Delay Data: Film D3D - 521 Seconds</td>
<td>91</td>
</tr>
<tr>
<td>8. Comparison of Three Types of Traffic Controls Data: Film D3D - 521 Seconds</td>
<td>92</td>
</tr>
<tr>
<td>9. Sample Calculations for the Grid System Film D3A - North Approach</td>
<td>122</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The Rotating Platform with the Bolex and the Television Cameras</td>
<td>12</td>
</tr>
<tr>
<td>2. The Remote Controlled Rotating Camera</td>
<td>13</td>
</tr>
<tr>
<td>3. The 70 mm Camera with the Mirror System</td>
<td>16</td>
</tr>
<tr>
<td>4. Photograph Taken by the Split-image Camera</td>
<td>17</td>
</tr>
<tr>
<td>5. Installation of the Rotating Camera</td>
<td>20</td>
</tr>
<tr>
<td>6. The Rotating Camera in Position</td>
<td>21</td>
</tr>
<tr>
<td>7. The Revised Beseler King Slide Projector</td>
<td>23</td>
</tr>
<tr>
<td>8. Setup of the Rear Projection Console</td>
<td>25</td>
</tr>
<tr>
<td>9. The Rear Projection Console</td>
<td>26</td>
</tr>
<tr>
<td>10. Illustration for the Theory of Cross Ratio</td>
<td>28</td>
</tr>
<tr>
<td>11. Layout of the Intersection</td>
<td>39</td>
</tr>
<tr>
<td>12. Schematic Summary of the Research</td>
<td>101</td>
</tr>
<tr>
<td>13. Sample Calculations for the Grid System Film: D3A North Approach</td>
<td>121</td>
</tr>
</tbody>
</table>
CHAPTER ONE

INTRODUCTION

1.1 Problem Description

The two major problems in traffic operations are accidents and capacity inadequacies. In urban as well as in rural areas, both problems tend to concentrate at intersections. As reported by the Automotive Safety Foundation, approximately one-fourth of all reported accidents occur at intersections (1). In rural areas, ten to fifteen per cent of all fatal accidents take place at intersections. The concentration is even more pronounced at urban intersections, where nearly half of all urban fatal accidents occur. Usually, the capacity problems of a roadway are also aggravated at intersections. The function of an intersection is to merge, diverge and cross traffic streams. The efficiency with which this function is performed depends largely upon the geometric layout and traffic control in relation to the prevailing traffic flow characteristics. The installation of traffic signals is usually preceded by manually conducted traffic studies. Such studies involve the observation of delay, traffic volumes, turning movements, vehicle classification, and possibly approach speeds. Once the signal has been installed, continued attention is frequently limited to the maintenance of the equipment. Traffic conditions, however, change over the years. Intersections that no longer meet the requirements of current traffic are bound
to increase the cost of transportation in terms of delay and accidents. In spite of this, the limitations of conventional study techniques do not permit a continuous observation of the changing conditions at intersections.

1.2 Intersection Study Techniques

 Basically, there are three approaches available to the study of intersections; namely: 1) field observations, 2) analytical methods, and 3) simulation techniques.

Field observations are by far the most frequently utilized in intersection studies. Prevailing conditions are observed and recorded by various means. The results of a typical intersection study are used to determine requirements for traffic control devices or to evaluate the efficiency of the existing system.

With manual field studies, the number of parameters that can be recorded is generally limited. At higher traffic volumes the method becomes very troublesome and quite unreliable.

In spite of the apparent need for new field study techniques, surprisingly little has been done in the past to meet this need. Innovations have been limited to the occasional use of a tape or multi-pen recorder. On rare occasions a camera or some other specialized piece of equipment has been employed. The photographic method in particular, has never been fully developed for use in conventional intersection operation investigation.

Traffic behavior is more complex at intersections than at other sections of the roadway. The number of lanes often changes at intersections. An approaching vehicle may change lanes, slow down or accelerate, turn or go
to increase the cost of transportation in terms of delay and accidents. In spite of this, the limitations of conventional study techniques do not permit a continuous observation of the changing conditions at intersections.

1.2 Intersection Study Techniques

Basically, there are three approaches available to the study of intersections; namely: 1) field observations, 2) analytical methods, and 3) simulation techniques.

Field observations are by far the most frequently utilized in intersection studies. Prevailing conditions are observed and recorded by various means. The results of a typical intersection study are used to determine requirements for traffic control devices or to evaluate the efficiency of the existing system.

With manual field studies, the number of parameters that can be recorded is generally limited. At higher traffic volumes the method becomes very troublesome and quite unreliable.

In spite of the apparent need for new field study techniques, surprisingly little has been done in the past to meet this need. Innovations have been limited to the occasional use of a tape or multi-pen recorder. On rare occasions a camera or some other specialized piece of equipment has been employed. The photographic method in particular, has never been fully developed for use in conventional intersection operation investigation.

Traffic behavior is more complex at intersections than at other sections of the roadway. The number of lanes often changes at intersections. An approaching vehicle may change lanes, slow down or accelerate, turn or go
straight, merge or diverge, or come to a stop. Approaching on the amber phase the driver must decide whether he should continue or stop. Drivers preparing to turn left must judge when a gap in the oncoming traffic stream is large enough for them to negotiate the turn safely. Another problem involves the concentration of interference between vehicles and pedestrians at intersections. This complexity of the traffic movement makes the quantitative analysis of the traffic condition more difficult at intersections than on sections of open highway. The photographic technique has the advantage over other methods of field measurement in that it provides a permanent record of all visual aspects of an intersection.

In spite of some of the preceding problems, the efficiency in the operation of an intersection can be evaluated by field observation. In order to compare the efficiency of alternative methods of intersection control, however, it is necessary to implement the alternative methods and to analyze the results of field observations on a "before and after" basis. The cost of experimenting with an operative system can be avoided only by the application of analytical or simulation techniques.

A frequently encountered analytical study involves the computation of the capacity of an intersection by mathematical formulas, such as those of the Highway Capacity Manual (2). These formulas were derived empirically, based on the results of large scale field studies.

In general, formal mathematical analysis is an expedient and potent approach to engineering problems. It involves the formulation of mathematical
relationships that describe the system under investigation. Unfortunately, in many cases this method is too complicated to utilize effectively. This holds true for the case of the complex behavior of a signalized intersection. Because of the continuous interaction between traffic signal and traffic flow and because traffic conditions on all approaches must be considered simultaneously, the analytical approach does not adapt itself particularly well to the problem. Considering for example an intersection controlled by a fully-traffic-actuated signal, the delay suffered by a vehicle crossing this intersection depends on the traffic signal. The state of the signal, in turn, is influenced by the character of the traffic flow approaching the intersection. A mathematical description of this problem would necessarily have to be based on considerable simplifications.

When applied to conditions under which simplifications are justified, however, the analytical method has a distinct advantage over the field observations technique in that it can be used to predict future conditions.

When a process is too complex for analytical description but enough is known about the elements of the process and their interrelationship, then simulation on an electronic computer can be a useful study technique. Simulation makes possible experimentation with a wide range of intersection controls under specified conditions, and provides a basis for the study of control patterns that will handle real traffic situations most efficiently. The simulation can be repeated many times with different conditions specified for each run. By studying the simulated results for alternative conditions, the relationship and interaction between traffic control and traffic flow can be investigated.
1.3 Research Objectives and General Approach

The objective of this dissertation is to develop a new intersection study technique that will facilitate efficient timing of traffic signals. The specific aims of the study are twofold:

1) To develop an accurate and efficient field observation method, utilizing time-lapse photography, that is capable of obtaining simultaneous traffic data on all approach lanes. The design and development of photographic as well as data reduction equipment are part of the program, and techniques are to be explored for efficient data reduction.

2) To develop a mathematical model of a signalized intersection, programmed for the IBM 7094 digital electronic computer, which is verified by the new field observation method. The model is to be flexible enough to permit the simulation of either pretimed, semi-traffic-actuated or fully-traffic-actuated signals.

The new intersection study technique involves the combined application of the field observation method and the simulation model. Once the model has been fitted to a specific intersection by the input data obtained by means of the photographic data collection method, the various faces of operation of the intersection are studied by experimenting on the model. Traffic demand and traffic control variables are manipulated systematically and the interrelationship is analyzed. By testing alternative traffic control schemes and observing the results, the most desirable scheme can be identified. The technique is to be tested at the intersection of State Route 3 and State Route 161 in Columbus, Ohio.
REFERENCES


CHAPTER TWO

THE NEW FIELD STUDY TECHNIQUE

2.1 Photographic Methods in Intersection Studies.
   Historical Background.

Time-lapse photography has long been recognized as an effective method for data collection in traffic engineering studies. In an article published in the Proceedings of the Thirteenth Annual Meeting of the Highway Research Board in 1933, Dr. Bruce D. Greenshields reported the results of a study which is generally considered to be the first employment of time-lapse photography in traffic engineering (1).

The application of the photographic technique to an exhaustive intersection study was reported in 1947 by Greenshields, Shapiro, and Ericksen (2). They photographed traffic flow with a 16 mm camera which was mounted on the roof of a tall building close to the intersection under investigation. Auxiliary equipment brought a frame counter and a signal phase indicator into the view of the camera. The exposure rate was 88 frames per minute. For convenience in analyzing the film, the projector was mounted overhead so as to project the image on white drafting paper placed on a horizontal surface. Based on chalk lines spaced twenty feet apart on the pavement, a grid was drawn on the paper. Most of the films were read to an accuracy of one foot which was considered acceptable for most purposes.
In 1960, Donald G. Capelle and Charles Pinnell applied the motion picture technique in their study of the capacity of signalized diamond interchanges (3). Data were collected by a 16 mm camera mounted on a hydraulic platform truck. Photographs were taken at the rate of ten frames per second so that time-headways could be accurately measured. The arriving time at a reference line, placed on the pavement, was estimated for each vehicle. Several other methods of data collection were considered by Capelle and Pinnell before the motion picture study was chosen as the most feasible method. The relatively small number of field personnel needed and the possibility of recreating all traffic events were the most valued advantages.

Two examples of photographic studies investigating traffic flow characteristics on expressways are by Donald O. Covault (4) in 1959 at the Georgia Institute of Technology, and by R. E. Worrall (5) in 1962 at Northwestern University.

In all the preceding examples of photographic studies, the camera was mounted on either a tripod, a hydraulic platform truck, or on a tall building. A new approach has been developed in the study which is described on the following pages.

2.2 Time-lapse Photography. Principle of Operation.

Time-lapse photography can be applied to collect permanent records of traffic conditions. A sequence of photographs taken at regular intervals will record graphically a series of traffic events in time. Each photograph records
all visible aspects of the particular event that is being photographed, including
the position of vehicles relative to the roadway elements, or relative to other
vehicles, and also some qualitative features of the traffic flow. The data thus
assembled can be analyzed by a great diversity of techniques of varying com-
plexity.

Examples of qualitative information that can be procured from the photo-
graphs are observance of traffic rules, effect of driveways on traffic flow,
parking maneuvers, or some hazardous practices. Quantitative analysis pro-
vides such traffic flow characteristics of general utility as traffic volumes,
travel speeds, traffic density, and lateral or longitudinal position of vehicles.
By defining the position of a vehicle on two successive frames, the velocity
can be computed from the distance increment and the time increment:

\[ V_1 = \frac{D_1}{t} \cdot 0.682 \tag{2.1} \]

where:

\[ V_1 = \text{vehicle velocity in miles per hour}, \]

\[ D_1 = \text{distance increment in feet, and} \]

\[ t = \text{time increment in seconds}. \]

By defining the distance increment for two successive time intervals, the
acceleration rate, a, is expressed in feet per second squared by the following
formula:

\[ a = \frac{D_2 - D_1}{t} \tag{2.2} \]
In order to achieve the desired accuracy, it is necessary to have maximum control over the time intervals between successive frames and to be able to define precisely the position of the vehicles on each photograph.

A 16 mm Bolex time-lapse camera and a 70 mm Maurer P.2 reconnaissance camera were used to collect data in this study. The timing of the Bolex camera is regulated by an intervalometer. The accuracy of the intervalometer was tested by a high speed electronic counter. From a sample of 150 readings, the actual interval was determined to be between 0.4924 and 0.5091 second, at the 95 per cent confidence level. The sample mean thus differed from the intended 0.5 second by less than 0.2 per cent.

The exposure rate of the reconnaissance camera is regulated by an Intervalometer Camera Control - Type CP-3. This intervalometer was also checked for accuracy by the electronic counter. A sample of 133 readings had a mean of 0.996 second with a standard deviation of 0.0029 second. The limits of the estimated 95 per cent confidence interval of the true mean are 0.9903 second and 1.0017 second. The sample mean differed from the theoretical one-second interval by 0.4 per cent.

The precise determination of the position of vehicles is facilitated by a grid system superimposed on the projected image of the roadway. The grid system consists of transverse lines drawn across the roadway at five foot intervals. The readings of the position of vehicles can be accomplished to the nearest foot without much difficulty.
Assuming a maximum error of e feet in the measurement of the vehicle position and assuming uniform travel speed for a time interval of t seconds, the corresponding maximum error in the estimated velocity, $E_{\text{max}}$, is expressed in miles per hour by the following equation:

$$E_{\text{max}} = \pm \frac{2e}{t} \cdot 0.682$$  \hspace{1cm} (2.3)

Using one-second intervals between frames and assuming a maximum error of 1/2 foot in the reading of the position of vehicles, the corresponding expected maximum error in the estimated velocities is then 0.682 mph. This is well within the limits of what is considered acceptable for the requirements of this study. The principal factors responsible for the accuracy of this method are: first, the advantageous location of the camera over the center of the intersection; and second, the conveniently large size of the projected image on which the measurements are made, namely 30" x 30".

2.3 Problems involved in the Installation of the Camera.

When photographic techniques are employed in traffic engineering studies, the position of the camera largely determines the quality and quantity of data provided by the photographs. The field of view of a camera that is mounted on a tripod at street level would generally be inadequate for intersection studies. A better coverage can be obtained by a camera mounted on a hydraulic platform truck. It may be difficult at times, however, to find a suitable parking space for the truck near the intersection. Also, it is likely to attract the attention of
Figure 1 - The Rotating Platform with the Bolex and the Television Cameras
Figure 2 - The Remote Controlled Rotating Camera
drivers and may thus have a biasing effect on the traffic data. The best view is provided by a camera that is mounted on the roof of a tall building, provided the building is sufficiently close to the intersection and the view is not obstructed by other structures. However, dependence on a conveniently located tall building near the intersection to be studied is a rather serious limitation. Searching for a solution to the problem, Dr. Joseph Treiterer, in 1965, originated the idea of a time-lapse camera suspended by a steel cable over the intersection.

2.4, Main Features of the Rotating Camera.

The equipment consists of a 16 mm Bolex time-lapse camera mounted on a rotating platform. The camera is protected from the effects of the weather by a metal housing. The unit is suspended over the center of the intersection from a cable that is attached to the supporting poles of the traffic signal. Such poles are available at most signal controlled intersections, making this method generally applicable. Electrical power is drawn from the control box of the traffic signal.

The camera is equipped with a set of interchangeable lenses: a 13 mm wide angle, a 10 mm wide angle, and a zoom lens. The zoom lens is furnished with a built-in automatic exposure control. The feature is particularly desirable on days with partial overcast when light conditions tend to vary rapidly. The zoom range of the lens is 18 mm to 86 mm.
The 10 mm lens has an angle of view of 58° x 38° which is sufficiently wide to bring both the stop line and the horizon into the field of vision of the camera. The through-lens viewing system provides a 1:1 image of the field of view contributing to the good control of framing and evaluation of depth of field.

The camera is equipped with a Bolex Unimotor making remote controlled operation possible. In addition to the footage indicator, a frame counter has also been built into the camera. During single frame or time-lapse operation the exposure time is 1/30th of a second. The specifications for the construction of the rotating platform call for a maximum speed of one revolution per second. The platform is rotated by a synchronous electric motor powered by 60 cps, 110 volt A.C. By mechanical contact points placed on a disc, the camera shutter is actuated at the instant when the camera is facing one of the legs of the intersection. Thus four pictures are to be taken per second, or one for each approach in every second.

Results with this setup during field tests were not quite satisfactory. The rotation and swaying resulted in blurred photographs. This problem could be solved by reducing the rate of rotation, but this would decrease the utility of the data. The principle of operation was revised and instead of rotating continuously the camera is now rotated periodically to photograph one approach for several minutes before turning toward another approach.

The revised platform also houses a television camera (see Figure 1). The field of vision of the television camera is similar to that of the time-lapse
Figure 3 - The 70 mm Camera with the Mirror System
Figure 4 - Photograph Taken by the Split-image Camera
camera. The operator, who controls the equipment with a remote controlled Tenna-Rotor, can rotate the camera to the desired direction by observing the view on a closed circuit television receiver. Both cameras can be tilted on a horizontal axis by remote control to insure the proper field of vision (Figure 2).

2.5 Main Features of the Split-image Camera.

The second instrument was designed to provide data of traffic conditions on all four approaches simultaneously. This instrument is based on a 70 mm Maurer P.2 camera, made available by the Wright-Patterson Air Force Base. This unit is suspended over the intersection, in a similar way as the rotating camera. The camera is mounted in a vertical position on the bottom of a frame. It is aimed at a set of four mirrors installed over the camera (see Figure 3). Each of the four mirrors is adjusted so as to bring one of the four approaches into view of the camera. Between the four mirrors a data chamber is visible in which a set of lights is synchronized with the lights of the traffic signal. Each photograph, therefore, records the traffic condition on all approaches and also the state of the traffic signal, as shown in Figure 4.

The adjustment of the mirror takes place in the field, after the frame has been installed on the supporting cable, with the help of a viewing device attached to the frame in place of the camera. Through a prism, this device reproduces the field of vision of the camera for the operator who can then adjust the mirrors. By turning one of two screws, a mirror may be rotated either around
the longitudinal or the lateral axis. The operator is lifted to the proper elevation for this procedure by the hydraulic lift truck that is also used to lift the unit into place. Following the adjustment of the mirrors the camera is installed and the power supply is connected.

The camera is started and stopped by remote control from the control console. This console is installed in the back of a station wagon that is parked near the intersection. A frame counter is built into the console that automatically records the movement of the film through the camera.

The camera can be used with 50 foot or 100 foot magazines. At one frame per second exposure rate the 100 foot roll has the capacity to record approximately nine minutes of traffic data.

The current design of the system evolved from a long period of testing and modifications. Problems developed with the shutter of the 70 mm camera and a new camera of the same model was made available by the Wright-Patterson Air Force Base in early 1967. The camera is equipped both with 50 foot and 100 foot magazines. However, the motor in the camera is underpowered for operation with the 100 foot magazine. An auxiliary motor was installed on the take-up reel of the 100 foot magazine. The mirror system was rebuilt when the first version proved to be hard to adjust in the field.

2.6 Field Installation of the Equipment.

The equipment is suspended over the intersection by a steel cable. A hydraulic lift truck is used to lift the equipment and the personnel to the required
Figure 5 - Installation of the Rotating Camera
Figure 6 - The Rotating Camera in Position
position (see Figure 5). The truck is parked in a position so that traffic may flow as freely as possible. In no case was any serious backup observed during the installation of the equipment. The camera itself did not appear to attract any attention during operation. Suspended between several traffic signal heads and directional signs, the camera remains quite inconspicuous, as shown in Figure 6. It is unlikely, therefore, that it could have any biasing effect on the traffic flow. This is a definite advantage when this method is compared with more conventional techniques of data collection at intersections.

2.7 Problems Involved in Data Reduction.

The analysis of photographic traffic data is generally considered to be exceedingly difficult and slow. However, difficulties vary with the particular problem investigated and depend on the analysis tools employed. Characteristics of intersection traffic flow such as vehicle classification, lane distribution, turn signalling frequencies, queuing, and turning movements can readily be obtained by observing the film as it is projected on a screen at a convenient speed. The film can be projected several times, permitting the observer to concentrate on a different item at each time. Qualitative judgments regarding some hazardous practices at a problem intersection can often be made after a few minutes of film viewing, while the same judgments could be very difficult to arrive at based on information collected by more conventional study techniques. Traffic volume can be obtained easily by counting the vehicles appearing on the screen if some reference to time is available. Stopped delay can be obtained
Figure 7 - The Revised Beseler King Slide Projector
also, since stopped vehicles can be identified by their unchanging position relative to some fixed background object. Traffic density can be acquired simply by counting the number of vehicles on a section of roadway of known length.

The procedure only becomes complex when it is necessary to define the velocity of the vehicles. However, the difficulty is still inversely proportional to the degree of accuracy desired. Since reading distances to the foot is judged acceptable for the purposes of this study, it was possible to design a method that does not require expensive instrumentation and yet facilitates rapid data analysis.

2.8 The Rear-projection Console.

One of the two cameras employed in this study is a Maurer P.2 camera which uses 70 mm size film. A movie projector designed to handle this type of film proved to be an expensive instrument and not readily available. Reading distances from the negative would have required the application of some precision reading instrument. Past experiences with the Bensen Lehner Reader and the Nistri Stereo comparator proved them to be highly accurate but very time consuming. It was also rather difficult to get time on the instruments, partly because of high demand, partly because of frequent break-down periods. The decision was made to design and build our own equipment that would always be available, more reliable and faster to operate, and would still be sufficiently accurate.
Figure 8 - Setup of the Rear Projection Console
Consequently a Beseler Slide King projector, originally designed to handle slides up to 3-1/4" x 4" size, was converted to suit our specifications (see Figure 7). Two auxiliary reels were added, powered by an electric motor, to advance the film through the projector. The motor is remote controlled from the viewing console and can be operated either continuously at an approximate rate of four seconds per frame or finer adjustments can be made by depressing a push button. The 750 watt lamp of the projector produces a bright image, and the blower type cooling system permits prolonged continuous operation.

The image is projected to the rear of a 30" x 30" screen. The screen consists of a glass plate that is covered by drafting paper and built into the top of a console, as illustrated in Figures 8 and 9.

Prior to the installation of the camera at the intersection, white paint marks were sprayed at 25 foot intervals at both edges of all approach lanes. The marks were approximately three inches wide and twelve inches long. It is important that these markings be kept as small and inconspicuous as possible to avoid any biasing effect. Transverse lines painted the full width of the pavement would influence the behavior of drivers. Although quite small, most of the marks are still visible on the photographs, thus providing a built-in reference scale. Data could be obtained by measuring the movement of vehicles on the projected image relative to these markings. The accuracy of the measurement is significantly improved, however, by the construction of an analysis grid. A frame, with no cars present that would obstruct the markings, is projected on the
Theory of Cross Ratio:

\[
\frac{AC}{BC} = \frac{ac}{bc} = \text{Constant}
\]

Let:

\[
y = \frac{bd}{bc} \cdot \frac{AD}{AC} = \frac{AD}{BD}
\]

Then:

\[
ad = cd \cdot \frac{y}{y - 1}
\]
screen and all identifiable markings as well as some control lines, such as the center line, are transferred to a vellum overlay. The missing marks are reconstructed by a technique that is based on the fundamental principle of projectivity, namely the theory of cross ratio. The theory states that the cross ratio of distances between four points on a straight line is invariant under projection. Using the notation of Figure 10, this is expressed as:

\[
\frac{AC}{BC} \cdot \frac{AD}{BD} = \frac{ac}{bc} \cdot \frac{ad}{bd} = \text{constant}
\]  

(2.4)

Consequently, if the distances between four collinear points on the pavement are known and three of these points are identifiable on the photograph, then the location of the missing fourth point can be computed.

The same principle was utilized to develop from the 25 foot marks a grid on which every five foot line is shown. The zero line is placed over the stop line. The grid system extends 200 feet on all approach lanes. Reading of the position of vehicles to the foot becomes difficult beyond this distance. For a sample calculation of the grid system, see the Appendix.

The same rear projection console is used to analyze the 16 mm film. The projector in this case is a Kodak Analyzer, equipped with frame counter and with provision for single frame viewing. The projector is remote controlled by the operator who is seated in front of the console. A grid system is constructed again with transverse lines at every five feet extending back to 200 feet. The analysis of the 16 mm film is somewhat faster than that of the 70 mm film,
due to the instantaneous advancing of the single frame by the Kodak Analyzer.

As mentioned previously, it requires approximately four seconds to advance one frame with the Beseler Slide King projector.
REFERENCES


CHAPTER THREE

THE DIGITAL SIMULATION MODEL OF
SIGNALIZED INTERSECTIONS

3.1 Introduction

A model is a simplified representation of an object or a process, designed to incorporate those features of the real object or process that the developer of the model assumes to be significant for a given problem. Simulation can be defined as the investigation of a problem through the development and operation of models.

Engineers have for many years been applying simulation techniques to design problems. Simulation permits the engineer to test specific aspects of the design and avoid costly mistakes. The use of scale models has been of considerable value in the design of structural elements and hydraulic systems. In the field of ship design, hull shapes are tested by propelling scale models in a tank. It is often possible to build a mathematical model of a certain process or system. Since the introduction of high speed electronic computers, simulation utilizing mathematical models has become a practical tool in engineering. Simulation of traffic flow on electronic computers has also received some attention. The ability to represent traffic of a characteristic particularly desired, that might be difficult to obtain in the field is one of the advantages of simulation. Furthermore,
the hazard and inconvenience to which drivers might be subjected by field experimentation can be eliminated by the simulation technique.

Consider a traffic signal controlled isolated intersection. A typical design problem involves the timing of the traffic signal. The generally accepted measurement of the efficiency of the signal control at isolated intersections is stopped time delay. Let a mathematical model be developed that relates stopped time delay on an approach lane to signal timing. Assume that left turns are prohibited at the intersection and that the signal is of the pretimed type. Vehicles arriving at the intersection on green are assumed to cross the intersection without being delayed. Actually, a vehicle arriving at the beginning of the green phase may be stopped by the queue just being discharged. Let this delay be ignored in this discussion so that only vehicles arriving on red need to be considered in the model.

Let $R = \text{red phase, seconds};$

$Q = \text{hourly volume per lane, vehicles per hour};$

$h = \frac{3600}{Q}, \text{average headway between vehicles, seconds};$

$q = \frac{R}{h}, \text{average number of cars arriving during red phase};$

$s = \text{starting delay, separating the movement of two successive members of the queue, seconds};$

$d_i = \text{stopped time delay for vehicle i, seconds},$

$D = \text{total stopped time delay per cycle on the lane considered}.$
The delay suffered by a vehicle will consist of two parts: first, the portion of the red phase remaining after the arrival of the vehicle; second, the starting delay involved in the discharge of the queue following the end of the red phase. On the average, the first vehicle stopped by the signal arrives \( \frac{h}{2} \) seconds after the beginning of the red phase and leaves \( s \) seconds following the end of the red phase. The corresponding starting delay is expressed then by the following equation:

\[
d_1 = R - \frac{h}{2} + s
\]

The second vehicle arrives \( h \) seconds later and leaves \( s \) seconds later than the first vehicle:

\[
d_2 = R - 3\frac{h}{2} + 2s
\]

The stopped time delay suffered by the \( i \).th vehicle:

\[
d_i = R - \left( \frac{h}{2} \right) \cdot (2i - 1) + i \cdot s
\]

The total delay caused by the red phase is the sum of the delay suffered by all the vehicles arriving during \( R \) seconds:

\[
D = qR - \sum_{i=1}^{q} \left( \frac{h}{2} \right) (2i - 1) + \sum_{i=1}^{q} i \cdot s
\]

Since

\[
\sum_{i=1}^{q} (2i-1) = q^2
\]

and

\[
\sum_{i=1}^{q} i = \frac{q(q+1)}{2}
\]

the preceding equation becomes

\[
D = qR - \frac{hq^2}{2} + \frac{q(q+1)}{2} s
\]
Depending on the validity of the assumptions made regarding uniform arriving rates, prohibited left turns and undelayed crossing by vehicles arriving on the green phase, the preceding mathematical model is easily applicable to intersection studies. With the help of a slide rule, a large number of alternative signal timings can be tested in a short period of time.

The weakest point of the preceding model is the assumption of a uniform arriving rate. Only at near capacity and in fully restrained situations does the traffic flow approach uniform distribution. Under free flow conditions some random distribution functions provide a much better description of the distribution of the traffic. The composite exponential, the Pearson Type III, and the lognormal distribution functions are examples of popular mathematical representation of headway distribution. Assume that such a distribution function has been tested and found acceptable for representation of traffic flow at a given intersection. Then the Monte Carlo method can be used to reproduce the traffic data in the same manner as would occur in a real life situation. The Monte Carlo method is a computational technique of introducing data of a random nature into a model.

Consider again the design of a model of a pretimed signal controlled intersection where left turns are prohibited. The probability of a headway of a given size occurring is computed from the distribution function. Assign a group of random numbers to each possible headway in proportion to the probability of the occurrence of the same headway. Proceed to draw random numbers from a table of random numbers. To each random number picked there is a correspond-
ing headway. Thus, in effect, the arrival of traffic at the intersection is being simulated. It is a simple problem now to compare arriving times with the prevailing signal phase and to determine the position of a given vehicle in the waiting queue to determine the corresponding stopped time delay. This model can be based on hand calculation in a tabulated form. Although this model is still very simple and straightforward, the calculations are time consuming and the programming for an electronic computer is very desirable.

Now consider an intersection where left turns are permitted and where the traffic signal is of the vehicle-actuated type. It is clearly impossible to describe the process by a useful mathematical formula. It is still possible, however, to write formulas for the individual elements of the process and thus build a model of the intersection. By considering all parts of the model in a long sequence of steps, the operation of the intersection can be simulated. Only the high speed of the electronic computers can, however, permit the practical use of such involved models.

The development of a complex model such as the intersection model described in the following, is a long process. An initial understanding of the system is necessary in order to begin the construction of the model. The building of the model is, however, a learning process. Much is discovered about the interrelationship between various elements of the system through preliminary failures of the model. Typically, malfunctions in seemingly unimportant details in a given situation tend to result eventually in some obviously distorted and unrealistic results. At the same time, prolonged problem-free
operation of the model, supported by field data, indicates that all the details fit
together and no significant element has been overlooked.

Considering the gratifying results obtained by simulation of systems, in
which physical experimentation is costly and perhaps dangerous, and in which
the exact mathematical description is impracticable, it seems justifiable to
assume that the popularity and practicality of simulation will increase in the
field of engineering.

3.2 Purpose of the Model

The objective of this phase of the study is to develop a model which, utilizing
information obtained by the photographic equipment, can simulate the operation
of a signalized intersection to such a degree of accuracy that the effect of traffic
control can be predicted. The control can be effected by fixed-time, semi-
actuated, or fully-actuated traffic signal.

The efficiency of control is measured in terms of delay. For each lane the
number of stopped vehicles, the sum of the stopped time delay, average stopped
time delay per stopped vehicles, and average stopped time delay per all vehicles
is determined. By comparing travel time of all vehicles to the ideal travel time
of an undelayed vehicle, travel time delays are also measured for all lanes.

Summarizing all delays for the intersection, the effect of various signal con-
trol systems can be compared. By considering the delay per traffic lane, it is
possible to compare delay on the major street with that on the minor street or to
account for the effect of uneven traffic distribution.
3.3 The Structure of the Model

The development of the intersection model involves the identification of those elements of an intersection that are assumed to be critical for the purpose of this study. The model is a computer program which, when given a certain set of input parameters related to the intersection, will manipulate the components in a manner to act comparably to that of a real intersection.

The three components of an intersection are: the physical properties of the intersection, the traffic control, and the traffic flow. The properties of the components are represented by three methods:

1) Mathematical equations,
2) Variables,
3) Statistical distributions.

The time scanning technique is used to update the system. At each time period the following procedure is repeated:

1) The traffic signal is checked and reset if so required,
2) The list of arriving times is checked for arriving vehicles and the list of vehicles in the system is updated if required,
3) The position and the velocity is recomputed and a new acceleration rate is assigned for each vehicle as dictated by present conditions,
4) If any vehicle has exited the system, the list of vehicles in the system is updated,
5) Current time is checked against time limit. If the time limit has been reached, the results of the simulation are printed out and the run is terminated.
Figure 11 - Layout of the Intersection
For the notations used in the computer program see the listing at the end of this chapter.

3.4 Representation of the Intersection

The model simulates an intersection which has two approach lanes from each direction. The lanes are identified by the subscript I, as indicated on Figure 11. Lanes 1, 3, 5, and 7 are left turning lanes. Lanes 0, 2, 4, and 6 accommodate both straight and right turning movements. The position of any vehicle is defined by the distance between the stop line and the front bumper of the vehicle. A negative distance identifies vehicles approaching the stop line while a positive distance refers to vehicles that have already crossed the stop line and have entered the intersection. The variable EL defines the length of the simulated approach lanes. Observations were made at the intersection of SR-3 and SR-161 to determine the distance within which an approaching vehicle is influenced by the traffic signal. Observing the brake-lights of vehicles approaching on red, the average distance at which vehicles began to decelerate was found to vary from 200 feet on the west approach to 280 feet on the north approach. Therefore, the value of EL is defined in this range. It may become necessary to increase the length of the approach lane when the length of the queue that is waiting at the red light approaches the value of EL. When required, this is done automatically within the model during simulation.

Beyond the stop line, only that portion of a traffic lane is considered in the model on which a potential conflict exists between left turning vehicles and
straight through or right turning traffic. A left turn may not be completed as long as the conflicting straight through or right turning vehicle did not pass EXL as shown on Figure 11. Therefore the simulated length of lanes 0, 2, 4, and 6 is defined by the variable EXL. The length of the left turning lanes is defined by CPT.

Applying the model to any intersection, the distances EXL and CPT are to be measured at the site. The minimum suggested value for EL is 200 feet. Using an unreasonably large EL will result in wasted computer time.

Other physical characteristics of the intersection are not considered directly in this model. Since such input parameters as approach speeds, travel times, and turning speeds, are obtained from field data, the most significant physical characteristics of an intersection are taken into account indirectly in terms of their effect on these traffic parameters.

3.5 Representation of the Vehicles

The vehicles are represented in the model by a set of double subscripted variables. The subscripts identify the lane on which the vehicle is traveling and the order in which the vehicles arrive. For example, the arriving time of a vehicle to the entry point is denoted by ARR (I, J). Thus ARR (0, 1) specifies the time when the first vehicle arrives on Lane 0.
Three of the variables are recomputed during each scanning interval:

a) the position, POS(I,J),

b) the velocity, V(I,J), and

c) the acceleration rate, A(I,J).

The position and the velocity are computed first by the following expressions:

\[
\text{POS}(I,J) = \text{POS}(I,J) + V(I,J) \times ST + 0.5 \times A(I,J) \times ST^2 \quad (3.1)
\]

and

\[
V(I,J) = V(I,J) + A(I,J) \times ST. \quad (3.2)
\]

The preceding expressions from the computer program are the equivalents of the following equations:

\[
l_2 = l_1 + v_1 t + \frac{at^2}{2} \quad (3.3)
\]

and

\[
v_2 = v_1 + at \quad (3.4)
\]

where:

- \(l_2\): position of the vehicle at time \(t_2\), in feet,
- \(l_1\): position of the vehicle at time \(t_1\), in feet,
- \(v_1\): velocity at time \(t_1\), in feet per second,
- \(t\): time interval \(t_2 - t_1\), in seconds,
- \(a\): acceleration rate, in feet per second per second,
- \(v_2\): velocity at time \(t_2\), in feet per second.

The position and the velocity of each vehicle is evaluated in relation to the current traffic condition and an appropriate acceleration rate is
computed by one of the subroutines.

The following is a list of the double subscripted variables that are used to represent certain characteristics of each vehicle:

- **NFT**(I, J) : direction of movement (straight, right, or left)
- **NVDL**(I, J) : position in relation to the vehicle detector,
- **NSTOP**(I, J) : identifies vehicles that were delayed by the intersection,
- **DEL**(I, J) : stopped time delay,
- **NGAP**(I, J) : denotes result of investigation of gaps in conflicting traffic stream by left turning vehicles (accepted or rejected gap).

The purpose and the application of the latter variables is explained in more detail in the following description of the subroutines.

### 3.6 The Car-following Procedure

During the last decade, computer simulation of the car-following situation has become a widely used traffic research tool. Models of a great variety of sophistication were developed, depending on the objectives of the research program. Much work has been done in this field at the Ohio State University, where the objective was the development of safety controls for an automated electronic highway. Some of the earlier work was reported in 1962 by Nemeth and Reebel in Report No. 202-1 of the Transportation Engineering Center,
The car-following model developed here for the intersection simulation was designed to fit the following specifications:

(1) No rear-end collision should occur in the system. While most car-following models have been built for the specific purpose of investigating stability within a platoon, such investigation is beyond the scope of this research program. Realism in this case is measured in terms of stopped time delay only. Therefore response time could be eliminated from the car-following behavior. The instantaneous response and the identical limits on the performance of vehicles eliminate the possibility of rear-end collision in the system.

(2) A specified average spacing, SMIN, should be provided between vehicles in a stopped queue. The spacing between moving vehicles should increase as travel speeds increase. The desired spacing therefore consists of a constant part, SMIN, and a part which varies with the speed.

Assume that a vehicle traveling at \( v_2 \) ft/sec is approaching a slower lead vehicle moving at \( v_1 \) ft/sec. The distance between the two vehicles is then to be reduced by 1 ft. to obtain the desired spacing and the speed of the following vehicle is to be reduced to \( v_1 \) ft/sec simultaneously. During the deceleration period, \( t \), the following vehicle travels 1 foot farther than the lead vehicle, depending on the average relative speed:

\[
l = \frac{v_2 - v_1}{2} \cdot t.
\]
The time period can be expressed from the preceding equation in seconds:

\[ t = \frac{2 \cdot 1}{v_2 - v_1} \]

The acceleration rate that is required to reduce the velocity to \( v_1 \), during \( t \) seconds is equal to:

\[ a = \frac{v_2 - v_1}{t} \]

or, replacing \( t \) by the preceding, the following form is obtained:

\[ a = \frac{(v_2 - v_1)^2}{2 \cdot 1} \] \hspace{1cm} (3.5)

Let the variable part of the desired spacing be the distance traveled by the following vehicle during one second. The desired spacing then expressed, using the notations of the program as:

Desired Spacing = SMIN + V(I, J).

In the preceding expression \( V(I, J) \) represents distance.

The difference between present spacing and desired spacing is then expressed by the following formula:

\[ D_1 = \text{POS}(I, J) - \text{POS}(I, J-1) + \text{SMIN} + V(I, J) \] \hspace{1cm} (3.6)

Introducing the notations of the computer program into the preceding acceleration formula the following expression is obtained:

\[ A(I, J) = \frac{(V(I, J) - V(I, J-1))^2}{2 \cdot D_1} \] \hspace{1cm} (3.7)
(3) Provision should be made so that a right turning vehicle following a straight through vehicle will not arrive at the stop line at a velocity exceeding the desired turning velocity. The variable NTF(I, J) indicates the direction of movement of each vehicle and is used to detect such a situation. The car-following acceleration rate can thus be compared with the turning acceleration rate and the lower of the two can be assigned to the vehicle.

3.7 Description of the Intersection Model

The program deck is made up of eighteen parts: the initialization part, sixteen subroutines, and the data deck. In the following, each part is described briefly. The flow chart and the listing of the statements of the program is included in the Appendix.

There are many styles of algebraic language programming. The initial work carried out in the development of this model utilized the FORTRAN II language. However, the Numerical Computation Laboratory of the Ohio State University introduced SCATRAN as the preferred language. To receive quicker service at the Numerical Computation Laboratory, SCATRAN was used in the development of the model. The revision of the program involved minor changes in the source language statements and control cards.
**Initialization**

This part of the program serves the following purposes:

1. The "dimension" statement reserves space in the core memory required to store the indexed variables.

2. The "read input" statements transfer into the core memory the information fed in on punched cards.

3. The "do" statement sets the traffic signal into the required initial position. The indication of the signal on a given lane is specified by the current value of NSPF(I).

4. The simulation run is initiated by setting the current time, denoted by TIME, equal to the starting time, START, which is usually predetermined to be zero in the input data.

This initialization part of the program may need to be updated for each run if the reserved storage space in the core needs to be increased to accommodate higher traffic volumes or if the initial setting of the signal is to be changed. The maximum number of cars that can be generated on any lane is determined by the dimension statement and is equal to NNN minus one.

**Subroutine TGI - Traffic Generator**

When arriving times are not read in as input, then this subroutine is used to generate traffic by a random process. The hourly rate of flow, VOL(I), is read in for each lane. The corresponding headway distribution is approximated by the lognormal distribution (1). The probability density
function is given as follows:

\[
f(x) = \begin{cases} 
\frac{1}{x \sigma \sqrt{2\pi}} e^{-\frac{(\lg x - \mu)^2}{2\sigma^2}} & , x > 0 \\
0 & , x \leq 0
\end{cases}
\]  

(3.8)

For the mean \( \mu \) and the variance \( \sigma^2 \) the maximum likelihood estimates \( \hat{\mu} \) and \( \hat{\sigma}^2 \) are to be substituted, as determined from a sample of size \( n \):

\[
\hat{\mu} = \frac{\sum_{i=1}^{n} \lg x_i}{n}
\]  

(3.9)

\[
\hat{\sigma}^2 = \frac{\sum_{i=1}^{n} (\lg x_i - \hat{\mu})^2}{n-1}
\]  

(3.10)

From field data consisting of samples ranging from 339 vehicles per hour to 1369 vehicles per hour, \( \hat{\mu} \) and \( \hat{\sigma}^2 \) values were computed. Regression equations were then developed using volume as the independent variable and the mean and variance as dependent variables:

\[
\hat{\mu} = \text{YMEAN}(I) = 2.076 - 0.001 \text{ VOL}(I)
\]  

(3.11)

\[
\hat{\sigma}^2 = \text{VARY}(I) = 0.5670 - 0.00006 \text{ VOL}(I)
\]  

(3.12)

The probability of a headway between \( x - 1/2 \) seconds and \( x + 1/2 \) seconds
occurring is obtained by integrating the probability density function over the interval from \( x - 1/2 \) to \( x + 1/2 \) seconds. The Monte Carlo Method is then used to generate headways for traffic arriving on a given lane. The arriving time of a vehicle is obtained by adding the generated headway to the arriving time of the preceding vehicle. The one second class interval limits the shortest headway to one second which is in agreement with the accuracy of the data obtained by the time-lapse photography.

When the generation of traffic for the specified time period is completed on all lanes, the simulated time is set back to START and the simulation of the intersection operation begins. The list of arriving times generated by this subroutine is scanned periodically for newly arrived vehicles by Subroutine UD7.

**Subroutine SC2 - Pretimed Signal**

This subroutine is included in the program only when pretimed signal control is simulated. The corresponding input data include the length of the cycle as well as the starting time of all phases, measured from the beginning of the cycle. During each time increment, the current time is compared with the starting times of the phases. The current signal phase for a given lane is indicated by the variable \( \text{NSPF}(I) \). The changing of the signal is achieved by assigning the corresponding new value to \( \text{NSPF}(I) \).

The beginning of the current cycle is indicated by the variable \( \text{BGTO} \). At the end of each cycle, \( \text{BGTO} \) is incremented by the cycle length.
**Subroutine SC3 - Semi-actuated Signal Controller**

This subroutine replaces SC2 when semi-actuated traffic control is simulated. It is used in conjunction with Subroutine SD5, which simulates the operation of the detectors. During each time increment the signal phase in the major direction is checked.

If the signal phase is green, then the cross road is checked for waiting traffic, the presence of which is indicated by the variable NWV. If the minimum green phase has been exceeded on the major road then the right of way is transferred to traffic waiting on the cross road.

If the signal phase is amber or red on the major road, then the current value of TIME is compared with a set of variables, each of which specifies the time when a new phase is to begin. These variables are updated by the following subroutine, depending on the cross road traffic registered by the vehicle detectors.

**Subroutine SD5 - Detectors for Semi-actuated Signals**

Traffic lanes of the minor road are equipped with vehicle detectors. The position of the detectors in relation to the stop line is defined by the input variable VDL. One of the variables that represents various characteristics of each vehicle is NVDL(I,J). Initially this variable is set to be equal to zero. During each time increment, starting with the first vehicle approaching the intersection, the current position of the vehicles is compared to the location of the detector. If a vehicle is observed to have crossed over
the detector and the variable NVDL(I,J) is still set at zero, then it is concluded that the detector has just been actuated. The variable NVDL(I,J) is now set equal to one, causing this vehicle to be disregarded during subsequent scannings.

The response triggered by the detector actuation depends on the prevailing signal phase. During amber or red phase, the variable NWV is set equal to one, inducing a change in the right of way, as soon as the minimum green phase has been exceeded in the major direction.

During green phase, each actuation is followed by an assured green time, called vehicle extension period. The green phase can be thus extended from the minimum green phase to a predetermined maximum green phase, after which the right of way is returned to the major flow.

A vehicle arriving near the end of the maximum green phase cannot be allowed the vehicle extension period and will be therefore retained by the traffic signal. In this case the variable NWV is set equal to one, assuring the return of the right of way even without further actuations of the detectors.

Subroutine SC4 - Fully-actuated Signal Controller

For fully-actuated signals both the minimum and the maximum green phases are specified for both directions. Vehicle detectors are installed on all approach lanes. Once the minimum green phase is exceeded, the right of way can be transferred in two ways, namely: either (1) the maximum green phase has been reached following continuous actuations of the detector, or (2) no actuation is received for a period longer than the vehicle extension period.
During each scanning period, the present state of the signal is checked by observing the value of NSPF(I). Depending on the prevailing phase, the current value of TIME is compared to the variable which indicates the time of the next change in the signal setting. The variables, indicating the beginning of the next amber phase, are determined either by vehicle actuation or by predetermined time limits as explained in the preceding paragraph. At the instant the amber phase begins in one direction, the beginning of the red phase in the same direction as well as the beginning of the green phase in the opposite direction is computed from the current value of TIME and from the predetermined inter-green and amber periods.

Subroutine SD6 - Detectors for Fully-actuated Signals

As in Subroutine SD4, the occurrence of detector actuation is determined from the present location of vehicles and from the variable NVDL(I,J). Actuations received from near the end of the minimum green phase will cause the green phase to extend, until the maximum green phase has been reached. Detector actuations occurring during amber or red phase have no effect on the traffic signal timing.

Subroutine UD7 - Up-date List of Arrived Vehicles

During each time increment, the simulation procedure begins with the checking and, if necessary, with the resetting of the traffic signals, as described in the preceding paragraphs. The next step involves the updating of the list of arrived vehicles. Arriving times were either read in as part of
the input or have been generated by Subroutine TG1. The current time is now compared with this list. If it matches one of the items in the list, then the following steps are taken:

1. The position of the vehicle is usually defined as the entrance line. However, if there is a queue extending past the entrance line, then the newly arrived vehicle is moved back as far as it is necessary.

2. For vehicles in the outside lane, the direction of travel is determined by the Monte Carlo Method. All vehicles in the inside lane are to turn left.

3. The two variables, NVP(I) and KSUM(I) are incremented by one. The first variable indicates the number of vehicles present on the lane considered, and the latter variable indicates the number of cars that have arrived on this lane so far.

4. For left turning vehicles the index variable L is specified. This index refers to the outside lane from the opposite direction, which is to be scanned by left turning vehicles for acceptable gaps. For example, if Lane 1 is considered, then left turns are in conflict with traffic flow on Lane 2 and therefore L is set at 2.

Subroutine QU8 - Queue Discharge

Two basically different system updating techniques may be used in the construction of a traffic model: event scanning, and time scanning. The event scanning technique determines the times when important events are to occur
and the system will be updated at these times. It is quite apparent that this method gets very involved when applied to the simulation of complex situations. The consideration of interaction between elements of the model is especially cumbersome. The advantage of this method is its speed.

The more commonly used method of the two is time scanning, which updates the system at regular time intervals. This method is more applicable to the microscopic simulation of traffic flow, since it represents more closely the real situation in which drivers regularly make decisions depending on a continuous surveillance of the environment. Time scanning, however, requires more computer time than event scanning.

The model that is being described here is basically designed on the time scanning principle. The discharge of a delayed platoon, however, provides an opportunity to combine the two techniques and improve the real time to computer time ratio. The behavior of a platoon starting up at the beginning of the green phase is simulated in the following way: a starting delay time separates the beginning of the acceleration of the first vehicle from the beginning of the green phase. A constant response time separates the movement of any vehicle in the platoon from the movement of the preceding vehicle. The exit time of the first vehicle is based on an average travel time from the stop line to the exit line. The exit time of any other vehicle in the queue is obtained by incrementing the exit time of the preceding vehicle by a constant. This constant represents in effect the headway between vehicles during saturation flow conditions.
When the signal changes to green, the whole stopped queue is processed. The total stopped time delay, the exit time, and the travel time delay is computed for each vehicle. The variables NVEX(I) and NVP(I), indicating the number of vehicles that have exited and the number of vehicles present in the system, are updated. During subsequent scanning periods, this lane would appear to be free of traffic to vehicles turning left from the opposite direction. It is necessary therefore to introduce a new variable, BLOK(I). This variable is set equal to the exit time of the last vehicle in the discharged platoon and it indicates that the lane is in fact blocked.

This event scanning subroutine is applied to traffic in the outside lanes only. It is not possible to predict at this time when left turns from the inside lanes may be completed since it will depend not only on the stopped queue but also on conflicting traffic that may arrive at the intersection in the immediate future.

Subroutine FG9 - Free Flow on Green; Straight Through or Right Turning Traffic

This subroutine handles those vehicles in the outside lanes whose behavior is not influenced by the traffic control or by preceding vehicles. The system updating begins by the computation of the current position, POS(I,J), and the velocity, V(I,J), of the vehicle. If the vehicle has crossed the exit line during the latest time increment, then the vehicle is removed from the system. Otherwise the proper acceleration rate is computed, depending on
the direction of travel, by one of two methods:

(a) The velocity of a straight through vehicle is compared with its desired velocity. If the difference exceeds a specified margin then a uniform acceleration rate, AVA, or deceleration rate, AVD, is assigned to the vehicle.

(b) Right turning vehicles are to assume the turning velocity VLR when they reach the stop line. Accordingly, the acceleration rate A(I,J) is computed by the following expression, using the notation of the computer program:

\[ A(I,J) = \frac{V(I,J)^2 - V_{LR}^2}{2 \text{POS}(I,J)} \] (3.13)

The distance traveled by a vehicle accelerating at a constant rate for t seconds is expressed by the equation:

\[ l = V_i t + \frac{a t^2}{2} \] (3.14)

where: \( l \) = distance in feet,

\( V_i \) = initial velocity, feet per second,

\( a \) = acceleration, feet per second per second.

Let \( V_f \) be the final velocity, then

\[ t = \frac{V_f - V_i}{a} \]

Introducing this into the preceding equation to replace \( t \) we obtain the following form:
\[
1 = V_i \frac{V_f - V_i}{a} + \frac{a}{2} \left( \frac{V_f - V_i}{a} \right)^2
\]

which can be reduced to:

\[
l = \frac{V_f^2 - V_i^2}{2a}
\]

Now express the acceleration rate from the preceding equation:

\[
a = \frac{V_i^2 - V_f^2}{2(-1)}
\]  

(3.15)

Since \(\text{POS}(i,j)\) is the negative distance between the stop line and the present position of the vehicle, the above equation is identical in meaning to the preceding acceleration expression of the computer program (equation 3.13).

The limitations of automobile performance are represented by \(A_L\), the acceleration limit, and \(D_L\), the deceleration limit. The computed \(A(i,j)\) is always compared to the limits and reduced if necessary.

**Subroutine CFG10 - Car-following on Green; Straight Through or Right Turning Traffic**

After Subroutine FG9 has processed the lead vehicle of an approaching platoon, this subroutine takes over the manipulation of the other vehicles. Based on the current relative position of two subsequent vehicles, an acceleration rate is assigned to the following vehicle, if there is a difference
in the velocities. The minimum spacing to be maintained at a given speed is equal to the sum of the specified minimum spacing between stopped vehicles and the distance traveled during one second. If the difference between the relative position and the minimum spacing is denoted by \( D_1 \), then the acceleration equation has the following form:

\[
A(I, J) = \frac{V(I, J)^2 - V(I, J-1)^2}{2 \cdot D_1}
\]  

(3.16)

If a right turning vehicle is following a straight through vehicle then the acceleration rate required to reduce the velocity to the turning velocity is also computed. The lower of the two rates will be applied.

Once a following vehicle approaches the lead vehicle within the minimum spacing, then it will maintain the same relative position.

**Subroutine FG11 - Free Flow on Green; Left Turns**

A turning vehicle is assumed to decelerate at a uniform rate until it reaches the stop line and to travel from there to the conflict point at the specified turning speed, \( V_{LL} \). The acceleration rate is obtained by the formula:

\[
A(I, J) = \frac{V(I, J)^2 - V_{LL}^2}{2 \cdot \text{POS}(I, J)}
\]  

(3.17)

The distance from the stop line to the conflict point is defined by the input variable CPT. At any given instant, the travel time TL to the conflict point is obtained by the equation:
\[
TL = \frac{VLL - V(I,J)}{A(I,J)} + \frac{CPT}{VLL}
\]

(3.18)

When the left turning vehicle approaches the intersection within a pre-determined distance, gaps in the opposing traffic stream on Lane L are investigated. The end of the queue, released at the beginning of the green phase on Lane L, is indicated by the flag word: BLOCK(L). If the queue has not yet cleared the intersection, then the turning vehicle decelerates to stop at a waiting point beyond the stop line.

If the queue has cleared the conflict point but other traffic is approaching, then the available time lag, TLAG, is computed by the following equation:

\[
TLAG = \frac{EXL - POS(L,K)}{V(L,K)} - TL
\]

(3.19)

In the preceding equation K is the index of the first vehicle whose arriving time to the conflict point is greater than the previously computed arriving time of the turning vehicle. The distance to the conflict point from the stop line on Lane L is defined by EXL. It is assumed that all time lags or time gaps equal to or greater than five seconds are accepted. If the time lag is not accepted then the arriving time of the next vehicle is computed to obtain the available gap, GAP.

\[
GAP = \frac{EXL - POS(L,K)}{V(L,K)} - TLAG - TL
\]

(3.20)

In the preceding equation, K is the index of the second vehicle. If the gap is not acceptable then the turning vehicle decelerates to stop at the waiting point.
During subsequent time increments the situation is reappraised until an acceptable gap is found. When the decision to accept a gap is made, the event scanning method is applied and the turning vehicle is processed instantaneously and removed from the system. This step permits the next turning vehicle to operate as a lead vehicle and to scan the opposing traffic for acceptable gaps during the current time increment.

Subroutine CFG12 - Car-following on Green; Left Turns

This car-following subroutine is based on the same equations as subroutine CFG10. It brings the platoon to a stop behind a delayed lead vehicle at an average spacing of SMIN. The deceleration equations are based on available stopping distance and thus zero velocity is obtained when the vehicle reaches a certain point on the roadway. However, because of the time scanning nature of the model, the vehicle will continue to decelerate until the end of the time increment. It is necessary, therefore, to include a check in the system updating procedure and correct the position of the vehicle when negative velocity has occurred.

Let \( -a \) denote the uniform deceleration rate. If a negative velocity \(-v\) is detected then \( t = v/a \) represents the time period during which the vehicle has been traveling at a negative velocity. The distance traveled during this time period is equal to

\[
 s = \frac{1}{2} a t^2 .
\]
Replacing \( t \) by the ratio \( v/a \), the following form is obtained:

\[
s = \frac{v^2}{2a}
\]  

(3.21)

The revised position of the vehicle is then obtained by correcting the previously computed position by the preceding distance. Using the notations of the computer program, the correct position is determined by the following expression:

\[
\text{POS}(I, J) = \text{POS}(I, J) - \frac{v(I, J)^2}{2 \cdot A(I, J)} .
\]  

(3.22)

The preceding check is made in all subroutines where velocity and position are computed.

**Subroutine FA13 - Free Flow on Amber; Straight Through and Right Turns**

It is assumed that a vehicle traveling in the outside lane when the signal changes to amber will enter the intersection only if he cannot stop at a moderate deceleration rate. Let \( d \) denote this deceleration rate and let \( l \) be the distance to the stop line. Then, assuming a response time of \( R \) seconds, a vehicle traveling at a speed of \( v \) can stop within the available distance if

\[
l > R \cdot v - \frac{1}{2} a t^2
\]

where

\[
t = \frac{v}{d},
\]

and therefore the preceding inequality can be expressed as

\[
l > R \cdot v - \frac{v^2}{2 \cdot d} .
\]  

(3.23)
Assuming one second response time and introducing the notations of the program, then, since POS(I, J) refers to the negative distance to the stop line, the vehicle stops if

\[ \text{POS}(I, J) \leq -V(I, J) + \frac{V(I, J)^2}{2 \cdot DL} \]  

(3.24)

Those vehicles that cannot stop are processed in the event scanning manner and are removed from the system. The computation of the exit time is based on the assumption that the vehicle will accelerate at a uniform rate to a limiting speed and continue at that rate until it leaves the system at the exit line.

Let \( d \) denote the distance in feet between the current position of the vehicle and the exit line. The vehicle accelerates for \( t_1 \) seconds at the rate of \( a \) feet per second squared from an initial velocity of \( v_i \) feet per second to a final velocity of \( v_f \) feet per second and continues at that rate for \( t_2 \) seconds. The acceleration period is obtained by the following formula:

\[ t_1 = \frac{v_f - v_i}{a} \]

The distance traveled during this period is expressed as:

\[ d = \frac{v_f + v_i}{2} \cdot \frac{v_f - v_i}{a} \]
or

\[ d = \frac{v_f^2 - v_i^2}{2a} \]

The remaining distance \( d_2 \) is equal to:

\[ d_2 = d - d_1 \]

or

\[ d_2 = d - \frac{v_f^2 - v_i^2}{2a} \]

The corresponding travel time is obtained by the equation below:

\[ t_2 = \frac{d}{v_f} - \frac{v_f^2 - v_i^2}{2av_f} \]

The total travel time is the sum of \( t_1 \) and \( t_2 \):

\[ t = t_1 + t_2 \]

or

\[ t = \frac{v_f - v_i}{a} + \frac{d}{v_f} - \frac{v_f^2 - v_i^2}{2av_f} \]
which may be reduced to the shorter form below:

\[ t = \frac{(v_f - v_i)^2}{2av_f} + \frac{d}{v_f} \]  \hspace{1cm} (3.25)

If the notations used in the computer program are introduced into the preceding equation then it will take the following form:

\[ t = \frac{(VLT - V(I, J))^2}{2 \cdot VLT \cdot AVA} + \frac{EXL - POS(I, J)}{VLT} \]

The exit time \( EXT \) is obtained by adding this travel time to the current value of \( TIME \):

\[ EXT = TIME + \frac{(VLT - V(I, J))^2}{2 \cdot VLT \cdot AVA} + \frac{EXL - POS(I, J)}{VLT} \]  \hspace{1cm} (3.26)

The exit time of right turning vehicles is obtained by the following expression:

\[ EXT = TIME + \frac{VLR - V(I, J)}{A(I, J)} + \frac{EXL}{VLR} \]  \hspace{1cm} (3.27)

The difference between the turning velocity \( VLR \) and current velocity \( V(I, J) \) divided by the acceleration rate gives the travel time to the stop line. The remaining travel time is obtained by dividing \( EXL \) by the turning velocity.
VLR, and thus the preceding exit time formula is obtained.

The deceleration rate assigned to the first vehicle stopped by the traffic signal is expressed by the equation below:

\[ A(I,J) = \frac{V(I,J)^2}{2 \cdot \text{POS}(I,J)} \]  \hfill (3.28)

The following vehicles are handled by the car-following subroutine.

Subroutine FA14 - Free Flow on Amber; Left Turns

Delayed left turning vehicles tend to take advantage of the caution phase and complete their turning movement. Consequently the stop-or-go decision in this subroutine is based on an assumption different from that in Subroutine FA13. It is assumed here that a "go" decision is made if the left turning vehicle can enter the intersection on amber. The exit time and deceleration rate are obtained the same way as that of the right turning vehicles.

Subroutine TR15 - Traffic Flow on Red

The acceleration rate to the first vehicle on each lane is assigned by the following formula:

\[ A(I,J) = \frac{V(I,J)^2}{2 \cdot \text{POS}(I,J)} \]  \hfill (3.29)

The following vehicles are governed by the car-following equation. Each time the current position and velocity is computed for the vehicles, the following procedures are completed:

(1) If the velocity of a vehicle is less than 2 feet per second then it is
Table 1

Sample Computer Output

<table>
<thead>
<tr>
<th>SEMI-ACTUATED SIGNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMAX= 521.  CTL= 5.0  EL=-200.0  DV=45.0  SMIN=25.0  VLT=55.0  VLR=25.0  VLL=25.0  CPT= 80</td>
</tr>
<tr>
<td>EXL= 65.0  SHOK=2.0  SD=2.6  AVA= 5.0  AVU= -7.0  ATTS= 7.5  ATTR= 9.5  ATTL= 9.5</td>
</tr>
<tr>
<td>TTEXS= 4.0  TTEXR= 4.0  TTEXL= 5.0  VTH= 2.5  AL=10.0  DL= -10.0</td>
</tr>
<tr>
<td>GMIN03= 30.0  GMIN47= 12.0  GMAX47= 40.0  ESPV= 7.0  VDL= -110.0  IG= 5  IA= 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LANE</th>
<th>JMAX</th>
<th>ACTUAL NO OF DELAY</th>
<th>DELAY</th>
<th>DELAY</th>
<th>DELAY</th>
<th>TRAVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NO. OF STOP-D PFR PFR PFR PFR TIME CARS CARS LANES CARS S.CAR DELAY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>25</td>
<td>5</td>
<td>77.0</td>
<td>3.1</td>
<td>15.4</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>59.0</td>
<td>8.4</td>
<td>14.7</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>29</td>
<td>17</td>
<td>353.6</td>
<td>12.2</td>
<td>20.8</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>22.0</td>
<td>7.3</td>
<td>22.0</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>36</td>
<td>16</td>
<td>363.6</td>
<td>10.1</td>
<td>22.7</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>52.0</td>
<td>7.4</td>
<td>10.4</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>27</td>
<td>16</td>
<td>285.0</td>
<td>10.6</td>
<td>17.8</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>19</td>
<td>14</td>
<td>211.0</td>
<td>11.1</td>
<td>15.1</td>
</tr>
</tbody>
</table>
considered to be delayed. The corresponding list of stopped delay times is incremented by the scanning period ST, which is usually one second:

\[ \text{DEL}(I, J) = \text{DEL}(I, J) + ST. \]

Also the variable \( \text{NSTO}(I, J) \) that has the initial value of zero, is set to be equal to one, thus indicating that this vehicle has been delayed.

(2) If the velocity is negative, then the required correction is made in the computed position of the vehicle, as previously described.

**Subroutine WO16 - Write Output**

This subroutine specifies what is to be printed out as the output of a simulation run. It is changed frequently to suit the objectives of a given simulation run. The type of traffic control is always identified and most of the input parameters are printed out. The tabulated results characteristically include the specified traffic volume, \( \text{JMAX}(I) \), the actual generated volume, the number of stopped vehicles, stopped delay per lanes, stopped delay per vehicles, stopped delay per stopped vehicles and travel time delay.

A typical example of the printed output is shown on Table 1.

3.8 Comparison of Five Intersection Models

The Bibliography section of this report contains nineteen entries under the heading: Simulation of Isolated Intersections. An abstract is provided for each entry. In the following discussion, the model developed in this
study (referred to as OSU model) is compared with four of the models.

At the Program Review Meeting of the Bureau of Public Roads in December, 1966, James H. Kell reported on the results of an eighteen month research project (2). The basic objective of this study was to "...examine the basic components of existing simulation models to provide knowledge to facilitate the future design of advanced simulations that will model traffic operations". After an extensive search of literature, four intersection models were found worthy of detailed examination. The others were eliminated for various reasons, such as errors in the logic, omission of significant factors of intersection operation from the model, or design for left hand traffic.

The same four models are compared here with the OSU model. The models are referred to by the name of the authors: Bleyl, Gerlough, Kell, and Lewis (3, 4, 5, 6). The result of the comparison of the components of the five models is summarized in Table 2. Considering the purpose of the models the OSU model is unique in that it is designed to be used in combination with the new field observation technique for the investigation of a specific intersection. The system updating technique of the OSU model combines the advantages of the two available techniques. The time scanning technique permits the simulation of the interaction between vehicles. In situations where the interaction is negligible, the event scanning technique is used to increase the speed of the simulation. The roadway is represented
<table>
<thead>
<tr>
<th></th>
<th>Bleyl</th>
<th>Gerlough</th>
<th>Kell</th>
<th>Lewis</th>
<th>OSU</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose of the model</strong></td>
<td>Comparison of flashing and regular operation of pretimed signals</td>
<td>Development of new criteria of signal timing—primary pretimed signals</td>
<td>Evaluation of effect of signal timing—results of pretimed signals reported</td>
<td>Development of warrants for semi-actuated signal control</td>
<td>Investigation of pretimed, semi-actuated or fully-actuated signal control at specific intersections, in combination with a new field observation technique</td>
</tr>
<tr>
<td><strong>System updating technique</strong></td>
<td>Time scanning</td>
<td>Time scanning</td>
<td>Event scanning</td>
<td>Time scanning</td>
<td>Combination of time scanning and event scanning</td>
</tr>
<tr>
<td><strong>Roadway representation</strong></td>
<td>Discrete coordinate system</td>
<td>Continuous coordinate system</td>
<td>Explicit distance has no significant role in this system</td>
<td>Continuous coordinate system</td>
<td>Continuous coordinate system</td>
</tr>
<tr>
<td><strong>Vehicle generation</strong></td>
<td>Shifted negative exponential</td>
<td>Shifted negative exponential</td>
<td>Combined shifted exponential</td>
<td>Combined binomial distribution</td>
<td>Lognormal distribution or input obtained by new field observation technique</td>
</tr>
<tr>
<td>Vehicle behavior control</td>
<td>Bleyl</td>
<td>Gerlough</td>
<td>Kell</td>
<td>Lewis</td>
<td>OSU</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------</td>
<td>----------</td>
<td>------</td>
<td>-------</td>
<td>-----</td>
</tr>
<tr>
<td>Vehicle jumps one block each second or stays stopped</td>
<td>Vehicle jumps one block each second or stays stopped</td>
<td>Uses two stimulus-response equations: car-following or free flow</td>
<td>No interaction</td>
<td>Governed by four factors: 1. spacing, 2. acceleration, 3. slowing for turns and 4. stopping for signal</td>
<td>Governed by one of several sets of free-flow and car-following equations depending on signal phase and direction of movement</td>
</tr>
<tr>
<td>Gap acceptance by left turning vehicles</td>
<td>Not available</td>
<td>Monte Carlo technique</td>
<td>Monte Carlo technique</td>
<td>Fixed value for gap acceptance</td>
<td>Fixed value</td>
</tr>
<tr>
<td>Yellow decision</td>
<td>Monte Carlo technique</td>
<td>Monte Carlo technique</td>
<td>Monte Carlo technique</td>
<td>Monte Carlo technique</td>
<td>Governed by either of two deterministic equations, depending on direction of movement</td>
</tr>
<tr>
<td>Queue discharge</td>
<td>Fixed Headways</td>
<td>Governed by one of the vehicle behavior relationships</td>
<td>Headway depends on the position of the vehicle in the queue</td>
<td>Governed by one of the vehicle behavior relationships</td>
<td>Vehicle behavior relationship governs left turns. Fixed headways for others</td>
</tr>
<tr>
<td>Measure of effectiveness of traffic control</td>
<td>Delay</td>
<td>Delay</td>
<td>Delay</td>
<td>Delay</td>
<td>Delay and stopped vehicles</td>
</tr>
</tbody>
</table>
in the OSU model as a continuous coordinate system which permits greater accuracy than the discrete coordinate system. The latter method divides the roadway into blocks of equal length and during one scanning period the vehicles move at a rate of one block, or remain stationary. All models generate vehicles by some mathematical distribution function. The OSU model is usually used with vehicle arriving time data obtained from field observations, although a random arriving time generator subroutine is available. While most models use the Monte Carlo technique to govern gap acceptance and yellow decision, the OSU model handles both problems by deterministic equations. Not enough is known about the gap and lag acceptance situation to make a strong point for either method. Not one of the models tested by Kell agreed well with the field data on both lag and gap acceptance. Also, data collected at one location do not agree closely with data from other locations. Gap acceptance characteristics at a given location vary with changing traffic characteristics, as it was shown by Rorbech (7) and Wagner (8). The same appears to be true in the amber decision problem. In a study of the yellow decision problem Herman et al. compared probability of stopping curves developed by Webster with the curves based on their own observations and found them to differ considerably (9, 10). Consequently the deterministic handling of both situations by the OSU model seemed to be more justifiable than developing a probability distribution function from a limited amount of data and expecting it to be generally applicable.
The Bleyl and the Kell models handle the queue discharge by assigning a headway to each delayed vehicle. This is hardly applicable to left turning vehicles but is a reasonable method of handling straight through or right turning vehicles. Vehicle behavior relationships are used by the Gerlough and the Lewis models. The OSU model combines the two methods. Fixed headways are assigned for straight through and right turning vehicles but stimulus–response equations govern vehicles in a left turning queue. Delay is used as a measure of effectiveness by all models.
NOTATIONS USED IN THE COMPUTER PROGRAM

<table>
<thead>
<tr>
<th>Notation;</th>
<th>Meaning:</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>Beginning of amber on Lanes 0 to 3, measured in seconds from beginning of cycle.</td>
<td>Pretimed signal.</td>
</tr>
<tr>
<td>A4</td>
<td>Same as preceding but on Lanes 4 to 7.</td>
<td>Pretimed signal.</td>
</tr>
<tr>
<td>A(I, J)</td>
<td>Acceleration rate of Vehicle J on Lane I, in feet per second per second (ft/sec^2).</td>
<td>Recomputed during each scanning interval.</td>
</tr>
<tr>
<td>AL</td>
<td>Limit of vehicle accelerating performance. Values up to 10 ft/sec^2 have been used.</td>
<td>Same for all vehicles.</td>
</tr>
<tr>
<td>ARR(I, J)</td>
<td>Arriving time of Vehicle J on Lane I, in seconds.</td>
<td>Input data or generated internally.</td>
</tr>
<tr>
<td>ATTL</td>
<td>Average travel time of an undelayed left-turning vehicle from EL to CPT, in seconds.</td>
<td>Computed.</td>
</tr>
<tr>
<td>ATTR</td>
<td>Average travel time of a right-turning vehicle from EL to EXL, in seconds.</td>
<td>Computed.</td>
</tr>
<tr>
<td>ATTS</td>
<td>Average travel time of a straight-through vehicle from EL to EXL, in seconds.</td>
<td>Computed.</td>
</tr>
<tr>
<td>AVA</td>
<td>Average acceleration rate, in ft/sec^2.</td>
<td>Used in free-flow situations.</td>
</tr>
<tr>
<td>AVD</td>
<td>Average rate of deceleration, in ft/sec^2.</td>
<td>Used in free-flow situations.</td>
</tr>
<tr>
<td>BGT0</td>
<td>Beginning of green phase on Lanes 0 to 3. Measured in seconds from beginning of simulation run.</td>
<td>Semi-actuated and fully-actuated signals.</td>
</tr>
<tr>
<td>Notation:</td>
<td>Meaning:</td>
<td>Remarks:</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>BLOK(I)</td>
<td>Indicator shows the time until which the path of left-turning vehicles is blocked by through traffic on Lane I, in seconds.</td>
<td></td>
</tr>
<tr>
<td>CPT</td>
<td>Exit line for left-turning vehicles, measured in feet from the stop line. A left-turning vehicle had cleared the conflict area when it reached this line.</td>
<td>Measured at site.</td>
</tr>
<tr>
<td>CYCLE</td>
<td>Cycle length, measured in seconds from the beginning of green phase on Lane 0 to the end of the red phase on Lane 0.</td>
<td>Pretimed signals.</td>
</tr>
<tr>
<td>D(I)</td>
<td>Sum of the travel time delay of all vehicles on Lane I, in seconds. Travel time delay is the difference between actual travel time and the travel time of an undelayed vehicle.</td>
<td>Part of the output.</td>
</tr>
<tr>
<td>DEL(I, J)</td>
<td>Stopped delay time of Vehicle J on Lane I, in seconds. A vehicle is considered stopped when its velocity is reduced to 2 ft/sec.</td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>Limit of decelerating performance of any vehicle. Usually defined as 10 ft/sec².</td>
<td></td>
</tr>
<tr>
<td>DPSV(I)</td>
<td>Average stopped delay time per stopped vehicles on Lane I, in seconds per vehicle.</td>
<td>Part of output.</td>
</tr>
<tr>
<td>DPV(I)</td>
<td>Average stopped delay time per all vehicles on Lane I, in seconds per vehicle.</td>
<td>Part of output.</td>
</tr>
<tr>
<td>DSUM(I)</td>
<td>Sum of stopped delay time in seconds on Lane I.</td>
<td>Part of output.</td>
</tr>
<tr>
<td>DV</td>
<td>Desired velocity of straight-through vehicles, from data. In ft/sec. Also approach speed of all vehicles.</td>
<td></td>
</tr>
<tr>
<td>EL</td>
<td>Length of the approach lane, in feet.</td>
<td></td>
</tr>
<tr>
<td>ESPV</td>
<td>Unit extension time in seconds.</td>
<td>Semi-actuated and fully-actuated signals.</td>
</tr>
<tr>
<td>Notation:</td>
<td>Meaning:</td>
<td>Remarks:</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>EXL</td>
<td>Exit line for straight-through and right-turning vehicles, in feet. Measured from the stop line.</td>
<td>Measured at site.</td>
</tr>
<tr>
<td>EXT(I,J)</td>
<td>Exit time of Vehicle J on Lane I, in seconds.</td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Beginning of green phase on Lanes 4 to 7, measured in seconds from the beginning of current cycle.</td>
<td>Pre-timed signal.</td>
</tr>
<tr>
<td>GAP</td>
<td>Difference in the arriving time of two successive vehicles to the conflict point, as observed by a left-turning vehicle, in seconds.</td>
<td></td>
</tr>
<tr>
<td>GMAX03</td>
<td>Maximum green phase on Lanes 0 to 3, in seconds.</td>
<td>Fully-actuated signals.</td>
</tr>
<tr>
<td>GMAX47</td>
<td>Maximum green phase on Lanes 4 to 7, in seconds.</td>
<td>Semi-actuated and fully-actuated signals.</td>
</tr>
<tr>
<td>GMIN03</td>
<td>Minimum green phase on Lanes 0 to 3, in seconds.</td>
<td>Semi-actuated and fully-actuated signals.</td>
</tr>
<tr>
<td>GMIN47</td>
<td>Minimum green phase on Lanes 4 to 7, in seconds.</td>
<td>Semi-actuated and fully-actuated signals.</td>
</tr>
<tr>
<td>I</td>
<td>Index, ranging from 0 to 7, identifies lanes.</td>
<td></td>
</tr>
<tr>
<td>IA</td>
<td>Amber phase in seconds.</td>
<td>All signals.</td>
</tr>
<tr>
<td>IG</td>
<td>Intergreen period, in seconds.</td>
<td>All signals.</td>
</tr>
<tr>
<td>J</td>
<td>Index, ranging in value from 1 to JMAX(I), identifies vehicles in order of arrival to the system.</td>
<td></td>
</tr>
<tr>
<td>JMAX(I)</td>
<td>Specifies the maximum number of vehicles that may enter Lane I during simulation run.</td>
<td></td>
</tr>
<tr>
<td>Notation:</td>
<td>Meaning:</td>
<td>Remarks:</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>KSUM(I)</td>
<td>Counter; indicates the number of vehicles that have entered the system so far.</td>
<td></td>
</tr>
<tr>
<td>NGAP(I, J)</td>
<td>This variable has an initial value of zero to identify left-turning vehicles that have not made a decision yet regarding gap acceptance. It is set equal to one when gaps are evaluated and rejected.</td>
<td></td>
</tr>
<tr>
<td>NNN</td>
<td>Number of columns, beginning with column zero, in the array assigned to a double subscripted variable by a dimension statement.</td>
<td>Initialization</td>
</tr>
<tr>
<td>NNWV</td>
<td>Initial value is zero. It is set equal to one to indicate that a vehicle has arrived on the minor road near the end of the green phase and is not expected to clear the intersection on the current green phase.</td>
<td>Semi-actuated signal</td>
</tr>
</tbody>
</table>
| NSPF(I)  | Signal phase indicator:  
NSPF(I) = -1 ; red phase  
NSPF(I) = 0 ; amber phase  
NSPF(I) = 1 ; first second of green phase - further explanation in text  
NSPF(I) = 2 ; green phase | |
| NSTOP(I, J)| Initial value is zero. Set equal to one when the velocity falls below 2 ft/sec to indicate that Vehicle J on Lane I has been subjected to delay. | |
| NSV(I)   | The number of delayed vehicles on Lane I, obtained by summing NSTOP(I, J), for J ranging from one to JMAX(I), at the end of the simulation run. | Part of output. |
| NTF(I, J) | Turn indicator. Assigned to each vehicle during updating of vehicle list.  
NTF(I, J) = -1 ; left-turn  
NTF(I, J) = 0 ; right-turn  
NTF(I, J) = 1 ; straight-through | |
<table>
<thead>
<tr>
<th>Notation:</th>
<th>Meaning:</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVDL(I,J)</td>
<td>Initial value is zero. Set at one when Vehicle J has been detected by the vehicle detector.</td>
<td>Semi-actuated or fully-actuated signal.</td>
</tr>
<tr>
<td>NVEX(I)</td>
<td>Counter of vehicles exiting the system on Lane I.</td>
<td></td>
</tr>
<tr>
<td>NVP(I)</td>
<td>Counter of vehicles currently present on Lane I.</td>
<td></td>
</tr>
<tr>
<td>NWV</td>
<td>Initial value is zero. Set at one when vehicle arriving on amber or red has been detected on minor road.</td>
<td>Semi-actuated signal.</td>
</tr>
<tr>
<td>POS(I,J)</td>
<td>Position of vehicle expressed in feet in relation to the stop line. Negative distance refers to a vehicle approaching the stop line, positive distance indicates that the vehicle has crossed the stop line.</td>
<td></td>
</tr>
<tr>
<td>PRT(I)</td>
<td>Percentage of right-turning vehicles on Lane I.</td>
<td>Input.</td>
</tr>
<tr>
<td>R0</td>
<td>Beginning of red phase on Lanes 0 to 3, expressed in seconds from beginning of cycle.</td>
<td>Pre-timed signal.</td>
</tr>
<tr>
<td>R4</td>
<td>Beginning of red phase on Lanes 4 to 7, expressed in seconds from beginning of cycle.</td>
<td>Pre-timed signal.</td>
</tr>
<tr>
<td>SD</td>
<td>Starting delay of the first vehicle of a delayed queue. Defined as the difference in seconds between the beginning of the green phase and the start of the vehicle. Typical value is 2.6 seconds.</td>
<td></td>
</tr>
<tr>
<td>SHOK</td>
<td>The difference in seconds between the movement of two consecutive vehicles of a starting queue. Typical value used in the program is 2 seconds.</td>
<td></td>
</tr>
<tr>
<td>SMIN</td>
<td>Minimum spacing between vehicles in a stopped queue. Typical value used in the program is 25 feet.</td>
<td></td>
</tr>
<tr>
<td>Notation</td>
<td>Meaning</td>
<td>Remarks</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>ST</td>
<td>Scanning time. One second is the commonly used value in this program.</td>
<td></td>
</tr>
<tr>
<td>START</td>
<td>The simulated time at the beginning of a simulation run. Usually specified at zero seconds.</td>
<td>Input</td>
</tr>
<tr>
<td>TIME</td>
<td>Time index shows current simulated time in seconds.</td>
<td></td>
</tr>
<tr>
<td>TL</td>
<td>Travel time of a left-turning vehicle to the conflict point from the current position, in seconds.</td>
<td></td>
</tr>
<tr>
<td>TLAG</td>
<td>The difference in seconds between the arriving time of a left-turning vehicle and the arriving time of a conflicting vehicle to the conflict point.</td>
<td></td>
</tr>
<tr>
<td>TTEXL</td>
<td>Average travel time of a left-turning vehicle from the stop line to CPT, in seconds.</td>
<td></td>
</tr>
<tr>
<td>TTEXR</td>
<td>Average travel time of a right-turning vehicle from the stop line to EXL, in seconds.</td>
<td></td>
</tr>
<tr>
<td>TTEXS</td>
<td>Average travel time of a straight-through vehicle from the stop line to EXL, in seconds.</td>
<td></td>
</tr>
<tr>
<td>V(I, J)</td>
<td>Velocity of Vehicle J on Lane I in ft/sec.</td>
<td></td>
</tr>
<tr>
<td>VDL</td>
<td>Position of vehicle detector, defined as the negative distance in feet to the stop line.</td>
<td>Semi-actuated and fully-actuated signals.</td>
</tr>
<tr>
<td>VLL</td>
<td>Average left-turning velocities, in ft/sec.</td>
<td></td>
</tr>
<tr>
<td>VLR</td>
<td>Average right-turning velocities, in ft/sec.</td>
<td></td>
</tr>
<tr>
<td>VLT</td>
<td>Maximum velocity of a straight-through vehicle in ft/sec.</td>
<td></td>
</tr>
<tr>
<td>Notation</td>
<td>Meaning</td>
<td>Remarks</td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>VTH</td>
<td>Velocity threshold. Defined as the minimum difference between desired velocity and actual velocity that causes the driver to begin corrective acceleration. Common value used here is 2.5 ft/sec.</td>
<td></td>
</tr>
</tbody>
</table>

The following notations refer to intermediate values arrived at during computation. They are necessary for temporary storage of such intermediate values but have no significant role in the understanding of the program.

AA, AB, C, CK, D1, DT, K, L, N, PT, T, TF, TL, VT, XT.

The following notations are used in the traffic generator subroutine only:

- **F(I, L)**: The probability of the occurrence of a headway less than L seconds.
- **HW(I, J)**: The headway of Vehicle J on Lane I, in seconds.
- **NUM**: The number of class intervals used in the computation of the headway distribution.
- **TH(I, L)**: The theoretical number of vehicles having headways of L seconds on Lane I.
- **THF(I, L)**: The probability of a headway occurring between L and L-1 seconds.
- **TIMEL**: The time limit on the simulation run.
- **TIMET**: Counter indicates the arriving time of the latest vehicle. Subroutine is shut off when TIMET exceeds TIMEL.
- **VARY(I)**: Estimate of the variance, based on the traffic volume on Lane I.
- **VOL(I)**: Traffic volume on Lane I, expressed in vehicles per hour.
Notation:   Meaning:

YMEAN(I)  Estimate of mean on Lane I, depending on VOL(I).

The notations S, SLN, and Z refer to intermediate values arrived at during computation.
REFERENCES


81
CHAPTER FOUR

TESTING OF THE NEW TECHNIQUE

4.1 Scope of the Test

The digital simulation model is designed to be employed in conjunction with the split-image camera in the study of signalized intersections. The technique has been tested at the intersection of State Route 3 and State Route 161. The test has achieved the following three objectives:

1. Simultaneous traffic data on all four approaches to the intersection have been obtained by the split-image camera,

2. The simulation model has been validated by thorough comparison of simulated and observed situations,

3. The application of the technique to the investigation of various traffic control elements in relation to their effect on the traffic flow has been demonstrated.

4.2 Results of the Test

Approximately sixteen minutes of traffic data were obtained on two 100 foot rolls of 70 mm film and used in the preparation of the traffic input for the simulation runs. The input consisted of the arriving times, average approach speeds, average turning speeds, and turning volumes. The intersection
is controlled by a semi-actuated traffic signal. Traffic control input included the minimum and maximum green phases on State Route 3; the minimum green phase, the unit extension time and the location of the detectors on State Route 161; the yellow phase and the all-red period for both highways.

The results of the simulation runs were the subject of intensive comparative analysis. The details are shown on Tables 3, 4, and 5. The first two tables show each of the two films compared with the results of the simulation runs separately. The simulated results represent the arithmetic mean of three simulation runs. The agreement between the observed and the simulated conditions is quite close. In both cases the simulated total stopped delay time is within eight per cent of the observed stopped delay time. However, the difference is practically eliminated when the data from the two films are combined on Table 5. Comparing the 2940 seconds stopped delay time observed during the total 16 minutes study period with the 2879 seconds obtained through simulation, the difference is found to be 2.1 per cent only. The difference between the simulated and the observed average stopped delays per stopped vehicles is one second. The agreement becomes even better when stopped delays per all vehicles are compared; observed and simulated delays match on State Route 3; the difference is 0.4 seconds on State Route 161; and the difference considering the whole intersection is 0.3 seconds.

It can be concluded that the operation of the intersection has been successfully simulated when evaluated in terms of stopped time delay suffered by the traffic during the 16 minutes study period.
### Table 3

**Results of Simulation Compared with Data**

**Film D3A - 446 Seconds**

<table>
<thead>
<tr>
<th>Roadway:</th>
<th>SR 3</th>
<th>SR 161</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of vehicles during study period</strong></td>
<td>46</td>
<td>51</td>
<td>97</td>
</tr>
<tr>
<td><strong>No. of stopped vehicles:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>13</td>
<td>38</td>
<td>51</td>
</tr>
<tr>
<td>Simulated</td>
<td>10</td>
<td>47</td>
<td>57</td>
</tr>
<tr>
<td><strong>Stopped delay time in seconds:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>140</td>
<td>924</td>
<td>1064</td>
</tr>
<tr>
<td>Simulated</td>
<td>94</td>
<td>1055</td>
<td>1149</td>
</tr>
<tr>
<td><strong>Stopped delay per stopped vehicles in seconds:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>10.8</td>
<td>24.3</td>
<td>20.9</td>
</tr>
<tr>
<td>Simulated</td>
<td>9.4</td>
<td>22.5</td>
<td>20.2</td>
</tr>
<tr>
<td><strong>Difference in seconds:</strong></td>
<td>1.4</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Stopped delay per all vehicles, in seconds:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>3.0</td>
<td>18.1</td>
<td>11.0</td>
</tr>
<tr>
<td>Simulated</td>
<td>2.0</td>
<td>20.7</td>
<td>11.8</td>
</tr>
<tr>
<td><strong>Difference in seconds:</strong></td>
<td>1.0</td>
<td>2.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Table 4

Results of Simulation Compared with Data
Film D3D - 521 Seconds

<table>
<thead>
<tr>
<th>Roadway:</th>
<th>SR 3</th>
<th>SR 161</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of vehicles during study period</td>
<td>64</td>
<td>89</td>
<td>153</td>
</tr>
<tr>
<td>No. of stopped vehicles:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data:</td>
<td>26</td>
<td>56</td>
<td>82</td>
</tr>
<tr>
<td>Simulated:</td>
<td>24</td>
<td>57</td>
<td>81</td>
</tr>
<tr>
<td>Stopped delay time in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data:</td>
<td>361</td>
<td>1515</td>
<td>1876</td>
</tr>
<tr>
<td>Simulated:</td>
<td>409</td>
<td>1321</td>
<td>1730</td>
</tr>
<tr>
<td>Stopped delay per stopped vehicles in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data:</td>
<td>14.9</td>
<td>27.0</td>
<td>22.9</td>
</tr>
<tr>
<td>Simulated:</td>
<td>17.0</td>
<td>23.2</td>
<td>21.4</td>
</tr>
<tr>
<td>Difference in seconds</td>
<td>3.1</td>
<td>3.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Stopped delay per all vehicles, in seconds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data:</td>
<td>5.7</td>
<td>17.0</td>
<td>12.3</td>
</tr>
<tr>
<td>Simulated:</td>
<td>6.4</td>
<td>14.9</td>
<td>11.3</td>
</tr>
<tr>
<td>Difference in seconds:</td>
<td>0.7</td>
<td>2.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Table 5

Results of Simulation Compared with Data
Combined Films D3A and D3D
16 Minutes and 7 Seconds

<table>
<thead>
<tr>
<th>Roadway</th>
<th>SR 3</th>
<th>SR 161</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of vehicles during study period:</td>
<td>110</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>No. of stopped vehicles:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>39</td>
<td>94</td>
<td>133</td>
</tr>
<tr>
<td>Simulated</td>
<td>34</td>
<td>104</td>
<td>138</td>
</tr>
<tr>
<td>Stopped delay time in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>501</td>
<td>2439</td>
<td>2940</td>
</tr>
<tr>
<td>Simulated</td>
<td>503</td>
<td>2376</td>
<td>2879</td>
</tr>
<tr>
<td>Difference in per cent:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0.4</td>
<td>2.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay per stopped vehicles in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>12.8</td>
<td>25.9</td>
<td>22.1</td>
</tr>
<tr>
<td>Simulated</td>
<td>14.8</td>
<td>22.8</td>
<td>20.8</td>
</tr>
<tr>
<td>Difference in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>2.0</td>
<td>3.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay per all vehicles, in seconds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>4.6</td>
<td>17.4</td>
<td>11.8</td>
</tr>
<tr>
<td>Simulated</td>
<td>4.6</td>
<td>17.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Difference in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Simulated</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Semi-actuated signals can be used to advantage at locations where traffic flow on the minor street is relatively low but fluctuates widely. Flow in the major direction is stopped only by the presence of traffic demand on the minor street. The semi-actuated signal at the study site has been in operation since 1950. The traffic condition appears to have changed since then. According to the 1964 traffic survey the average daily traffic on State Route 3 is 7130 vehicles north of the intersection and 5860 vehicles south of the intersection. On State Route 161 the average daily traffic is 8550 vehicles west of the intersection and 7380 vehicles on the east approach (1). The distribution of the average daily traffic on the two highways is similar to the sample distribution obtained from the films. Let it be assumed that the traffic volumes recorded on Film D3D are typical of the period of the day for which the traffic signal is to be timed. By varying one parameter and holding all others constant during repeated simulation runs, the effect of this parameter on traffic delay can be shown and desirable changes in the timing of the signal can be identified.

Under prevailing conditions the major direction (SR 3) is favored by the traffic control as it is indicated by both the total stopped delay time and the ratio of the delay per vehicles as shown in Tables 3, 4, and 5. Continuous demand on the minor road may cause the signal to operate like a pretimed signal, providing a minimum green phase of 35 seconds for the major direction and a maximum green phase of 40 seconds for the minor flow. Even in this case State Route 3 receives approximately 48 per cent of the total green time, while it carries less than 42 per cent of the traffic. However, in practice the
minor direction does not always receive the maximum green phase, since the right-of-way is transferred as soon as a headway greater than the 6 second unit extension time is detected. For this reason the extension of the maximum green phase on State Route 161 is not expected to improve the situation. The reduction of the minimum green phase in the major direction appears to be a more promising improvement. Therefore the minimum green phase on State Route 3 is varied and the effect on delay is investigated. The results of the simulation runs are shown in Table 6. Two reduced minimum green phases are tested: 30 seconds and 25 seconds. The reduction to 30 seconds increases the delay on State Route 3 and reduces the delay on State Route 161. The combined delay shows a reduction of 0.8 seconds per stopped vehicle and 0.5 seconds per all vehicles for the intersection. The total number of stopped vehicles remains virtually unchanged. A further reduction of 5 seconds from the minimum green phase increases the number of stopped vehicles. However, the delay per stopped vehicles is reduced by 2.4 seconds and the delay per all vehicles is again reduced 0.5 seconds. In conclusion, the reduction of the minimum green phase to 30 or 25 seconds increases somewhat the delay on State Route 3 but results in a net reduction when the whole intersection is considered.

Next, the effect of the unit extension time was investigated. A longer unit extension time tolerates a large gap in the minor flow before the right-of-way is transferred to the major flow. Consequently an increased unit extension time is expected to decrease traffic delay on State Route 161 while an extension time shorter than the prevailing 6 seconds should result in increased delay.
Table 6

Effect of Major Roadway Minimum Green on Traffic Delay
Data: Film D3D - 521 Seconds

<table>
<thead>
<tr>
<th>Minimum Green on SR3 seconds</th>
<th>Roadway:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SR 3</td>
<td>SR 161</td>
<td>Combined</td>
</tr>
<tr>
<td>No. of vehicles during study period:</td>
<td>64</td>
<td>89</td>
<td>153</td>
</tr>
<tr>
<td>No. of stopped vehicles:</td>
<td>24</td>
<td>57</td>
<td>81</td>
</tr>
<tr>
<td>35</td>
<td>29</td>
<td>51</td>
<td>80</td>
</tr>
<tr>
<td>30</td>
<td>31</td>
<td>55</td>
<td>86</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay time in seconds:</td>
<td>409</td>
<td>1321</td>
<td>1730</td>
</tr>
<tr>
<td>35</td>
<td>516</td>
<td>1129</td>
<td>1645</td>
</tr>
<tr>
<td>30</td>
<td>574</td>
<td>982</td>
<td>1557</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay per stopped vehicles in seconds:</td>
<td>17.0</td>
<td>23.2</td>
<td>21.4</td>
</tr>
<tr>
<td>35</td>
<td>17.8</td>
<td>22.2</td>
<td>20.6</td>
</tr>
<tr>
<td>30</td>
<td>18.5</td>
<td>17.8</td>
<td>18.2</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay per all vehicles in seconds:</td>
<td>6.4</td>
<td>14.9</td>
<td>11.3</td>
</tr>
<tr>
<td>35</td>
<td>8.1</td>
<td>12.7</td>
<td>10.8</td>
</tr>
<tr>
<td>30</td>
<td>9.0</td>
<td>11.0</td>
<td>10.2</td>
</tr>
</tbody>
</table>
The question is what the net effect on the whole intersection is going to be. In Table 7 the effect of a 1 second increase and a 1 second decrease is shown. The 7 second extension time resulted in approximately the same reduction in the total delay that the 25 second minimum green phase was found to produce, as shown in Table 6. A closer investigation reveals that considerably fewer cars are stopped in this case, but for an average of 21.4 seconds as opposed to 18.2 seconds, as shown in Table 7. In a full scale intersection study this might be a significant point to be considered. A cost function expressing the vehicle operation cost associated with stopped delay time is likely to include an item which is constant for each stop regardless of the extent of the delay. An economic analysis based on such a cost function would favor the improvement through increased unit extension time over the decreased minimum green phase.

The reduction of the minimum green phase to 25 seconds on State Route 3 results in a 10 per cent reduction in the stopped delay at the intersection. The reduction in delay affected by the increased unit extension time is 8.7 per cent. When both changes are introduced simultaneously the total stopped time delay is reduced by 17.5 per cent or nearly the sum of the reductions achieved separately by each change in the signal timing. The detailed results of the latter improvement in the timing of the semi-actuated signal are shown in Table 8, referred to as improved semi-actuated signal.

Results of the 1964 traffic survey indicate that, considering the traffic distribution, the semi-actuated traffic signal is not well suited to the control of this intersection. Although methods have been demonstrated on the preceding pages
Table 7

Effect of Unit Extension Time on Traffic Delay
Data: Film D3D - 521 Seconds

<table>
<thead>
<tr>
<th>Unit extension time in seconds</th>
<th>Roadway:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SR 3</td>
<td>SR 161</td>
<td>Combined</td>
</tr>
<tr>
<td>No. of vehicles during study period:</td>
<td></td>
<td>64</td>
<td>89</td>
<td>153</td>
</tr>
<tr>
<td>No. of stopped vehicles:</td>
<td></td>
<td>22</td>
<td>52</td>
<td>74</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>24</td>
<td>57</td>
<td>81</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>28</td>
<td>70</td>
<td>98</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay time in seconds:</td>
<td></td>
<td>432</td>
<td>1146</td>
<td>1579</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>409</td>
<td>1321</td>
<td>1730</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>302</td>
<td>1692</td>
<td>1994</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay per stopped vehicles in seconds:</td>
<td></td>
<td>19.6</td>
<td>22.0</td>
<td>21.4</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>17.0</td>
<td>23.2</td>
<td>21.4</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>8.0</td>
<td>24.2</td>
<td>20.4</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopped delay per all vehicles in seconds:</td>
<td></td>
<td>6.6</td>
<td>12.9</td>
<td>10.3</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>6.4</td>
<td>14.9</td>
<td>11.3</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>4.7</td>
<td>19.0</td>
<td>13.0</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 8
Comparison of Three Types of Traffic Controls
Data: Film D3D - 521 Seconds

<table>
<thead>
<tr>
<th>Traffic Control</th>
<th>SR 3</th>
<th>SR 161</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of vehicles during study period:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR 3</td>
<td>SR 161</td>
<td>Combined</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>89</td>
<td>153</td>
<td></td>
</tr>
<tr>
<td>No. of stopped vehicles:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-actuated:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>present</td>
<td>24</td>
<td>57</td>
<td>81</td>
</tr>
<tr>
<td>improved</td>
<td>27</td>
<td>51</td>
<td>78</td>
</tr>
<tr>
<td>Pretimed:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50/50 split</td>
<td>29</td>
<td>52</td>
<td>81</td>
</tr>
<tr>
<td>42/58 split</td>
<td>35</td>
<td>41</td>
<td>76</td>
</tr>
<tr>
<td>Fully-actuated:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>54</td>
<td>89</td>
</tr>
<tr>
<td>Stopped delay time in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-actuated:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>present</td>
<td>409</td>
<td>1321</td>
<td>1730</td>
</tr>
<tr>
<td>improved</td>
<td>508</td>
<td>920</td>
<td>1428</td>
</tr>
<tr>
<td>Pretimed:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50/50 split</td>
<td>501</td>
<td>893</td>
<td>1394</td>
</tr>
<tr>
<td>42/58 split</td>
<td>608</td>
<td>772</td>
<td>1380</td>
</tr>
<tr>
<td>Fully-actuated:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>388</td>
<td>609</td>
<td>997</td>
</tr>
<tr>
<td>Stopped delay time per stopped vehicles in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-actuated:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>present</td>
<td>17.0</td>
<td>23.2</td>
<td>21.4</td>
</tr>
<tr>
<td>improved</td>
<td>18.8</td>
<td>18.0</td>
<td>18.3</td>
</tr>
<tr>
<td>Pretimed:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50/50 split</td>
<td>17.3</td>
<td>17.2</td>
<td>17.2</td>
</tr>
<tr>
<td>42/58 split</td>
<td>17.4</td>
<td>18.8</td>
<td>18.2</td>
</tr>
<tr>
<td>Fully-actuated:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.1</td>
<td>11.3</td>
<td>11.2</td>
</tr>
</tbody>
</table>
Table 8 - Continued

<table>
<thead>
<tr>
<th>Traffic Control</th>
<th>Roadway:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SR 3</td>
<td>SR 161</td>
</tr>
<tr>
<td>Stopped delay time per stopped vehicles in seconds:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-actuated:</td>
<td>present</td>
<td>6.4</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>improved</td>
<td>7.9</td>
<td>10.3</td>
</tr>
<tr>
<td>Pretimed:</td>
<td>50/50 split</td>
<td>7.8</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>42/58 split</td>
<td>9.5</td>
<td>8.7</td>
</tr>
<tr>
<td>Fully-actuated:</td>
<td></td>
<td>6.1</td>
<td>6.8</td>
</tr>
</tbody>
</table>
that result in a significant reduction of delay, other types of traffic control are expected to perform even better. The efficiency of the semi-actuated signal control is compared with the efficiency of the fully-actuated and the pretimed signal control and the results are shown in Table 8. The fully-actuated signal is timed to have 12 second minimum green and 40 second maximum green phase on both highways. The vehicle detectors are located 110 feet from the stop line. The pretimed signal is tested with two designs, namely with 50/50 split of the green time and with 42/58 split. The latter split is based on the distribution of the traffic volumes on the two highways. The cycle is 60 seconds in both cases. The delay obtained by the pretimed signals is much lower than that obtained by the semi-actuated signal at the present, and slightly lower than that obtained by the improved timing of the semi-actuated signal. The total delay is not reduced significantly by changing the split from 50/50 to 42/58. However, the number of stopped cars is reduced and is more evenly distributed on the two roadways. It can be concluded that under the condition represented by the traffic data on film D3D, the pretimed signal is more efficient than the semi-actuated signal. A further drastic reduction in delay is observed when the intersection is controlled by a fully-actuated signal. The average stopped time delay per vehicles is reduced from 11.3 seconds to 6.5 seconds. This represents a very significant reduction of 42.5 per cent. In the Appendix, current signal timing practices in Ohio are reviewed and it is noted that the trend is to phase out of service the semi-actuated signals in favor of the fully-actuated signals. The proportion of expected saving in stopped time delay suggested by the information in Table 8 and the corresponding saving in transportation cost provide strong support for this policy.
REFERENCES

CHAPTER FIVE

SUMMARY

5.1 Description of the Study.

The function of a traffic signal is to alternate right-of-way for conflicting traffic movements. The efficiency in performing this function depends essentially on the relationship between signal timing and traffic flow characteristics. For the lack of more sophisticated measuring devices, manually conducted traffic studies generally precede the installation of traffic signals. Once the signal has been installed, continued attention is by and large limited to the maintenance of the hardware. Traffic characteristics change over the years. Manpower requirements and costs of manually conducted field studies, however, do not permit regularly conducted intersection studies. In addition, the number of parameters that can be recorded manually is generally limited. At higher traffic volumes the method becomes very troublesome and quite unreliable. Delay data are especially difficult to obtain. The need for a more efficient and accurate field observation method is obvious.

The timing of a traffic signal must be set for the particular traffic characteristics of an intersection. A variety of rules are in use today for determining optimal signal settings but engineering judgment remains to play an important role in signal timing. Because of the great complexity of traffic movements at
intersections and the limitations of the data obtained by manual studies, signal timing often becomes a "trial and error" process.

Similar problems exist in the decisions regarding the application of traffic signals at intersections previously unsignalized. Warrants have been developed for the application of pretimed signals but, as yet, no specific warrants have been established for detector actuated signals. At present, engineering judgment determines whether actuation controlled signals should be installed. It is evident that the application and the timing of traffic signals today involve an undesirable amount of experimentation with the operating signal. There is a need for the development of a tool that would reduce or eliminate the reliance on field experimentation.

The objectives of this dissertation were twofold: (1) to develop more accurate and efficient methods of field measurements at intersections, and (2) to develop a simulation model that could be used to predict the effect of alternative traffic control schemes on delay.

Two field data collecting methods were developed. The first method involves a 16 mm Bolex time-lapse camera and a television camera installed on a rotating platform over the center of the intersection. The cameras and the rotating platform are remote controlled by the operator, who bases his decisions on the traffic conditions observed on the television receiver. At a rate of one frame per second, over one hour of data can be recorded on a 100 foot roll. The data can be reduced by a Kodak Analyzer. The second method is based on a 70 mm Maurer P.2 reconnaissance camera, also suspended over the center of
the intersection. This camera has been transformed into a split-image camera by a set of four mirrors. All four approaches are brought into the field of vision of the camera. Simultaneous traffic data can thus be obtained on all four approaches. At one frame per second, approximately ten minutes of data can be recorded on a 100 foot role of film. A data chamber included in the photographs indicates the signal phases. A rear projection console was built and a slide projector modified for the analysis of the 70 mm film. The film furnishes a permanent record of all visual aspects of the traffic flow on all approach lanes. Stopped time delay and the number of stopped vehicles provide a quantitative description of the efficiency of the intersection operation under prevailing conditions. A simulation model was developed by which the effect of various changes in the intersection control can be predicted.

The model is a computer program which, when given a set of input parameters related to the intersection, will manipulate the components in a manner to act comparably to that of a real intersection. The components of the intersection include the principal geometric features of the intersection, the operating features of the traffic signal, and such basic features of the traffic flow as volume distribution, vehicle performance, and driver decision in a number of situations. The properties of the components are represented by mathematical equations, variables or statistical distributions. The time scanning technique is used to update the system. At each time increment the position and velocity of each vehicle is re-examined and a new acceleration rate is computed accordingly. Also, the list of vehicles is updated to account for newly arrived or
exited vehicles. When appropriate, the traffic signal is reset. A record is compiled containing the number of delayed vehicles, stopped time delay and travel time delay for all vehicles over a given period of time. The simulated intersection can have three or four legs intersecting at any angle. Each leg has two approach lanes. The left hand lane is reserved for left turning traffic. Any one of the approach lanes may be omitted. The introduction of a third approach lane requires only minor changes in the program. The behavior of a single vehicle is controlled by one of five subroutines depending on the signal phase and on the direction of travel. Vehicles in a platoon are controlled by the car-following subroutines, assuring a minimum spacing between vehicles which depends on speed. Left turns are negotiated if a gap in the opposite traffic stream larger than a specified minimum is available. The flexibility of the model permits the simulation of pretimed, semi-traffic-actuated, or fully-traffic-actuated signals by interchangeable signal subroutines.

The development of a model as complex as required for the intersection situation is an involved process. An initial understanding of the system to be simulated is necessary in order to separate those elements of the real system that are critical for the purpose of the study. The development of the model, however, in a sense becomes a learning process. Much is discovered about the interrelationships between various parts of the system through initial failures of the model. Prolonged, problem-free operation on the other hand indicates that the structure of the model is basically sound. The final test involved the comparison of the results of simulation with field data obtained at the intersection of
State Route 3 and State Route 161, Columbus, Ohio. The traffic input data were provided by two 100 foot rolls of 70 mm film. The parameters used included arriving times, turning movements and approach speeds. The timing of the simulated traffic signal was based on design values identical to that of the semi-actuated signal at the study site. The average delay values obtained by repeated simulation runs were in very close agreement with the observed delays. Once the model was thus adapted to the study site, it was used to evaluate the effect of various changes in traffic control. Timing of the semi-actuated signal was systematically revised and the resulting changes in delay were observed. It was found, for example, that under conditions represented by the traffic data, total stopped time delays could be reduced significantly by reducing the minimum green phase on State Route 3 and increasing the vehicle extension time on State Route 161.

In addition to simulating semi-actuated signals, the model can be adapted to simulate pretimed and fully-actuated signals. Using the same traffic input data as in the preceding test, these three signal types were compared for efficiency. The semi-actuated signal was found to be the least efficient of the three. The application of the pretimed signal resulted in reduced total stopped time delay, but the number of cars delayed remained virtually the same. Although the proportion of delayed cars was slightly increased by the fully-actuated signal, the total stopped time delay was reduced significantly. The study objectives and procedures can be summarized in the form of a block diagram as shown on Figure 12. This diagram indicates that the major achievements can be
Figure 12 - Schematic Summary of the Research
related to four phases of the study, as follows:

1. A technique of obtaining simultaneous traffic data on all approaches of an intersection by a split-image camera, suspended over the center of an intersection was successfully developed and tested.

2. An inexpensive rear-projection console was built and tested in conjunction with a modified slide projector in the analysis of the 70 mm film.

3. A versatile digital simulation model of a signalized intersection was developed and tested. The results of the simulation compared well with field observations.

4. The efficiency of the intersection operation was successfully related to alternative schemes of traffic control by simulation.

5.2 Significance of the Results

The development of the split-image camera provides a practicable method by which simultaneous traffic data can be obtained on all approaches to the intersection. The results of this study suggest that

1) Simultaneous data (including traffic volumes, arriving times and stopped time delay) are necessary for any meaningful investigation of intersection operation,

2) Time-lapse photography appears to be the best method to obtain such data, providing permanent records of all visual aspects of the intersection operation,

3) Heretofore, the collection of such photographic data was considered to
be impractical for other than research purposes, mainly because of the reliance of conventional photographic studies on a conveniently located tall building near the study area.

The efficiency in the operation of an intersection can be evaluated by analyzing representative samples of traffic data collected by the preceding photographic technique. A two-man crew can install the suspended camera and can collect the required data. The analysis of the data can be performed by one person in the laboratory. Stopped time delay and other quantitative characteristics of the intersection operation are readily available from the photographs. Also, some qualitative features of intersection operation may become apparent during observation of the photographs. Inadequacies in the geometric design may be exposed by some unusual or hazardous vehicle maneuvers.

Intersection simulation models developed in the past were oriented toward research problems. Many were developed for the sole purpose of exercise in model building and represented only a very simplified version of an intersection. The four models, reviewed in some detail in Chapter Three, were compared with field data within a Bureau of Public Roads sponsored research project (1). It was concluded that each model had some components which were valid and some which were not. There was no question, however, that definite differences were found between field locations. This led to the conclusion that all differences will have to be interpreted and explained before a totally valid model can be developed.

The simulation model developed in this dissertation is designed to be
adapted to a specific intersection with the data obtained by the split-image camera. The difference between field locations is accounted for by the input data. The combination of the new photographic method and the simulation model thus becomes a powerful tool in the design of signal control. The costly trial and error method in the field can be eliminated. Instead, controlled experiments can be conducted to predict the effect of various revisions in the traffic control. The traffic engineer can identify in the laboratory the most desirable improvements in the timing of the signal. Also, the flexibility of the model permits the comparison of the efficiency of pretimed, semi-traffic-actuated or fully-traffic-actuated signals at a given location. The application of the model to such a problem is demonstrated in Chapter Four. According to the literature review, this appears to be the first model developed for the design of signal timing for a specific intersection.

Digital simulation techniques have been used for years in many fields of engineering to solve challenging problems. In transportation engineering, the article, "Computer Simulation of Peak Hour Operations in a Bus Terminal," by N. H. Jennings, and J. H. Dickins, is an example of the application of simulation technique toward more efficient design of terminals (2). Increasing automobile ownership and the increasing rate of urbanization of the nation tends to concentrate traffic demands and thus accelerate the problems of roadway transportation. Difficulties in terms of accidents and capacity inadequacies are compounded at intersections. New tools must be found by which the efficiency of the intersection operation can be improved.
The new intersection study technique developed in this dissertation certainly has the potential to become such a tool. It can facilitate the identification of the type of traffic control that is best suited to a particular intersection. Through the testing of alternative signal timing schemes it can provide the correlation between traffic demand and traffic control that is required for efficient intersection operation.

The model can finally be applied to research problems and can be useful as a teaching aid in traffic engineering education. Through simulation, the interaction between various elements of the signalized intersection can be explained and demonstrated.
REFERENCES


ADVANTAGES OF THE PHOTOGRAPHIC TECHNIQUE

The application of the photographic technique to the investigation of complex traffic problems at intersections has numerous advantages over more conventional study methods. It is especially valuable when the number of personnel, required for other methods, is not available. A two-man crew can install the suspended camera, as described on the preceding pages, and collect the required data. The analysis of the data can be performed by one person in the laboratory. Also, some information that is readily obtainable by photographic techniques would be very complicated or impractical to collect by other techniques. On the following pages a comparison of the photographic technique and the more conventional intersection study techniques is presented.

Vehicle Volumes. The conventional equipment used to collect volume data typically consists of two components: a vehicle detector, and a counting device. The most commonly used temporarily installed detector is the pneumatic tube. The "electrical contact" or "tape" detectors are used at both permanent and temporary counting sites. Some of the permanently installed detectors are the pressure-sensitive, the magnetic, and the inductive loop detectors. These are used mainly as detectors for traffic actuated signals but can be adapted for volume counts. Detectors mounted above the pavement are of three general types: "radar," "ultra-sonic," and "light". The counter can be a register on
which actuations are registered, or it may be equipped with a mechanism that transfers the data to a paper tape, a punched tape, or to a graphic chart.

These instruments are better suited for long-term volume counts than photographic instruments. However, short-term counts on multi-lane facilities where permanent detectors are not available are usually conducted manually because of the difficulty of installing the portable detectors and counters. In this case the photographic technique may be considered as an alternative solution. At a rate of three seconds per frame the 100 foot capacity of the 16 mm camera permits continuous operation for three hours and eighteen minutes. The Maurer P.2 camera has the advantage of covering all four approaches simultaneously. Operated at three seconds per frame this camera has a 26 minute capacity.

Vehicle Classification. Manual counts are usually conducted when classification of vehicles by type is necessary. The portable detectors cannot distinguish between types of vehicles. When vehicular volumes are read from photographs, vehicle classification can be obtained simultaneously and with 100 per cent accuracy. This method may also be used to develop correction factors for automatic counters connected to axle detectors.

Law Observance Studies. Law observance studies are conducted to determine the effectiveness of regulations and control devices employed at an intersection. Observance of stop signs and turn prohibitions, compliance with the rule requiring the yielding of right-of-way to pedestrians, and pedestrian obedience
to signals are the most frequently required items in this category of traffic data. Since the objective of these studies is to observe persons violating certain traffic rules, it is vitally important that the observers conducting the investigation are inconspicuous. This requirement presents no problem when the photographic technique is applied. The capacity of the reconnaissance camera is too small for this purpose; but the 16 mm camera may be utilized to advantage, since the required information need not be observed on all approaches simultaneously.

**Approach Speeds.** One method of obtaining speed data utilizes a radar meter. Graphic recorders are available to provide a permanent record of the speeds. It is difficult, however, to distinguish between individual vehicles under high volume conditions. The more commonly used technique consists of measuring the time required by a vehicle to travel a known distance. Commercially available speed meters use pneumatic tubes, contact strips, light beams or wires at each end of the course. Multiple-pen graphic recorders, actuated by pneumatic tubes, can also be used to obtain speed data. All techniques utilizing road tubes will unavoidably influence the behavior of drivers, since the appearance of two road tubes spaced at a distance apart on the pavement is strongly associated with enforcement of speed limits.

The photographic technique has two major advantages when compared with the preceding methods of speed data collection: first, it provides a complete record even under high volume conditions; and second, it is relatively easy to mount the camera in an inconspicuous position to avoid any biasing effect.
**Intersection Delay.** Intersection delay studies are conducted to obtain qualitative information concerning the operation of intersections. Travel time delay is usually obtained by one of the following methods:

1. **Observers stationed at strategic locations and recording travel times between predetermined points.** A multiple pen recorder may be used with a combination of road tube and manually operated pens.

2. **License plate numbers and arriving times recorded by observers at entrance and exit points.**

3. **Test cars operated between two points to obtain a sample of travel times through the intersection.**

4. **The photographic technique.**

Stopped-time delay is obtained by field observers who count the number of stopped vehicles at regular time intervals. This study is difficult to conduct at high volumes and it requires a large crew. When such a large crew is not available, the photographic technique is the only solution.

**Summary.** The advantages of the photographic technique are enhanced with the complexity of the data required, since the film is a permanent record of all visible aspects of the traffic situation at an intersection. It is only necessary to project the same film repeatedly to reduce all the required information at the convenience of a laboratory. The technique requires a small number of field personnel. Furthermore, it provides a 100 per cent sample, and the method of analysis can be changed to meet the accuracy required for a specific purpose.
It is most useful where the interrelationship of several factors is investigated since all factors are observed simultaneously.

Photographic techniques are best suited for relatively short-term field studies, since the capacity of the cameras is limited. When the requirements of a particular study are limited, e.g., when spot speeds or approach volumes only are required, more expeditious or less involved methods may be available.
The at-grade intersection of two roadways, carrying a significant amount of vehicular traffic, is usually controlled by traffic signals. The warrants and standards of the installation of such devices is prescribed in the Manual on Uniform Traffic Control Devices for Streets and Highways (1). The primary function of a traffic signal is to ascertain orderly movement of traffic by assigning and alternating the right-of-way for conflicting traffic movements. By eliminating confusion and competition it also reduces the frequency of accidents.

Traffic signals may be pretimed or traffic-actuated. A pretimed signal may operate on the same cycle and phasing continuously, or it may be programmed to alternate different designs of signal timing to accommodate regular variations in the traffic pattern. Traffic-actuated signals are able to adjust to random variations in the traffic demand. They may be either semi-actuated or fully-actuated. Where traffic flow on the minor street fluctuates widely the semi-traffic-actuated signal may be used to advantage with vehicle detectors placed on the minor roadway only. The signal remains green for the main direction of traffic flow until the detectors are actuated by the approaching traffic in the minor direction. As long as traffic volumes are low, the semi-actuated traffic control is especially efficient at the intersection of a major roadway and a minor roadway by interrupting the major flow only when actually required. The maximum green for the minor direction and the minimum green for the major direction is predetermined providing for pretimed-type operation during periods of heavy traffic demand on the minor roadway. The
A fully-traffic-actuated signal is equipped with vehicle detectors on all approaches. Minimum and maximum green phases are predetermined. The cycle length thus varies between a minimum and a maximum value as the traffic demand fluctuates. Both of the preceding actuated-type signals only count vehicles crossing the detectors during a period beginning near the end of the minimum green phase and ending near the end of the maximum green phase. All the other vehicles are counted as only one vehicle. More sophisticated are the traffic-density type of actuated signals that take into account a number of factors in the alternation of the right-of-way. Such factors are the number of cars waiting for the green light, their waiting time, and the time gap between vehicles in the moving traffic stream.

To assure efficient and effective operation, traffic signals must be properly installed, adjusted, and maintained. Furthermore, the timing must be designed to suit the particular traffic characteristics of the intersection. Signal timing must be based on an engineering study of the physical and operating peculiarities of the intersection.

Engineering data desired to define the operating and physical conditions at an intersection consist of the following:

1. A volume count of vehicles entering the intersection per approach lane.
2. A count of the number of turning movements made by the entering vehicles.
3. A classification count of entering vehicles.
5. A pedestrian volume count.

6. Average vehicular and pedestrian delays.

7. The accident history of the intersection.

8. The physical properties of the intersection (approach widths, number of lanes, sight distances, gradients, etc.)

9. Any other factor that might affect the operation of the intersection (such as proximity to nearest signalized intersection, etc.)

The Ohio Department of Highway's practice in collecting vehicle volume data is to conduct a 24-hour weekday volume count manually. Turning movements and commercial vehicles are counted during each of the 24 hours. During periods of peak flows, the hourly counts are reduced to 15-minute periods. Approach speeds at a site are either measured directly or assumed to be equal to the speed limits. Current manpower does not permit routine delay studies to check intersection operations. Delay studies are only performed if specifically called for.

The Highway Department analyzes the collected data to determine if any of the traffic signal warrants are satisfied. Warrants have been established for pretimed signals but, as yet, no specific warrants have been established for detector actuated signals. At present, engineering judgment determines whether actuation controlled signals should be installed.

Design of pretimed signals involves:

1. Selecting cycle length with the help of cycle capacity probability design curves, based on Poisson arrival rates.
2. Proportioning green times according to the ratio of the hourly volumes on the intersecting roadways. In urban areas, 15 minute volumes are used when greater accuracy is required.

3. Amber periods are selected according to approach speeds and intersection geometry. The practice in Ohio is to select amber periods of 3 to 5 seconds duration. Where longer intergreen periods are necessary, because of high approach speeds, exceedingly wide intersections, or offset intersections, an all-red period is used.

For vehicle-actuated signals, the proper position of the detector is determined by either of the two following methods commonly used by the Ohio Department of Highways:

1. Curves are furnished by the manufacturer of the hardware, showing the suggested distance between detector and stopline corresponding to observed approach speeds. Each curve represents a specific type of controller. The proper position selected from a curve for a particular speed condition and a given controller is adjusted to take into account the approach gradients and the number of approach lanes.

2. A range of adequate detector spacing is determined from the median of the speed distribution and the minimum and maximum dial settings. A specific value is chosen within the range depending on the layout of the intersection.
Once the position of the detector has been determined, the maximum number of vehicles that may accumulate between stopline and detector can be estimated. Minimum green is then computed by either of the two following methods:

1. It is assumed that the first vehicle requires 4.8 seconds to begin its motion and it takes 2.0 seconds for the first and all the other vehicles to proceed through the intersection.

2. All vehicles are assumed to require 2.5 seconds to proceed through the intersection.

The minimum green consists of the initial interval plus one vehicle interval or unit extension. The unit extension is determined by the time required for a vehicle, traveling at the 20-th percentile speed, to cover the distance between the detector and the stopline. For semi-actuated signals, a maximum green is introduced for the cross street to return the right-of-way to the major flow even during high demand on the minor street. The right-of-way will not be returned for the minor flow before a minimum green time has been provided for the major flow.

In case of a fully-actuated traffic signal, minimum and maximum green times are set for both roadways. The cycle time then varies with the traffic demand.

The intersection of State Route 3 and State Route 161, where the field studies were conducted, is controlled by a semi-actuated traffic signal. The trend in Ohio is, however, to phase out of service this type of signal in favor of fully-actuated signals.
REFERENCES

Figure 13 - Sample Calculations for the Grid System
Film: D3A North Approach
Table 9

Sample Calculations for the Grid System
Film D3A. North Approach.

<table>
<thead>
<tr>
<th>No.</th>
<th>bd</th>
<th>bc</th>
<th>AD</th>
<th>AC</th>
<th>BD</th>
<th>BC</th>
<th>y</th>
<th>y-1</th>
<th>cd</th>
<th>ad</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.40</td>
<td>29.20</td>
<td>75.00</td>
<td>50.00</td>
<td>50.00</td>
<td>25.00</td>
<td>1.242</td>
<td>0.242</td>
<td>19.20</td>
<td>98.6</td>
</tr>
<tr>
<td>2</td>
<td>48.40</td>
<td>29.20</td>
<td>70.00</td>
<td>45.00</td>
<td>50.00</td>
<td>25.00</td>
<td>1.290</td>
<td>0.290</td>
<td>19.20</td>
<td>85.5</td>
</tr>
<tr>
<td>3</td>
<td>48.40</td>
<td>29.20</td>
<td>65.00</td>
<td>40.00</td>
<td>50.00</td>
<td>25.00</td>
<td>1.347</td>
<td>0.347</td>
<td>19.20</td>
<td>74.5</td>
</tr>
<tr>
<td>4</td>
<td>48.40</td>
<td>29.20</td>
<td>60.00</td>
<td>35.00</td>
<td>50.00</td>
<td>25.00</td>
<td>1.421</td>
<td>0.421</td>
<td>19.20</td>
<td>64.8</td>
</tr>
<tr>
<td>5</td>
<td>48.40</td>
<td>29.20</td>
<td>55.00</td>
<td>30.00</td>
<td>50.00</td>
<td>25.00</td>
<td>1.520</td>
<td>0.520</td>
<td>19.20</td>
<td>56.2</td>
</tr>
</tbody>
</table>
APPENDIX D
SUBROUTINE SC3
SUBROUTINE UD7

L40
I=4

L128
J=NEV(I) + 1

L130
NVDL(I,J) = 1

L129
J > KSUM(I)

L133
I=I+1

I ≤ 7

L139
POS(I,J) < VDL

SUBROUTINE WONG L60

SUBROUTINE SDS

EGT4 = TIME + ESPV

EGT4 ≤ BGT4 + GMIN47

EGT4 ≤ BGT4 + GMAX47 + 3

EGT4 ≤ BGT4 + GMAX47

BRT4 = BTA4 + IA

BATA = BATA + IS

BGT0 = BATA + IS

NNWV=1

NWV = 1
SUBROUTINE SD6

SUBROUTINE - UD7

I = 0

NSPF(I) > 1

J = NVEX(I) + 1

I < 4

J = KSUM(I)

I = I + 1

J = J + 1

NVOL(I,J) = 0

POS(I,J) < VOL

NVOL(I,J) = 1

ECTO < TIME + ESPV

BGTO + GMAXO >= TIME + ESPV

EGTO + TIME + ESPV

BGTO + GMAXO <= TIME + ESPV

EGTO = BGTO + GMAXO

EGTO = TIME + ESPV

EGT4 < TIME + ESPV

BGTO + GMAXO7 >= TIME + ESPV

EGT4 = BGTO + GMAXO7

EGT4 = TIME + ESPV

SUBROUTINE - WO16

LS
SUBROUTINE - QU8 3 of 3

\[ \text{POS}(I,J) = \text{POS}(I,J) + V(I,J) \cdot ST + .5A(I,J) \cdot ST^2 \]

\[ V(I,J) = V(I,J) + A(I,J) \cdot ST \]

\[ \text{IF } V(I,J) < 0 \text{ THEN } XT = V(I,J)/A(I,J) \]

\[ \text{IF } V(I,J) \leq 2.0 \text{ THEN } V(I,J) = 0 \]

\[ A(I,J) = 0 \]

\[ \text{DEL}(I,J) = \text{DEL}(I,J) + ST \]

\[ \text{NSTOP}(I,J) = 1 \]

\[ \text{SUBROUTINE - FG9} \]

\[ \text{EXT} = \text{TIME} + T \]

\[ \text{BLOK}(I,J) = \text{EVT} \]

\[ D(I) = D(I) + \text{EXT} - \text{ARR}(I,J) - \text{ATTR} \]

\[ \text{NVEX}(I) = \text{NVEX}(I) + 1 \]

\[ \text{NVD}(I) = \text{NVD}(I) - 1 \]

\[ \text{NVD}(I) = 0 \]

\[ J = J + 1 \]

\[ \text{POS}(I,J) = \text{POS}(I,J) + V(I,J) \cdot ST + .5A(I,J) \cdot ST^2 \]

\[ V(I,J) = V(I,J) + A(I,J) \cdot ST \]
SUBROUTINE - CFG10

SUBROUTINE - UDT

J = J + 1
J = KSUM(I)
POS(I,J) = POS(I,J) + V(I,J) * T + \frac{1}{2} * A(I,J) * ST^2
V(I,J) = V(I,J) + A(I,J) * ST
D1 = POS(I,J) - POS(I,J-1) + SINV * V(I,J)
NTF(I,J) = NTF(I,J-1)
L91: D1 = 0
F
NTF(I,J) = 0
F
AA = (V(I,J)^2 - VL^2) / (2 * POS(I,J))
D1 = 0
F
AB = (V(I,J)^2 - V(I,J-1)^2) / (2 * D1)
AA = AB
F
A(I,J) = AA

V(I,J) = V(I,J-1)
A(I,J) = A(I,J-1)
L92

L93: A(I,J) = DL
F
A(I,J) = AL
T
A(I,J) = D1
F
A(I,J) = AL
T
A(I,J) = AB
L94

SUBROUTINE - FG9
SUBROUTINE FGII 2 of 2
SUBROUTINE - FG11

L115
I = I + 1

J = KSUM(I)

POS(I,J) = POS(I,J) + VI(J,J) x ST = \frac{1}{2} A(I,J) x ST^2

VI(J,J) = VI(J,J) + A(I,J) x ST

L116

V(I,J) < 0

XT = VI(J,J)/A(I,J)

V(I,J) = 0
A(I,J) = 0

L117

V(I,J) = 2

LSTOP(I,J) = 1

DEI(I,J) = DEI(I,J) + ST

L118

DI = POS(I,J) - POS(I,J-1) - SMAX + VI(J,J)

L119

-DI > 0

A(I,J) = A(I,J-1)

V(I,J) = VI(J,J-1)

A(I,J) = (VI(J,J) - VI(J,J)^2) / 2 x DI

L120

A(I,J) = DL

A(I,J) = AL

SUBROUTING CFG12
SUBROUTINE FA13

SUBROUTINE UD7
TRAIL 15

NSPF(I) = 0

J = NVEX(I) + 1

J < KSUM(I)

POS(I,J) = POS(I,J) + V(I,J) * ST + 1/2 * A(I,J) * ST^2

V(I,J) = V(I,J) + A(I,J) * ST

NTF(I,J) < 0

POS(I,J) = V(I,J) + (V(I,J) * DL) * (V(I,J) / DL)

A(I,J) = V(I,J) / 2 * POS(I,J)

NTF(I,J) = 1

EXT = TIME + (VLT - V(I,J))^2 / 2 * VLT * A(I,J) + EXL * POS(I,J) / VLT

D(I) = D(I) + EXT - ARR(I,J) + ATTS

NVEX(I) = NVEX(I) + 1

NVP(I) = NVP(I) - 1

SUBROUTINE TRS
TRAIL 5

NVEX(I) = NVEX(I) + 1

NVP(I) = NVP(I) - 1

SUBROUTINE FA14
TRAIL 4

SUBROUTINE UD7
TRAIL 5

SUBROUTINE FA13
SUBROUTINE - FA13

124 A(I,J) = AL

125 DI = VI.J*TA + SA(I,J)*TA^2

126 A(I,J) = V(I,J)^2 / 2POS(I,J)

SUBROUTINE - TRIS

L21

EXT = TIME + CPT-POS(I,J) / VII - (VI.J-VII) / AVO

L24 A(I,J) = AL

L25 DI = VI.J*TA + SA(I,J)*TA^2

1260 V(I,J) = 0

L26 A(I,J) = V(I,J)^2 / 2POS(I,J)

L270 D(I) = D(I) + EXT

L271 ARR(I) = ATPL

L272 NVEX(I) = NVEX(I) + 1

L273 NVP(I) = NVP(I) - 1

L274 J = J + 1

L275 POS(I,J) = POS(I,J) + V(I,J)*ST + SA(I,J)*ST^2

L276 V(I,J) = V(I,J) + A(I,J)*ST

SUBROUTINE - FA14
**EXECUTE**

**OSUSYS**

**RUN(50,0)**

**$SCATRAN**

**C INITIALIZATION SEMI-ACTIVATED SIGNAL**

```plaintext
BEGIN
  NNN = 151
  DIMENSION(JMAX(8),ARR(1208,NNN),NVP(8),NSPF(8),NVFX(8),
            POS(1208,NNN),V(1208,NNN),NTF(1208,NNN),NSUM(8),NCAP(1208,NNN),
            NTRT(8),A(1208,NNN),DFL(1208,NNN),NSTOP(1208,NNN),NVOL,
            (1208,NNN),DPSV(8),DPV(8),DFSUM(8),NSV(8),D(8),FLOK(8))
  READ INPUT, IN1, (START, TMAX, BGTO, SOK, SD, CT, FL, DV)
  READ INPUT, IN2, ((JMAX(1), I = 0, 1, LF, 7))
  READ INPUT, IN3, ((PRT(I), I = 0, 2, LF, 6))
  READ INPUT, IN4, ((START, AL, OL, SMIN, VLT, VLP, VLL, AVA, AVD, ATT, ATTR,
                      ATT-X, FXL, VTH, TFXS, TFXR, TFXL, 16, 1, A))
  READ INPUT, IN5, ((ARR(I, J), I = 0, 1, J = LF, JMAX(1)))
  READ INPUT, IN6, ((NWV, GMIN03, GMIN47, GMAX47, FSPV, VDL))
  RJ READ INPUT, IN7, (CNT, DATA READ IN)
  READ INPUT, IN7, (NWV, GMIN03, GMIN47, GMAX47, FSPV, VDL)
  DO THROUGH (RJ READ, I = 0, 1, LF, 7)
  DO THROUGH (SET), I = 0, 1, LF, 7
  PROVIDED (I, LF, 3), NSPF(I) = -1
  CONTINUE
  FGTO = BGTO + GMIN03
  NNWV = 0
  INITIATE SIMULATION RUN
  L1 TIME = START
  **TRANL** > CONTINUE
```
C INITIALIZE PRETESTED SIGNAL

DIMENSION (JMAX(8),ARR(1208,NNN),NVP(R),NREF(8),NVF(8),NVF(8)
POS(1208,NNN),V(1208,NNN),NTF(1208,NNN),SUNN(8),NGAP(1208
NNN),PRT(1),A(1208,NNN),DFL(1208,NNN),NETOP(1208,NNN),NVL
(1208,NNN),VPSV(R),NPV(R),SIMF(8),NSV(R),N(8),PLOK(8))

READ INPUT *IN1:* (START,TMAX,UNIT,SHQ,SE,CTL,FL,OV)

F IN1 (F40.0,F40.0,F40.0,F20.1,F20.1,F20.1,F20.1)
READ INPUT*IN2:*(JMAX(11),I=0,1,1,LF=7)

F INP (NATIONAL)
READ INPUT*IN3:*((PRT(1),I=0,2,1,LF=6)

F IN3 (API2.0)
READ INPUT*IN4:*(ST=AL,DL,SMIN,VLTV,VLRL,AV,AVD,ATTS,ATTR


C INPUT DATA READ IN
DO THROUGH (1READ),I=0,1,1,LF=7

C READ INPUT*INS:*(ARR(1,J),J=1,1,LF,JMAY(I))

F IN5 (AF40.0)
C INPUT END DATA READ IN
DO THROUGH (SET),I=0,1,1,LF=7

PROVIDED (I=LF=7),NREF(1)=1

PROVIDED (I=SG),NREF(1)=2

C SET CONTINUE
A7=21
BD=34
CA=26
A4=55
R=48
CYCLE=60

C INITIATE SIMULATION RUN
L1 TIME=START
TRANL3 CONTINUE
*EXECUTE OSYSYS
*OSYSYS RUN(50,0)
$SCATRAN
C INITIALIZATION FULLY-ACTUATED SIGNAL-

**BEGIN
NIN=151
**
DIMENSION(JMAX(8),ARR(1208,NNN),NVP(8),NSPF(8),NVEX(8))
POS(1208,NNN),V(1208,NNN),NTF(1208,NNN),KSUM(8),NGAP(1208,NNN),
NPP(8),PRF(8),A(1208,NNN),DFL(1208,NNN),NSTOP(1208,NNN),NVOL
(1208,NNN),DPSV(8),DPV(8),NSUM(A),NSV(A),N(A),ROK(A))
**
READ INPUT, IN1,(START,TMAX,AGT,SHOK,SHC,TLE,EL,OV)-

F IN1
(F4.0,F4.0,F4.0,F4.0,F2.1,F2.1,F2.1,F2.1,F9.1,F9.1)-
READ INPUT, IN2,(JMAX(1),I=0:E1,NNN)-
(F1.1)-

F IN2
READ INPUT, IN3,(PRF(I),I=0:E1,NNN)-
(F2.2)-
READ INPUT, IN4,(STAL,DL,SMIN,VLT,VRV,VLV,AVA,AVD,ATT,ATTR
+ATL,CTP,EXL,VTH,TFXS,TFXR,TFXL,I6,1)-

F IN4
(F2.1,F3.1,F9.1,F3.1,F3.1,F9.1,F3.1,F3.1,F2.1,F3.1)-

C INPUT
DATA READ IN-
NO THROUGH (IRFAD), I=0:E1,NNN-
IRFAD READ INPUT, IN5,(ARR(1,J),J=1:E1,NNN,J=JMAX(1))-0

F IN5
(BF4.0)-

C INPUT
END DATA READ IN-
READ INPUT, IN6,(GMIN03,GMIN07,GMAB03,GMAB07,VDV,FRSPV)-

F IN6
(F3.0,F3.0,F3.0,F3.0,F3.0,F3.0)-
NO THROUGH (SFT), I=0:E1,NNN-
PROVIDED (I1,NNN),NSPF(I)= 1 -
PROVIDED (I1,NNN),NSPF(I)= 2 -

SET CONTINUE-
EGT=EGT+GMIN03-

C INITIATE SIMULATION RUN-

L1 TIMF=START-
TRANL3 CONTINUE-
C SUBROUTINE SP2 - PRETIRED SIGNAL CONTROLLER -
TRANSFER TO (L58) PROVIDED (TIME*LGTO+60) -
TRANSFER TO (L59) PROVIDED (TIME*LGTO+60) -
TRANSFER TO (L61) PROVIDED (TIME*LGTO+4) -
TRANSFER TO (L62) PROVIDED (TIME*LGTO+4A) -
TRANSFER TO (L65) PROVIDED (TIME*LGTO+R4) -
TRANSFER TO (L66) PROVIDED (TIME*LGTO+CYCLE) -
DO THROUGH (D023), I=0, I+1, I,L+4 -

D023
   NSPF(I)=1 -
   LGTO=TIME -
   TRANSFER TO (L5) -

L58
   TRANSFER TO (L5) PROVIDED (TIME*NE*BGTO+ST) -
   DO THROUGH (D013), I=0, I+1, I,L+4 -
   D013
   NSPF(I)=2 -
   TRANSFER TO (L5) -

L59
   TRANSFER TO (L5) PROVIDED (TIME*NE*BGTO+ST) -
   DO THROUGH (D014), I=0, I+1, I,L+4 -
   D014
   NSPF(I)=0 -
   TRANSFER TO (L5) -

L61
   TRANSFER TO (L5) PROVIDED (TIME*NE*BGTO+R0) -
   DO THROUGH (D015), I=0, I+1, I,L+4 -
   D015
   NSPF(I)=1 -
   TRANSFER TO (L5) -

L62
   TRANSFER TO (L63) PROVIDED (TIME*NE*BGTO+G4) -
   DO THROUGH (D017), I=4, I+1, I,L+8 -
   D017
   NSPF(I)=1 -
   TRANSFER TO (L5) -

L63
   TRANSFER TO (L5) PROVIDED (TIME*NE*BGTO+G4+ST) -
   DO THROUGH (D018), I=4, I+1, I,L+8 -
   D018
   NSPF(I)=2 -
   TRANSFER TO (L5) -

L65
   TRANSFER TO (L5) PROVIDED (TIME*NE*BGTO+4) -
   DO THROUGH (D019), I=4, I+1, I,L+8 -
   D019
   NSPF(I)=1 -
   TRANSFER TO (L5) -
C SUBROUTINE SC3 - SEMI ACTUATED SIGNAL CONTROLLER

TRANSFER TO (L33) PROVIDED (NSPF(I),NF=1)-
DO THROUGH (DO8), I=0,1, I=LFS3-

DO8
NSPF(I)=2-

L34
TRANSFER TO (L5) PROVIDED (NWV,NF=1)-
TRANSFER TO (L5) PROVIDED (TIME, BRT0) (L5, GMIN03)-
DO THROUGH (DO1), I=0,1, I=LFS3-

DO1
NSPF(I)=0-

AGT4*TIME+IG-
BRT0=TIME+IA-
TRANSFER TO (L5)-

L33
TRANSFER TO (L34) PROVIDED (NSPF(I),NF=1)-

L4
TRANSFER TO (L6) PROVIDED (NSPF(I),NF=0)-
TRANSFER TO (L5) PROVIDED (TIME, BRT0)-
DO THROUGH (DO2), I=0,1, I=LFS3-

DO2
NSPF(I)=1-
TRANSFER TO (L5)-

L6
TRANSFER TO (L5) PROVIDED (TIME, BRT4)-
TRANSFER TO (L7) PROVIDED (TIME, BRT4)-
TRANSFER TO (L7) PROVIDED (TIME, BRT4)-
TRANSFER TO (L8) PROVIDED (TIME, BRT4)-
TRANSFER TO (L9) PROVIDED (TIME, BRT4)-
TRANSFER TO (L10) PROVIDED (TIME, BRT4)-
TRANSFER TO (L5)-

L35
DO THROUGH (DO7), I=0,1, I=LFS3-

DO7
NSPF(I)=2-
TRANSFER TO (L5)-

L7
DO THROUGH (DO3), I=0,1, I=LFS3-

DO3
NSPF(I)=1-

BRT4=TIME+GMIN47-
BRT4=BRT4+IA-
BRT4=BRT4+IG-
TRANSFER TO (L139) PROVIDED (NNWV,F=1)-

NNWV=0-
TRANSFER TO (L5)-

L139
NNWV=0-
TRANSFER TO (L5)-

L8
DO THROUGH (DO4), I=0,1, I=LFS3-

DO4
NSPF(I)=0-
TRANSFER TO (L5)-

L9
DO THROUGH (DO5), I=0,1, I=LFS3-

DO5
NSPF(I)=1-
TRANSFER TO (L5)-

L10
DO THROUGH (DO6), I=0,1, I=LFS3-

DO6
NSPF(I)=1-
SUBROUTINE SD5 -DEFECTORS FOR SEMI ACTUATED SIGNAL-

L40  I=4-
L128  J*NVEX(I)+1-
L129  TRANSFER TO (L133) PROVIDED (J*G*KSUM(I))-
       TRANSFER TO (L133) PROVIDED (POS(I,J)*L*VOL)-
       TRANSFER TO (L130) PROVIDED (NVOL(I,J)*NF*1)-
       J=J+1-
       TRANSFER TO (L129)-
L130  NVOL(I,J)=1-
       TRANSFER TO(L132) PROVIDED (NSPF(I)*E*0)-
       TRANSFER TO (L132) PROVIDED (NSPF(I)*F*1)-
       EGT4*TIME+ESPV-
       TRANSFER TO (L133) PROVIDED (FGT4*LF*RG4+GMIN47)-
       TRANSFER TO (L131) PROVIDED (FGT4*LF*RG4+GMAX47)-
       TRANSFER TO (L133) PROVIDED (FGT4*LF*RG4+GMAX47+7)-
       NWV=-1-
       TRANSFER TO (L133)-
L131  RAT4=FGT4-
       RAT4=RAT4+IA-
       RAT4=RAT4+IG-
       TRANSFER TO (L133)-
L132  NWV=1-
       TRANSFER TO (L133)-
L133  I=I+1-
       TRANSFER TO (L128) PROVIDED (I*LF*7)-
L138  CONTINUE -
C SUBROUTINE SCA -FULLY ACTUATED SIGNAL CONTROLLER-
TRANSFER TO (L33) PROVIDED (NSPF(0)=N=1) -
DO THROUGH (DO8)+1=0+1+1=L+4-

DO8 NSPF(1)=? -
TRANSFER TO (L3) -
L31 DO THROUGH (DO1)+1=0+1+1=L+4 -
DO1 NSPF(1)=0 -
AGT4=TIME+IG -
ARTO=TIME+IA -
TRANSFER TO (L5) -
L33 TRANSFER TO (L4) PROVIDED (NSPF(0)=L+1) -
TRANSFER TO (L5) PROVIDED (TIME=NF=FGTO) -
TRANSFER TO (L3) -

L4 TRANSFER TO (L6) PROVIDED (NSPF(0)=L+1) -
TRANSFER TO (L5) PROVIDED (TIME=L=ARTO) -
DO THROUGH (DO2)+1=0+1+1=L+4 -

DO2 NSPF(1)=1 -
TRANSFER TO (L5) -
L6 TRANSFER TO (L5) PROVIDED (TIME=L=AGT4) -
TRANSFER TO (L7) PROVIDED (TIME=FAGT4) -
TRANSFER TO (L33) PROVIDED (TIME=FAGT4+ST) -
TRANSFER TO (L6) PROVIDED (TIME=FACT4) -
TRANSFER TO (L9) PROVIDED (TIME=FACT4) -
TRANSFER TO (L10) PROVIDED (TIME=FACT4) -
TRANSFER TO (L5) -
L7 DO THROUGH (DO3)+1=4+1+1=L+4 -

DO3 NSPF(1)=1 -
AGT4=TIME+GMN=4 -
ART4=AGT4+IA -
ARTO=AGT4+IG -
TRANSFER TO (L5) -
L75 DO THROUGH (DO7)+1=4+1+1=L+4 -

DO7 NSPF(1)=2 -
TRANSFER TO (L5) -
L8 DO THROUGH (DO4)+1=4+1+1=L+4 -

DO4 NSPF(1)=0 -
TRANSFER TO (L5) -
L9 DO THROUGH (DO9)+1=4+1+1=L+4 -

DO9 NSPF(1)=1 -
TRANSFER TO (L5) -
L10 DO THROUGH (DO10)+1=0+1+1=L+4 -

DO10 NSPF(1)=1 -
FGTO=TIME+GMN=4 -
TRANSFER TO (L5) -
C SUBROUTINE SDF - DETECTORS FOR FULLY ACTIVATED SIGNAL -

L40  I=0 -
    TRANSFER TO (L45) PROVIDED (NSPF(I)LE1) -
L128  J=NFX(1)+1 -
L129  TRANSFER TO (L133) PROVIDED (J*G*KSUM(1)) -
    TRANSFER TO (L1301) PROVIDED (NVOL(I+J)LE0) -
    J=J+1 -
    TRANSFER TO (L129) -
L1301 TRANSFER TO (L133) PROVIDED (POS(I+J)LEVOL) -
L130  NVOL(I+J)=1 -
    TRANSFER TO (L138) PROVIDED (FGTA+GF*TIME+ESPV) -
    TRANSFER TO (L47) PROVIDED (FGTA+L*TIME+ESPV-GMAX3) -
    FGTA+TIME+ESPV -
    TRANSFER TO (L138) -
L47  FGTA=FGTA+GMAX3 -
    TRANSFER TO (L138) -
L139  I=I+1 -
    TRANSFER TO (L1281) PROVIDED (I*L4) -
    TRANSFER TO (L138) -
L45  I=4 -
    TRANSFER TO (L138) PROVIDED (NSPF(I)LE1) -
L44  J=NFX(I)+1 -
L57  TRANSFER TO (L2A) PROVIDED (J*G*KSUM(I)) -
    TRANSFER TO (L32) PROVIDED (NVOL(I+J)LE0) -
    TRANSFER TO (L2A) PROVIDED (POS(I+J)LEVOL) -
    NVOL(I+J)=1 -
    TRANSFER TO (L138) PROVIDED (FGTA+L*TIME+ESPV) -
    TRANSFER TO (L41) PROVIDED (FGTA+L*TIME+ESPV-GMAX47) -
    FGTA+TIME+ESPV -
    TRANSFER TO (L138) -
L32  J=J+1 -
L38  I=I+1 -
    TRANSFER TO (L44) PROVIDED (I*L4) -
    TRANSFER TO (L138) -
L41  FGTA=FGTA+GMAX47 -
    TRANSFER TO (L138) -
L138  TRANSFER TO (L60) -
C SUROUTINE UN7 -UP-DATE LIST OF ARRIVED VEHICLES-
L5 DO THROUGH (L11) i=10+1+10zF7-
J=KSUM(i)+1-
TRANSFER TO (L11) PROVIDED (J>G+JMAX(I))-
TRANSFER TO (L11) PROVIDED (TIME NF=ARR(I+J)-
TRANSFER TO (L1674) PROVIDED (NVP(I)=F=0) =
PT=((OV)=P*2-(V(I,J-1))+P*2)/(2*NL)+P0S(I+J-1)=25-(DV=ST)-
TRANSFER TO (L166) PROVIDED (FL=G=PT+NV)=
L167A POS(I+J)=FL+DV-
L167 V(I,J)=OV-
NVP(I)=NVP(I)+1-
KSUM(i)=KSUM(I)+1-
K=I/2-
C=I/P=0-
CK=C-K-
TRANSFER TO (L12) PROVIDED (CK=NF=0)-
CALL FUNCTION (TF) = FRKMN(I)-
TRANSFER TO (L13) PROVIDED (TF=G=PT(I))-
TRANSFER TO (L11)-
L166 POS(I+J)=PT-
TRANSFER TO (L167)-
L13 NTF(I,J)=1-
TRANSFER TO (L11)-
L12 NTF(I,J)=1-
L11 CONTINUE-
I=0-
TRAL15 TRANSFER TO (TRAL6) PROVIDED (NVP(I)=NF=0)-
L15 I=i+1-
TRANSFER TO (L39) PROVIDED (I=0) OR (I=F=7)-
TRANSFER TO (TRAL15) PROVIDED (I=0) OR (I=F=4) OR (I=F=6)-
TRANSFER TO (L38) PROVIDED (I=0) OR (I=F=9)-
TRANSFER TO (L40)-
L39 I=i-1-
TRANSFER TO (TRAL15)-
L3# I=i+1-
TRANSFER TO (TRAL15)
C SUBROUTINE QUB - QUIFUF DISCHARGE

TRNL7 TRANSFER TO (TRANL8) PROVIDED (NSPF(1)*NF*1) = N=0

L36 J=NVEX(1)+1 -
TRANSFER TO (L77) PROVIDED (NTF(1)*J) = NF*1 -
TRANSFER TO (L380) PROVIDED (NSTOP(1)*J) = NF*1 -
N=N+1 -
FX=TIME+N*SN+TTFX=-
BLOK(I)=FXT=-
D(I)=D(I)+FXT-ARR(I,J)-ATT-=-
NFL(I,J)=NFL(I,J)+5N*SN*SHK-
NVEX(I)=NVEX(I)+1 -
NVP(I)=NVP(I)-1 -
TRANSFER TO (L36) PROVIDED (NVF(I)*NF*0) -
TRANSFER TO (L15) -

L390 XT=V[I,J]/A[I,J] -
POS(I,J)=POS(I,J)+A[I,J]*XT -
P[I,J]=0 -
A[I,J]=0 -
NFL(I,J)=NFL(I,J)+ST -
NSTOP(I,J)=1 -
TRANSFER TO (L48) -

L380 POS(I,J)=POS(I,J)+V[I,J]*A[I,J] -
TRANSFER TO (L390) PROVIDED (V[I,J]*LF*0) -
TRANSFER TO (L400) PROVIDED (V[I,J]*LF*2*0) -
L48 TRANSFER TO (L83) PROVIDED (N*F*0) -
N=0 -

L141 X=FX+SN-TIME -
TRANSFER TO (L148) PROVIDED (A[I,J]*AL) -
VT=V[I,J]+A[I,J]*T -
TRANSFER TO (L149) PROVIDED (VT*LF*VLT) -
DT=(VLT*AL)(I,J)*((VLT-V[I,J])^2/2) -
T=VLT-V[I,J]/AL+(FXL-POS[I,J]-ST)/VLT -
FX=TIME+T -
BLOK(I)=FXT -
D(I)=D(I)+EXT-ARR(I,J)-ATT-=-
NVEX(I)=NVEX(I)+1 -
NVP(I)=NVP(I)-1 -
TRANSFER TO (L15) PROVIDED (NVF(I)*F*0) -
J=J+1 -
POS(I,J)=POS(I,J)+V[I,J]+5A[I,J] -
TRANSFER TO (L141) -
A[I,J]=0 -
TRANSFER TO (L83) -

L37 TRANSFER TO (L84) PROVIDED (NTF(I)*NF*2/1) -
TRANSFER TO (L58) PROVIDED (NSTOP(I)*NF*1) -
N=N+1 -
EXT=TIME+N*SN+TTXXR -
BLOK(I)=FXT -
D(I)=D(I)+EXT-ARR(I,J)-ATT-=-
NFL(I,J)=NFL(I,J)+5N*SN*SHK -
NVEX(I)=NVEX(I)+1 -
NVP(I)=NVP(I)-1 -
TRANSFER TO (L36) PROVIDED (NVF(I)*NF*0) -
TRANSFER TO (L15) -

L55 POS(I,J)=POS(I,J)+V[I,J]+5A[I,J] -
TRANSFER TO (L56) PROVIDED (V[I,J]*LF*0) -
TRANSFER TO (L57) PROVIDED (V[I,J]*LF*2*0) -
TRANSFER TO (L86) PROVIDED (N*F*0) -
N=0 -
C SUBROUTINE FGF -FREE FLOW ON GREEN STRAIGHT THROUGH-RIGHT TURNS-

TRANLA
J=NVFX(I)+1-
TRANSFER TO (LJ) PROVIDED (J*GSKUM(I))-
POS(I,J)=POS(I,J)+V(I,J)*5*8(I,J)-
V(I,J)=V(I,J)+A(I,J)-

TRANLO
TRANSFER TO (TRALO) PROVIDED (NTF(I,J)*NF*II)-
TRANSFER TO (LB3) PROVIDED (POS(I,J)*L*FXL)-
NVFX(I)=NVFX(I)+1-
NVP(I)=NVP(I)+1-
D(I)*D(I)+TIME=ARR(I,J)-ATTS-
TRANSFER TO (LB2)-

LB3
TRANSFER TO (LA4) PROVIDED (V(I,J)*L*(NV+VTH))-?
TRANSFER TO (LP) PROVIDED (V(I,J)*L*(NV+VTH))-
A(I,J)=AV-
TRANSFER TO (LA2)-

LA4
A(I,J)=AV-
TRANSFER TO (LA2)-

TRAL10
TRANSFER TO (LAC) PROVIDED (NTF(I,J)*NF*II)-
TRANSFER TO (LA5) PROVIDED (POS(I,J)*GF*II)-
A(I,J)=((V(I,J)+P*2-(VLR)*P*2)/(2*POS(I,J)))-
TRANSFER TO (LB8) PROVIDED (A(I,J)*L*FL)-
TRANSFER TO (LA8) PROVIDED (A(I,J)*GF*AL)-
TRANSFER TO (LA8)-

LB8
A(I,J)=AL-
TRANSFER TO (LA8)-

LB9
A(I,J)=AL-
TRANSFER TO (LB8)-

LB5
TRANSFER TO (LB6) PROVIDED (POS(I,J)*L*FXL)-
NVFX(I)=NVFX(I)+1-
NVP(I)=NVP(I)+1-
D(I)*D(I)+TIME=ARR(I,J)-ATTS-
TRANSFER TO (LA8)-

LB7
A(I,J)=8-
TRANSFER TO (LB2)-

LB6
TRANSFER TO (LA7) PROVIDED (V(I,J)*GF*VLR)-
A(I,J)=AV-
SUBROUTINE CFG10 - CAR FOLLOWING - GREEN STRAIGHT THROUGH - RIGHT TURN -

L82  J=J+1 -
TRANSFER TO (L15) PROVIDED (J*G=K51N*(I)) -
POS(I,J)*POS(I,J)+V(I,J)+G*A(I,J) -
V(I,J)=V(I,J)+A(I,J) -
D1=POS(I,J)-POS(I,J-1)+SIN+V(I,J) -
TRANSFER TO (L91) PROVIDED (NTF(I,J)+ENFT(I,J-1)) -
TRANSFER TO (L91) PROVIDED (NTF(I,J)+ENFT(I,J-1)) -
AA=((V(I,J))*P2-(VLR)*P2)/(P2*POS(I,J)) -
TRANSFER TO (L95) PROVIDED (D1*G*0) -
AR =((V(I,J))*P2-(V(I,J-1))*P2)/(P2*POS(I,J)) -
TRANSFER TO (L94) PROVIDED (AR*L*AA) -
A(I,J)=AA -
TRANSFER TO (L96) -

L91  TRANSFER TO (L92) PROVIDED (D1*G*0) -
A(I,J)=((V(I,J))*P2-(V(I,J-1))*P2)/(P2*POS(I,J)) -
TRANSFER TO (L95) PROVIDED (D1*G*A(I,J)) -
A(I,J)=A(I,J) -
TRANSFER TO (L82) -

L92  A(I,J)=A(I,J-1) -
V(I,J)=V(I,J-1) -
TRANSFER TO (L82) -

L95  A(I,J)=AL -
TRANSFER TO (L82) -

L94  A(I,J)=AR -
TRANSFER TO (L96) -
SUBROUTINE FG!! -EEE FLOW ON GREEN LEFT TURNS-

L07 TRANSFER TO (L09) PROVIDED (V(1,J)WF0)-

L08 DFL(1,J)=DFL(1,J)+ST-

L09 NSTOP(1,J)+1-

TRANSFER TO (L09)-

L154 A(1,J)=AL-

L155 TL=(VLL-V(I,J))/A(1,J)+CDT+POS(1,J)-V(I,J)+VLL-V(I,J)/2)-

* (VLL-V(I,J))/ A(1,J))/VL-

TRANSFER TO (L157)-

L155 K=K+1-

TRANSFER TO (L155) PROVIDED (K+L)+KSUM(L)-

L158 FXT=TIME+TL-

L159 A(LK)(L):=FXT-

L160 D(1)=D(1)+FXT-APP (1,J)-ATTL-

L161 NVFX(J):=NVFX(J)+1-

L162 NVP(J):=NVP(J)-1-

TRANSFER TO (L15) PROVIDED (NVP(J)+O)-

J=J+1-

L163 POS(1,J)=POS(1,J)+V(I,J)+S*A(1,J)-

V(I,J)=V(I,J)+*A(1,J)-

TRANSFER TO (L127)-

L164 NP(I,J)=1-

L165 A(1,J)=V(I,J)*P.2+/(-P.2*(VLL-POS(1,J)))-

TRANSFER TO (L127)-

L166 FXT=TIME+TL+TIME+2-

TRANSFER TO (L168)-

L167 A(1,J)=(V(I,J))/P.2-(VLL)*P.2/POS(1,J)-POS(1,J)-1.0)-

TRANSFER TO (L163) PROVIDED (A(1,J)=AL)-

L168 TL=(VLL-V(I,J))/A(1,J)+CDT+POS(1,J)-(V(I,J)+VLL-V(I,J)/2)-

* (VLL-V(I,J))/A(1,J))/VL-

TRANSFER TO (L164) PROVIDED (TIME+L)+ALK(L):=TL-

TRANSFER TO (L141)-

L169 A(1,J)=AL-

TRANSFER TO (L164)-

L170 TRANSFER TO (L77) PROVIDED (V(I,J)=GE0)-

L171 XT=V(I,J)/A(I,J)-

POS(I,J)=POS(I,J)+S*A(1,J)+S*V(I,J)+P.2-

V(I,J)=0-

A(I,J)=0-

DL(1,J)=DL(1,J)+ST-

NSTOP(I,J)=1-

TRANSFER TO (L170) PROVIDED (POS(1,J))=+)-

TRANSFER TO (L162) PROVIDED (NGAP(I,J)+L)-

TRANSFER TO (L163) PROVIDED (NVP(L)+O)-

A(I,J)=(V(I,J))/P.2-(VLL)*P.2/POS(I,J)-1.0)-

TRANSFER TO (L167) PROVIDED (A(I,J)=AL)-

L172 TL=(VLL-V(I,J))/A(I,J)+CDT/VL-

TRANSFER TO (L164) PROVIDED (TIME+L)+ALK(L):=TL-

K=NVFX(J)+1-

TRANSFER TO (L144) PROVIDED (K+L)+KSUM(L)-

L173 TLAG=(FLX-POS(L,K))/VL+K-2)-

TRANSFER TO (L166) PROVIDED (TLAG)+L)-

TRANSFER TO (L144) PROVIDED (TLAG)+L)-

K=K+1-

TRANSFER TO (L145) PROVIDED (K+L)+KSUM(L)-
GAPE^{EXL-POS(L+K)}/V(L+K)-TAG-\text{-TL-}
TRANSFER TO (L145) PROVIDED \( \text{GAP}_{\text{FCTL}} - \text{NGAP}(I,J)=1 \-
A(I,J)=(V(I,J))/P_{\text{P}}^{(-2*(I+\text{POS}(1,J)))}
\text{CONTINUE-}
C. SUBROUTINE CEG12 - CAR FOLLOWING ON GREEN, LEFT TURNS -

L115  J=J+1-
TRANSFER TO (L15) PROVIDED (J<GLSUM(I))-
POSI+J=POSI+J-V(1,J)*L+G(I,J)-
V(1,J)=V(1,J)+A(I,J)-
TRANSFER TO (L116) PROVIDED (V(1,J)<>L-)
TRANSFER TO (L117) PROVIDED (V(1,J)>L-)

L116  XT=V(1,J)/A(I,J)-
POSI+J=POSI+J-V(I,J)*P-
V(I,J)=0-
A(I,J)=0-

L117  DEL(I,J)=DEL(I,J)+ST-
NSTOP(I,J)=1-

L118  D1=POSI+J+5MIN+V(I,J)-
TRANSFER TO (L126) PROVIDED (D1<>0)-
A(I,J)=((V(I,J))*P*2-(V(I,J-1))*P*2)/2-1)-
TRANSFER TO (L127) PROVIDED (A(I,J)>AL)-
TRANSFER TO (L115) PROVIDED (A(I,J)=AL)-
A(I,J)=AL-
TRANSFER TO (L115)-

L127  A(I,J)=AL-
TRANSFER TO (L115)-

L128  A(I,J)=A(I,J-1)-
V(I,J)=V(I,J-1)-
TRANSFER TO (L115)-
C SUBROUTINE FAIR-FLOW ON AMBER, STRAIGHT-THROUGH AND RIGHT TURN-
TRANSLATE TRANSFER TO (TRANSLATE) PROVIDED (NSPF(I=1)*NF=0)

L1 J=NVFEX(I)+1
TRANSFER TO (L15) PROVIDED (J=G*SUM(I))
POS(I,J)=POS(I,J)+V(I,J)*S*A(I,J)
V(I,J)=V(I,J)+A(I,J)
TRANSFER TO (TRANSLATE) PROVIDED (NTF(I,J)=L=0)
TRANSFER TO (L16) PROVIDED (POS(I,J)=LFE(-V(I,J)+(V(I,J)))*P+/
2*A(I,J))
TRANSFER TO (L17) PROVIDED (NTF(I,J)=NF=1)

EXT=TIME+(VLT-V(I,J))*P2/(2*A(I,J))

D(I)=D(I)+EXT-ARR(I,J)-ATTR-
NVFX(I)=NVFX(I)+1
NVP(I)=NVP(I)-1
TRANSFER TO (L18)

L17

EXT=TIME+(EXL-POS(I,J)*VLR+(V(I,J)-VLR)*P2+/(2*A(I,J))

D(I)=D(I)+EXT-ARR(I,J)-ATTR-
NVFX(I)=NVFX(I)+1
NVP(I)=NVP(I)-1
TRANSFER TO (L18)

L16

A(I,J)=((V(I,J))*P+2)/(2*POS(I,J))
TRANSFER TO (L21)
C. SUBROUTINE FA14 -FREE FLOW ON AMBER: LEFT TURNS-

TRANSFR TO (L24) PROVIDED (POS(I,J)*G* (?*POS(I,J))+P*2)/(2*DL))=-
A(I,J)=((V(I,J))/*P*2/(VLL)*P*/(2*POS(I,J))-
TRANSFR TO (L24) PROVIDED (A(I,J)*G*AL)=

L25
DI=(V(I,J)/A+5*ALS(I,J)*I(I)*A-P-
TRANSFR TO (L26) PROVIDED (DI*LE(-POS(I,J)))-
EXT=TIME+(CPT-POS(I,J))/VLL+(V(I,J)-VLL)*P*/(2*POS(I,J))-
TRANSFR TO (L27) =

L26
EXT=TIME+(CPT-POS(I,J))/VLL-((V(I,J)-VLL)/P)*ARSE((V(I,J) )VLL)AVAIL)

L27
D(I)=D(I)+EXT-ARR(I,J)-ATTL-
NFX(I)=NFX(I)+1-
NVP(I)=NVP(I)+1-

J=J+1-
TRANSFR TO (L15) PROVIDED (J*G*KSUM(I))-
POS(I,J)=POS(I,J)+V(I,J)+P*ALS(I,J)=

L28
V(I,J)=V(I,J)+A(I,J)-
TRANSFR TO (TRANSF)-

L29
A(I,J)=AL-
TRANSFR TO (L25)-

L26
TRANSFR TO (L26) PROVIDED (V(I,J)+G*N)-
TRANSFR TO (L26) PROVIDED (POS(I,J)*G*-1+N)-
V(I,J)=5-N-

L26
A(I,J)=((V(I,J))*P*2)/(2*POS(I,J))-
TRANSFR TO (L21)-
C SUBROUTINE W016 -WRITE OUTPUT-

C INCREMENT TIME-

L60 TIME = TIME + ST-
TRANSFER TO (TRANL7) PROVIDED (TIME,LF,TMAX) -
L7 CONTINUE-
WRITE OUTPUT OUTPUT-
F OUTP3B (1H0:3AX:0#SEM1-ACTUATED SIGNAL)-
WRITE OUTPUT INP2 (TMAX,CTL,FL,DV,SMIN,VLT,VLR,VLL,CPT,EXL,S-
HOK,SD,AVA,AVD,ATT,ATTR,ATTL,TTRF,TTTXP,TTFXL,VTH,AL,DL)-
F INP2 (1H0:10X,TMAX=F4:1:6H CTL=F4:1:6H FL=F4:1:6H DV=F4:1:6H-
WRITE OUTPUT INP3 (GMIN03,GMIN47,GMAX47,FSPV,VDL,IG,1A)-
F INP3 (1H0:10X,THMIN03=F4:1:6H GMIN03=F4:1:6H GMAX47=F4:1:6H-
WRITE OUTPUT OUTPUT-
F OUTP2A (1H0:3AX:0#LANE JMAX ACTUAL NO. OF DELAY DELAY DELAY TRAVEL-
*45X:0#NO. OF STOP-D PER PER PER TIME*45X:0#CARS-
CARS LANES CARS $CARS DELAY*)-
DO THROUGH (DO12).I=0:1:JMAX(1)-
DO THROUGH (DO11).J=0:1:JL,F,JMAX(1)-
DO11 NSV(I)=NSV(I)+NSV(I)+
NSV(I)=NSV(I)+NSV(I)+
NSV(I)=NSV(I)+NSV(I)-
WRITE OUTPUT OUTP2A (1,JMAX(1),KSUM(1),NSV(I),DSUM(I),DPV(I)+
D012 CONTINUE-
STOP CALL SUBROUTINE ( )=FNJOA(1)-
END PROGRAM (BEGIN)-
BIBLIOGRAPHY

SIMULATION OF THE ISOLATED INTERSECTION

Models developed and tested to simulate traffic conditions at uncontrolled T-Junctions, based on a gap distribution function or on one of the following four headway distribution functions were: (1) exponential, (2) shifted exponential, (3) composite exponential, or (4) composite shifted exponential. The results from 46 samples are described.

A digital simulation model was developed for studying traffic flow at a signalized intersection. Regular and flashing traffic signal operations were compared during low volume conditions. Comparisons were based on the parameters of delay, inconvenience, and accident potential.

Author shows by a simple example how traffic at busy urban intersections can be simulated on digital computers. To verify a simulation model, a representative sample of data must be collected in the field. For complicated intersections (e.g., roundabouts) photography lends itself very well. For the less complicated intersections, author suggests a modified typewriter with moving tape to record the simple traffic operations.

This article is a discussion of the relative merits of using observed data vs. generated data as inputs to a computer controlled traffic simulation model. It is pointed out that where generated inputs can be used, they have a decided advantage from the standpoint of computer time. A method of generating Poisson inputs is also presented. The results of several sets of inputs that have been generated by this method are given.

A digital simulation model of an intersection controlled by a fixed-time signal was developed and tested. The model was used to test proposed new methods of signal timing and to evaluate the effect on delay of phasing schemes incorporating protected turns. A bibliography is presented.


A review of some of the work in the field of digital simulation is presented. Of particular interest is the brief description of models that were developed to study traffic control at intersections.


A method for modeling a signalized intersection on a digital computer is developed and used to estimate delays as a function of cycle time, percentage of turns, green time, and cars per hour.


The author discusses the design and application of a traffic simulator constructed and operated in Manchester, England. The main advantage of this special purpose simulator is its random generator design, that is, the computer is not wastefully used in generating random numbers. It has been successfully used to simulate simple intersections and rotaries, and has also been employed as a teaching device.


The author describes the development of a simulation model for the intersection of two 2-lane directional streets, with one street being controlled by stop signs. Results of the simulation are presented and are used to formulate the relationships between vehicular delay and individual approach volumes and turning movements.

The initial results of a simulation model of an orthogonal intersection of two 2-lane, two-way streets are presented. Nearly 14,000 hours of traffic were simulated on a computer for stop sign control on the minor street. Multiple regression techniques were used to relate total intersection delay to input volumes. Results are compared to the output from Phase II of the project, whereby a signalized intersection was simulated. Detailed charts and graphs are presented for each type of control studied.


This article describes a model used to simulate traffic at an intersection controlled by traffic signals. The model described was written for pre-timed, semi-actuated, or fully-actuated signal control. Only the results obtained from simulations of the pre-timed signal are presented. Graphs are used extensively to provide insight into the basic relationships between volumes and vehicular delay under various control and traffic conditions.


A research project is being conducted by the Traffic Research Corporation of California to examine the basic components of existing simulation models. Subjected to detailed analysis are models developed by Gerlough, Lewis, Bleyl, and Kell.


A digital simulation model was developed to determine volume warrants at street intersections. The particular type of intersection studied was the four-legged, right-angled intersection of a high-volume major arterial street with a lower-volume minor arterial street. The two types of traffic control studied consisted of semi-actuated signal control and two-way stop sign control. Delays encountered at the intersection were measured and used as criteria for the establishment of the warrants.


Discussed are certain philosophies and approaches in the utilization of high-speed electronic computers to investigate traffic problems. Computers, used as simulators, offer much promise in the solution of such problems as investigating in advance of installation the effects of traffic control devices and predicting the effect of proposed improvements on the capacity of the facility.

An intersection has been simulated on a digital computer. Both delays and fuel consumption of vehicles passing through the intersection are determined. Operating costs were thus developed for average flow levels for both signal controlled and stop sign controlled intersections. Warrants for traffic signals were then proposed.


A general discussion of simulation, its history and techniques, as applied to traffic flow, is presented. Methods of formulating a model to simulate freeway or intersection traffic are illustrated. Specific historical models are presented. A list of pertinent references is included.


An intersection controlled by two-way stop signs was simulated. The results of the study include the following observations: (1) average delay per side street vehicle appeared to increase logarithmically with increases in main street volumes, (2) average delay per side street vehicle increased with increases in the percentages of the more complex left and straight movements, and (3) average side street queues increased with increases in main street volumes.


A technique for simulating traffic movement on digital computers is described. The LaGrangian approach describes traffic as it would appear to an observer in each vehicle. Computations are performed as required rather than on an incremental time basis, to reduce the computer time.


Basic principles of simulation of traffic flow on digital computers are discussed. A model has been developed to simulate traffic at a priority intersection.
ANALYTICAL INVESTIGATION OF THE

ISOLATED INTERSECTION


A vehicle-actuated traffic light is assumed to control two intersecting traffic streams by keeping the light green for a given lane until any existing queue has been discharged and a headway of a certain duration is detected in the subsequent arrivals. The object of the paper is to investigate how one should choose the minimum control headway so as to minimize the average delay per vehicle at the intersection. A model is considered in which the arrival headways are exponentially distributed random variables, departure headways have a specified distribution, and there is a random lost time for each change of the traffic light. Formulas are derived for the moments of the cycle times, the average wait per vehicle, and the optimal control headway.


A mathematical analysis is given of the operational characteristics of a signalized intersection for which the control strategy is to switch right-of-way when the favored queue has been emptied. The vehicle arrivals are generated by a binomial process, and the departure rates are constant. A possible mode of computer control of an intersection is investigated.


A relationship between the mean waiting time of a vehicle at an intersection and the mean number of waiting vehicles at the beginning of a red phase is derived. The formula is valid under such general conditions as variable red and green phase and variable clearing time of vehicles.

The response delay in clearing a queue of automobiles waiting at a traffic light is modeled by allowing one car to leave at the end of each of a series of discrete time intervals. The steady-state queue formed at a traffic signal is discussed for general stationary arrival processes. A method of solution of the case where arrivals are Poisson is described. General formulas are given for the probability of not clearing the queue during a cycle and for the expected wait at the light.


Models are given for calculating the expected delay to a driver in making several maneuvers at or near a traffic light. Approaching traffic is assumed to be Poisson.


The gap between the theorist and the practicing engineer with regard to current knowledge on traffic flow theory is pointed out. Examples of the application of queueing theory approaches to traffic engineering problems are presented. Of particular interest is the example concerned with the queueing characteristics of traffic on a single lane approach to a fixed-time signalized intersection.


An analytical model is proposed for the traffic flow through a fixed cycle traffic signal on a narrow 2-lane highway. Left turns are assumed to occur with fixed probabilities in the two lanes. The author reveals that the existence of left turns tends to favor short cycle lengths and, under certain conditions, the competition between this effect and the obvious advantages of the long cycle length gives rise to an optimum cycle time at which the average flows have a maximum value. Some simple models for multilane intersections are also considered for optimization.


A model of a signalized intersection is proposed leading to a set of dynamical equations describing a relation between the times at which cars leave the signal in terms of the times at which they arrive. Equations are derived for the conditional probabilities that a car will leave at any specified time if it enters at some given time. A procedure for obtaining approximate solutions of these equations is derived which gives exact solutions.
for the special case in which the cars arrive with the maximum possible disorder in spacing.


An optimum method of traffic control at an intersection controlled by a fixed time traffic signal is presented. Two types of models concerning the arrivals of vehicles were considered and the problem was resolved into a general type of random walk. The optimum control problem was solved under certain conditions. The validity of the problem solution was ascertained by means of a numerical example which is presented.


Renewal theory techniques are used to solve the problems concerning the delay to a single car waiting at a stop sign for an adequate safe gap in the traffic stream so that the driver considers it safe to cross the highway. The assumption is that successive gaps in the main traffic are uncorrelated random variables with known probability density.


A modification of the single car intersection delay problem is presented in which the waiting driver, upon finding a suitable gap for crossing, also examines the succeeding one, and uses that if that is larger.
TRAFFIC CHARACTERISTICS AT INTERSECTIONS

Starting Delay:


Two parameters of traffic performance at intersections were studied: starting delay and time spacing of vehicles entering a signalized intersection. The experiment was conducted to measure some typical values of the parameters, to examine the variability of the parameters from intersection to intersection and from day to day at the same intersection, and to relate the variations of the parameter values to physical and traffic conditions. The experimental results obtained from 13 signalized intersections indicated that starting delay and time spacing are functions of conditions at individual intersections. It was found that the parameter values do not vary significantly from day to day in most cases, though variations from cycle to cycle were apparent.


Results are presented from an investigation, the objective of which was to determine the time required for each vehicle in a line of stopped vehicles to begin its forward motion after the beginning of the green signal at a signalized intersection. Data collected at five traffic lanes at two isolated intersections revealed the following observations:

1. Average distance occupied by a stopped vehicle was 25 feet
2. No appreciable difference could be found in starting response of left-turn lanes when compared with through lanes
3. The relationship between vehicle position and average time of starting from a stopped position approximated a straight line
4. No significant difference was found in starting response of peak traffic and off-peak traffic
5. An average time of 1.4 seconds between successive vehicle starts was found from 85 percentile data. Two examples of applying the results found are given.

Vehicle trajectories of accelerating queues from stop lines were obtained by cine-photographic recording equipment at urban intersections. An exponential relationship between acceleration and time was found to fit the observed data. Collected data revealed high initial accelerations of 7 to 8 ft/sec² for cars (including small and medium vans) and 5 ft/sec² for lorries.


The author demonstrates by a simple model that four well-defined policies of safe driving result in distinct patterns of driving, as evidenced by curvilinear relations between time-headway and speed. The flow of traffic released from a signalized intersection has the character of single lane saturated flow and is governed by some policy of safe driving. Time-distance diagrams are used to calculate the theoretical green time at a signalized intersection.


An experiment was carried out by General Motors Research Laboratories on behavior of traffic emanating from a signalized intersection. A digital computer was utilized in the analysis of arriving times and velocities at two locations. Experimental results appeared to support results obtained by a kinematic model of platoon behavior.


Observations of space-time data of vehicles were made at five locations downstream from an isolated signalized intersection at distances up to 0.65 mile. A definite pattern of vehicle performance was revealed and a method is suggested for coordinating the timing of a second signal to be placed up to 0.65 mile from the initial signal.

Spacing:


The effect of gradients on saturation flow has been investigated at 21 signal controlled intersections. Results indicate that in the range of
gradients of -5.2% to +8.1%, an increase of 1% in gradients yields a decrease of 3% in saturation flow.


Measuring saturation flow on 32 approach roads to 15 signalized intersections revealed 1) lost time can be approximated by a knowledge of speed of major flow, and percentage of opposing left turning traffic, and 2) stop line should be placed as close to the crossroad as possible in order to minimize lost time.


The proposed distribution is a modified binomial type which incorporates the platooning effect of vehicular traffic and provides for the existence of a minimum headway. This distribution has been used in a simulation study which obtained delays for various traffic controls at intersections.


The composite exponential, Pearson Type III., and the lognormal distribution functions are compared with headway distribution data. Particular attention is given to the lognormal distribution which resulted in the best fit.


Time headway data and the lognormal distribution function were compared within a range of 500 to 1400 vehicles per hour. A method of estimating the mean and variance for any given volume was developed using linear regression analysis.

Turning Movements:


Traffic flow through several signal controlled intersections was investigated to determine the effect of turning traffic on saturation flow. Results indicate that one left-turning vehicle is the equivalent of 1-3/4 straight moving vehicle and one right-turning vehicle equals 1-1/4 straight moving vehicle.

The frequency of turn signalling was observed at seven study sites and related to driver characteristics, to the type of turning movement, to prevailing traffic conditions, and to the roadway characteristics.


Turn signalling frequencies were related to driver-vehicle-environment characteristics. A "potential-conflict index" was developed and signalling frequencies were found to increase with increased hazard. It is suggested that turn signalling frequencies could be considered as an indirect measurement of the risk involved in a given turning movement. Turn signalling frequencies during over-taking maneuvers were also observed.


Experiments undertaken by the Road Research Laboratory compared saturation flow values for different turning radii of right-turns (under drive-on-left conditions). Both single-lane and dual-lane turns were investigated on a test track. The results indicated the following relationship between the time interval (T) in seconds between successive turning vehicles and the radius of curvature (R) in feet:

\[ T = 1.75 + \frac{8.5}{R} \]

It was found that a change in curvature makes the same proportional change in the time interval for cars turning from a single lane as for cars turning from a double lane.

Gap Acceptance:


Observations were made to determine how long a vehicle will have to wait for a specified gap, given the hourly volume of the traffic stream which is to be crossed. Observations were made of gaps and waiting times at five volume levels and the resulting probability curves are presented.


Measurements of critical lag (defined as that time lag in the main street traffic which will be accepted or rejected by side street traffic with equal
probability) were made at five unsignalized T-intersections in Copenhagen. The two most significant factors affecting critical lag were found to be: 1) the speed of the main street traffic (critical lag increased with increase in speed), and 2) the prevailing right-of-way regulations (the presence of "Stop" signs increased critical lag).

Delay:


A summary of delay studies performed at signalized intersections in the San Francisco Bay area is presented. The studies dealt with methods for field measurement of intersection delay, and with the effect of different signal timings on stopped-time delay.


Evaluation of various types of signal controls at two high volume intersections revealed: 1) average delay/vehicle increases linearly with entering volume up to about 1200 veh/lane/hr, 2) volume density controller yields least delay followed closely by vehicle actuated control, and 3) semi-actuated control is undesirable for high volume intersections.


A study of stopped-time delay was undertaken to provide data to support warrants for certain types of traffic control devices.

Results of the study indicate:
1. Under moderate traffic volumes, average delay to all vehicles is least with 2-way stop control and vehicle actuated control is generally more efficient than fixed-time control,
2. Stopped-time delay to any vehicle which is required to stop is much greater with fixed-time signal control than with any other form of control,
3. Stopped-time delay on the minor highway of a 2-way stop controlled intersection increases with increasing volume of traffic on the major highway.

Other:


The experiment conducted on the Road Research Laboratory's test track revealed: 1) a reduction of the forward visibility of cars (likened to
another model of car) produced a 10 per cent decrease in saturation flow at
traffic signals with a single lane stop line, 2) an increase in the power/weight
ratio of 48 per cent for a particular model of car produced an increase in
saturation flow of 10 per cent, and 3) a 10 per cent increase in saturation
flow was achieved by using cars with automatic transmission. The results
indicate that the capacity of intersections controlled by traffic signals and
hence of urban streets could be increased by improved performance of
vehicles. However, it appears that drivers do not normally use the full
capabilities of their vehicles, so the effect in practice would probably not be
as noticeable as that found in the experiments.

Newby, R. F., "Accident Frequency at Signal Controlled Crossroads with an All-

Generally accepted benefits of an all-red period are: 1) it helps to
clear the intersection of turning traffic, 2) more crossing time is given to
pedestrians, and 3) less risk to vehicles arriving after the green. Following
an accident study at twelve intersections, it was concluded that the all-red
period is also effective in preventing crossroad collisions.

Peleg, M., "Conflict Points at Intersections," Traffic Engineering and Control,

Mathematical expressions are developed to determine the number of
conflict points at intersections based on the number of intersection legs and
the number of traffic lanes per leg. Intersections of one-way streets and
two-way streets as well as rotary intersections are considered in detail. The
author distinguishes between the actual number of conflict points and the
probable number of conflict points, the latter being based on actual vehicle
volumes.

Shumate, Robert P., "Field Observations for Traffic Flow Model Validation,"
Traffic Engineering, Vol. 34, No. 3, December

A modified Coleman-Beattie 35 mm camera mounted at side of road
(disguised as a mailbox) is used to obtain traffic data. The speed of the
vehicle (as measured by radar) and the exposure time are photographed on
each frame. Microfilm viewers are used to reduce the data to usable form
for computer analysis. Headways, speed, travel times and number of over-
takings and passings can be determined.

Wagner, Frederick A., "An Evaluation of Fundamental Driver Decisions and

Field measurements and analysis of fundamental driver decision and
reactions parameters at a stop-controlled intersection indicate a lognormal
relationship between lag or gap size and percentage of acceptance. The
following factors were found to influence driver decisions significantly:
1) pressure of traffic demand, 2) direction of traffic movement during periods
of peak demand, and 3) sequence of gap formation during periods of peak demand.
INTERSECTION CONTROL

Signal Timing:


Equations were derived for computing reaction times for passenger cars and trucks at intersections (starting delay) and distance traveled in time T after green signal.

Diagrams were developed to be used to obtain signal capacity or signal timing, based on equal cycle length, approach speed, distribution of green time, based on probability calculations.


Three criteria are used to evaluate various cycle lengths: delay per vehicle, expected length of queue, and the probability of entering the intersection during the first green phase. Application of the method and the use of the formulas are illustrated in two examples.

The effects of variations in amber time usage, pedestrian intervals and driver reaction time are also presented. The effects of transferring green time allocations from a low to a high volume approach and the use of 3-dial controllers are discussed.

Computations are based on Webster's formula from England.


Two simplified graphs are presented to be used in signal timing. A linear relationship is shown between volume and vehicles/cycle for different cycle times. Also a linear graph is shown between green time/cycle and veh/cycle for different probability of performance levels.

Knowing volumes and the cycle time, author shows how the efficiency of the intersection can be determined. Examples are given.


A nomogram is presented for solving Webster's formula for computing the average delay per vehicle at a single approach to a signalized intersection.
Instructions as to the use of the nomogram and an example illustrating the procedure are presented.


Through a multiple regression analysis based on a sample of 60 intersection approaches, the magnitude of the peak period within the peak hour was expressed in terms of a) the population of the city in which the intersection was located, b) the location of the intersection relative to the CBD and the city limits, and c) the number of vehicle arrivals on a given approach. Average duration of the peak period was approximately 26 minutes. Though arrivals throughout the peak hour did not conform to Poisson, arrivals during the peak period were Poisson.


The functions of the various dial controls on the two-phase volume density traffic signal controller are explained. Factors to be considered in adjusting the timing are described.


This article is a summary of Road Research Paper No. 39, entitled Traffic Signal Settings, by Webster.

Turn Control:


This article is a summary of studies made at several high-volume signalized intersections to evaluate the effectiveness of different designs of roadside and overhead traffic signs for controlling multiple turns (dual left turns or dual right turns). The comparative effectiveness of different roadside double turn signs was also evaluated. It was concluded that the regulatory lane-use control signs in the 1961 edition of the Manual on Uniform Traffic Control Devices should be satisfactory for control of multiple turns until refinements are developed from further research.


The observation was made that a relationship exists between the number of pedestrians crossing the street on each signal cycle and the likelihood of a vehicle penetrating the pedestrian flow when executing a
left turn. Furthermore, it was assumed that the number of vehicles which will be trapped on the red signal, if the outside traffic lane is blocked for part of the cycle time by a vehicle waiting to make a left turn, is a function of both the prevailing volume and the available green time for each traffic lane. Data were collected at urban intersections and curves were produced relating pedestrian volumes, signal timings, and traffic counts. From these curves a critical value can be determined indicating at which point left turns should be banned to avoid the formation of a queue.


New Orleans' experience in permitting left turns at signalized intersections is discussed. The use of an additional phase, an added lane, and the presence of detection equipment are some of the methods used to handle the problem.


Based upon the difficulty of a vehicle making a left turn related to traffic gaps and physical features of the intersection, a Hazard Index is developed by the Oregon State Highway Department. The Hazard Index was then incorporated into a formula which considers construction cost and past traffic accident data. It is suggested that the Hazard Index could be used to establish a priority list of intersections as to the need for left-turn provisions.


Special bi-directional left turn traffic signal controls left turns from a two-way street having separate lanes for left-turn movements. The bi-directional, left-turn signal period trails the main phase for the street from which the left turns originate. Vehicle presence detectors located near the stop line sense the need for additional left-turn time.

Signal Warrants:


From the percentage of ADT volume occurring during the eighth highest hour during the day, the author establishes a confidence interval above and below which one is 95 per cent confident that a traffic signal does or does not meet the warrants. Tables are given based on 67-33 and 50-50 directional distributions.

Results of the research indicate that a warrant for traffic signal control could be based on the relation of the gap availability in the traffic on major streets to the lag or gap acceptance characteristics of the driver on minor streets. The methodology developed can be applied to any unsignalized intersection provided that data on the variations in the distribution of available gaps and characteristics of gap acceptance are collected.


A signal warrant rating system is presented based on the following warrants: 1) vehicle volume warrant, 2) pedestrian volume warrant, 3) accident warrant, 4) through street warrant, 5) progression warrant, 6) one-way street warrant, and any other warrants peculiar to the intersection. The final signal rating established whether 1) a signal is warranted, 2) a signal is not warranted, or 3) a more thorough study of the conditions is needed.

Intersection Capacity:


Some basic concepts of highway and intersection capacity are presented. The capacity parameter is related to the concept of service time in queueing theory, as illustrated by a number of graphs.


An extensive study of one intersection revealed 1) that maximum volumes can be moved through the intersection without complete prohibition of parking and 2) that clear distance required for maximum volumes is a function of the percentage of turns.


This article deals with the two major problems of the application of the level of service concept to the design and operation of freeways, and discusses capacity design of high-type signalized intersections. With regard to the latter, the design procedure developed: 1) permits consideration of lane design in place of total approach width, 2) considers all approaches of the intersection as a single unit to insure better balance, 3) gives consideration to peaking characteristics of traffic, 4) gives consideration to the phenomenon of random vehicle arrivals, and 5) permits the evaluation of a wide range of possible design and operating conditions.

A procedure in the form of nomographs is presented for the graphic solution of the capacity of signalized intersections to simplify the work required by the computational procedures in the 1965 Highway Capacity Manual. Full discussion of the principles and procedures in the application of the charts in addition to sample problems are included.


New criteria for improving traffic flow efficiency at intersections is presented. Other than one- and two-way operation and the presence of parked vehicles, the following factors were found to affect the hourly flow of traffic: 1) peak hour factor, 2) load factor, 3) approach width, and 4) city size. Their effect on hourly volumes is given in the form of graphs and tables.


Capacity figures are given for priority intersections, signalized intersections, and weaving sections and comparisons are made. Formulas are presented for calculating capacity of each type of intersection.

The Amber Phase:


The behavior of a small group of drivers who took part in an experiment on stopping at traffic lights is described. The data concerning their judgments and subsequent performance are given and compared. Equations have been derived from the data which link the proportion of occasions the drivers decided to stop, the proportion of successful stops, the overall stopping distance, the initial speed, the drivers' response times, and the average decelerations during the braking period. Examinations of the errors, hesitations and changes of mind suggest that the distances in which 95 per cent of the drivers stopped successfully might be used as a design parameter in the calculations of the minimum amber period for a traffic light.


A theoretical analysis and observations of the behavior of motorists confronted by an amber signal light are presented. Criteria are given for the design of amber phases whereby the "dilemma zones" are avoided.
This article is concerned with the problem a motorist faces when he is confronted with the onset of the amber phase and he is: 1) too close to the intersection to stop safely and comfortably, and 2) too far from the intersection to pass through before the red phase begins. Minimum amber times were computed: 1) based on probability of stopping curves, and 2) based on assumptions of reaction times and decelerations. Conclusions: "It would appear that amber phases are characteristically too short." The major argument against lengthening amber periods (that drivers would treat them as extensions of green) is questionable.

The problem which confronts the motorist approaching a traffic signal at a moderately high speed when the signal changes from green to amber was investigated. An experiment carried out to record the decisions and performances of drivers at various speeds and distances from a signal-controlled intersection when faced with the amber signal revealed the existence of a range of "critical sections" in the approach from which, if the amber signal were to appear, drivers might be unable either to stop safely or to carry on and clear the intersection before the appearance of the red signal. The lengths of "critical sections" for various approach speeds are given.

Some of the problems related to traffic signals in the City of Melbourne are discussed.

Features of traffic signals designed to control pedestrian traffic in Melbourne are discussed, including the scramble system, late start of vehicular green phase, and special illuminated pedestrian signs.

Before and after studies at 52 intersections revealed accident increase due to signal. A study of 78 flasher installations revealed accident decrease after installation of flasher.

A method of measuring in-service signal intensity is described and evaluated. The sample of signals measured by this method had an average on-axis intensity much less than that argued to be optimum. However, the average intensity of recently installed signals is considered to be adequate but affording little or no margin of safety under exacting conditions of observations. About one-third of the signals measured had intensities which would lead to a high degree of uncertainty when the signal is seen against a bright background.


Current philosophy of traffic signal control in Britain is described. A listing of values of design parameters (vehicle extension, inter-green period, etc.) is included in an appendix.


A pilot study was conducted by the Road Research Laboratory to determine whether or not pre-signals could be used to increase the efficiency of signal-controlled intersections. The results indicated only a slight increase in discharge capacity obtained with the use of the pre-signal. It was hypothesized that there might be a significant increase in discharge capacity if drivers had time to learn to use the system. The author comments that future research should be concerned with determining the effect which turning vehicles might have on the system and also examining the effect of a one-second red-amber period at the main signal on vehicle arrival times at the potential collision point of the intersection.


The author discusses current traffic signal practices in the state of New South Wales, Australia. Basic principles of urban traffic control are presented. The operational aspects of applying traffic signal control to isolated intersections, arterial route systems, and the CBD system are presented.


Current practices are summarized on the use of leading and lagging green intervals as a method of facilitating left turns at signalized intersections. Advantages and disadvantages are enumerated.

The requirements of an ideal detector for general usage in all traffic applications are enumerated. Advantages and disadvantages of over-pavement detectors, on-pavement detectors, in-pavement detectors, and under-pavement detectors are discussed. Author concludes that either the loop or fluxgate type of under-pavement detector comes closest to the ideal with the former most suitable for general usage, and the latter for difficult situations where sharp cut-off and a very clearly defined zone of detection are required.


The article summarizes the results of a study to investigate the use of 1) steady burning yellow arrow, 2) steady burning red arrow, 3) flashing yellow arrow, 4) flashing red arrow in traffic signal operations. Further research is needed to standardize this type of control.


A survey has been conducted on the traffic signal controllers used in some Western European countries. A description is given of the centralized traffic controls with automatic program selection and with traffic actuated signals that are used in coordinated systems. For isolated intersections, the experiences with pre-signals and signal funnels are explained.


An investigation is described, the objective of which was to investigate the operational characteristics of vehicle-actuated signal controllers. The author's approach to the problem has been to postulate models sufficiently representative of actual conditions, yet of sufficient simplicity to obtain their exact solution, both theoretically and by computer simulation. The authors have made the following conclusions regarding the behavior of an isolated two-phase vehicle actuated signal:

1) There exists an "optimum vehicle interval," defined as that unit extension which minimizes the average delay per vehicle using the intersection,

2) The optimum vehicle interval is independent of intersection geometry and is the same for both phases irrespective of the ratio of the traffic flows per phase,

3) The average delay per vehicle using the intersection is typically one-half that of an equivalent fixed cycle traffic signal,

4) The effect of using a value of the vehicle interval greater than optimum is to reduce the percentage of stopped cars, to increase the average cycle time, and to increase the average delay per vehicle.

The concept is presented that use of presence detector between detector and stop line alleviates the need for the initial and vehicle intervals.


The author discusses Toronto's efforts at solving the problem of providing for heavy left-turn movements on urban arterial highways in the face of opposing high volume through-movements. A successful solution involved flashing the green signal indication during the advance period. Analysis of studies made to evaluate the method indicated that the flashing green method of indicating the advance period was definitely superior to the steady green method.


The author reviews applications of presence detectors and proposes functional requirements for loop detectors for use in traffic signal control. The article is based on observation of various types and brands of loop detectors, utilizing roadway loops of various configurations and located at varying distances from the detector.


A brief description is given of installation of an experimental changeable message sign placed 600 feet in advance of the intersection. Sign messages include "Prepare to Stop" and "Slow Traffic Ahead". Though the light is green, the sign directs the driver to take a certain safe action.


The functions of traffic signals are outlined. Some of the management and technical decisions involved in the design of local and system installations are discussed. British and American practices are compared with those adopted in Australia. A sample calculation of signalized intersection capacity is included.
COORDINATED TRAFFIC SIGNALS


SIGNALIZED NETWORK


