*THE SIMULATION OF TRAFFIC FLOW
TO OBTAIN VOLUME WARRANTS
FOR INTERSECTION CONTROL*

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by
R. M. LEWIS

*PURDUE UNIVERSITY
LAFAYETTE INDIANA*

Final Report

THE SIMULATION OF TRAFFIC FLOW
TO OBTAIN VOLUME WARRANTS FOR INTERSECTION CONTROL

TO: K. B. Woods, Director
Joint Highway Research Project

September 5, 1962

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 8-4-26
Project: C-36-17Z

A final report entitled "The Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control" which has been authored by Mr. R. M. Lewis, research fellow (Ford Foundation), is attached. The research was performed under the supervision of Professor H. L. Michael. Mr. Lewis also utilized the research report as his thesis in partial fulfillment of the requirements for the Ph.D. degree.

The research developed suggested warrants for semi-actuated traffic signals and provides valuable information on the average delays sustained by traffic at two-way stop and actuated signalized intersections. The information was obtained by utilizing established quantitative values for traffic flow characteristics and simulating traffic flow through the controlled intersection on a 7090 IEM computer. The model developed was a new one and the results obtained appear to be realistic. The type of data obtained would have been extremely difficult, if not impossible, to obtain by any type of field study.

Simulation of traffic flow on digital computers for answers to traffic flow problems offers great possibilities, with the major current restriction imposed by an absence of quantitative information on traffic flow characteristics.

The report is presented for the record.

Respectfully submitted,

Harold L. Michael, Secretary

HLM:kmc

Attachments

Copy:	F. L. Ashbaucher	F. S. Hill	R. E. Mills
	J. R. Cooper	G. A. Leonards	M. B. Scott
	W. L. Dolch	J. F. McLaughlin	J. V. Smythe
	W. H. Goetz	R. D. Miles	J. L. Waling
	F. F. Havey		E. J. Yoder

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by

Russell M. Lewis
Research Fellow

Joint Highway Research Project

File: 8-4-26

Project: C-36-17Z

Purdue University
Lafayette, Indiana

September 5, 1962

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ABSTRACT

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The Simulation of Traffic Flow to Obtain Volume Warrants for Intersection Control. Major Professor: Harold L. Michael.

Several methods have been devised for controlling vehicular traffic at street intersections. It is important that the best method of control be used for each situation as intersections are the critical factor in determining the efficiency of the entire street system.

This thesis reports the results of a study in which a digital simulation model was developed to determine volume warrants for intersection control. The delays encountered at the intersection were measured and used as the criteria for the establishment of warrants.

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 major arterial had four travel lanes with parking prohibited, while the minor arterial had two travel lanes with parking permitted on both sides. Both arterials were operated as two-way streets. The intersection is typical of many intersections located in intermediate urban and suburban areas. Two types of intersection control were studied; the semi-traffic-actuated signal and the two-way stop sign.

The first phase of the study was the development of the simulation model. Inasmuch as total delay was desired, a realistic method for vehicle

movement was required. A mathematical mode of representation was used, with position, velocity, and acceleration continuous within the accuracy of the computer. A general car-following model was developed for the simulated vehicle, and mathematical expressions were derived to determine vehicle movement during each time increment. Vehicle behavior was governed by four factors — the spacing relationship with the preceding vehicle, acceleration capability, restrictions imposed in slowing for turns, and stopping for traffic control devices.

Vehicle arrivals were generated randomly. A modified binomial headway distribution was developed which incorporated a contagious or platooning effect. A method was devised whereby very short approach lanes were used without affecting vehicle delay, and the time increment of vehicle generation was separated from the time increment of scanning to permit the most advantageous selection of each.

Vehicles moved thru the intersection in accordance with their own desires as affected by the presence of other vehicles and the demands of the traffic control devices. All turning movements were accommodated. Passing was generally permitted when possible on the four-lane major street and was permitted in particular instances on the two-lane minor street.

Because vehicle behavior was specified in mathematical terms, an algebraic compiler was readily used for coding the model. The program was written in the FORTRAN language and run on an IBM 7090 computer. A single program which permitted the selection of either of the two types of control was used. A real time to computer time ratio of forty-five to one was achieved.

The second phase of the study was concerned with running the simulation program for a wide range of volume combinations. Two sets of traffic signal variables and two acceptable gaps at the stop sign were employed. Other variables were fixed at typical values. Output data included the average delay per vehicle for each street and for the intersection as a whole. This information was presented in a set of graphs which showed delay under both actuated-signal and stop-sign control for various traffic volume combinations. These graphs were then used to develop volume warrants. The criteria used was the minimization of average delay for all vehicles in all volume combinations where the average delay per minor-street vehicle was not excessive.

CHAPTER I

INTRODUCTION

The control of vehicular traffic at street intersections has been one of the most studied items in the traffic engineering field, yet much remains unknown. Intersections are the critical element of streets in that their characteristics determine the efficiency and capacity of the entire street system. Here one common area must accommodate the vehicular flow of two streets and the conflicting maneuvers of their several approaches.

Several methods of traffic control have been developed for intersections. These include the basic right-of-way rule, stop signs, and various types of traffic signals. General warrants have been proposed for these methods of control based on vehicular volume, pedestrian traffic, accident records, and other factors. These warrants were developed in part on empirical data, but in some cases are little more than "rules of thumb". While significant effort has been devoted to the determination of warrants for fixed-time traffic signals, specific warrants for actuated signals are lacking (35)*.

One of the foremost problems in the development of warrants is the difficulty of determining the specific behavior of a general class of intersections. There are three basic methods of analyzing the performance

* Numbers in parentheses refer to entries in the List of References.

of any such physical facility. The first is to locate a suitable facility in the field and measure its performance under varying conditions. The second is to build a model and test it. The third is to formulate the fundamental physical laws of its behavior and analyze it mathematically. In the study of traffic intersections there are numerous limitations to each of these methods.

The first complication to the empirical approach is the difficulty of locating an intersection which meets the prescribed specifications. Even having found such a facility it is often most difficult to find a period when it is operating under the required conditions. Furthermore, it is virtually impossible to reduce the number of variables existing so that the particular characteristics desired can be accurately correlated. The effect of local variables may be reduced if many locations are studied, but this procedure greatly expands the scope of such a project.

Another shortcoming of the empirical method is the limited amount of data thus obtained. Usually only a few quantities are observed and these are measured in the immediate vicinity of the intersection. Even in comprehensive studies, such as those employing time-spaced serial photographs, it is difficult to determine the behavior of traffic in the entire area of influence of the intersection. Moreover, the cost of these photographic studies is often excessive.

Some full scale model tests have been conducted at intersections (42), but in most cases the cost of such tests are prohibitive and the results questionable. Small scale laboratory models, in the usual sense, are completely inapplicable to the dynamic problem of traffic flow, since the decision making capabilities of the human operator can not be represented.

A strictly mathematical solution to intersection phenomena is most difficult, as traffic flow is a stochastic process and many variables are involved. Significant progress, however, has been made in reducing the flow of vehicles to a mathematical expression. Nevertheless, there are complications at intersections, such as traffic actuation, the amber light, turning movements, and the interaction of opposing flows, which have not yet been solved (26).

A relatively new research tool that offers much promise for this type of investigation is simulation.

The Simulation Method

Simulation may be thought of as a procedure that combines several of the characteristics of the afore-mentioned methods. Analog simulators of traffic have been suggested utilizing electric analogies (50). In the most part these are unsatisfactory because the vehicle is represented as a passive element completely controlled by external factors.

Digital simulation, however, offers tremendous possibilities in this area. The modern stored-program digital electronic computer possesses the high speed of computation and the logic capabilities that enable it to react in a manner analogous to vehicles traveling on a roadway. By proper programming the behavior of each vehicle represented within the computer may be calculated by following predetermined patterns derived from the observation of real vehicles and/or established mathematical theory.

Digital simulation possesses some unique properties as compared with more conventional methods. It possesses the important advantage of bringing the traffic facility into the laboratory for study under practically

limitless conditions. Precise control of the dynamic traffic process can be maintained and many unwanted variables eliminated. Parameters are varied at the discretion of the programmer, rather than by chance alone.

Simulation on digital computers is not new, but comparatively little work has been done in this area. The modern high-speed computer is a development of World War II. The computers made at that time were individually constructed and used almost exclusively for national defense. Production-model, general-purpose computers were not readily available until about 1954. It is only since that time that experience in traffic simulation has developed.

In 1956 three digital computer simulations were reported in the traffic engineering literature. Gerlough discussed the simulation of traffic flow on a freeway (18). Wong's paper described the simulation of a portion of a multilane boulevard (55). Goode, Pollmar, and Wright constructed a model of a signalized intersection (21). This and other early simulations of an intersection permitted only a limited and somewhat arbitrary action of vehicles.

Two separate studies of intersection simulation were performed by Benhard (6) and Lewis (34). These studies dealt with the intersection of two two-lane streets with actuated signal control. The models were greatly simplified, however, in that turning and passing were prohibited.

Later investigations in this field have incorporated several refinements. The simulation of freeway interchange traffic was presented by Perchonok, Levy, Glickstein, and Findley (38, 20). Wohl developed a model depicting the traffic behavior in a freeway merging area (54). A recent paper by Stark described the simulation of nine blocks of a city street (45).

Research currently being performed by Kell involves the simulation of the intersection of two two-lane urban streets under various types of traffic control (32).

Purpose and Scope

The purpose of this research was two-fold. The first phase of the study was the development of a model, whereby a traffic intersection could be simulated on a digital electronic computer. The model had to be refined to a point such that total delays could be measured. This requirement necessitated the establishment of a realistic acceleration and deceleration procedure for the model vehicles.

The particular intersection chosen for study was a four-legged, right-angled intersection of a high-volume major arterial street with a lower-volume minor arterial street. The major arterial had four lanes with parking prohibited, and the minor arterial had two travel lanes with parking permitted on both sides. Both arterials were operated as two-way streets. The intersection is typical of many intersections located in intermediate urban areas and in suburban areas.

The second phase of the study was the operation of the simulated intersection under two appropriate types of traffic control; namely, the two-way stop sign and the semi-traffic-actuated signal. The purpose was to establish a realistic set of volume warrants for the given class of intersections. Such warrants were to indicate when, from the standpoint of delay, it would be advantageous to go from stop sign control to actuated-signal control. The major variables used were the traffic volumes carried by the two streets.

The Significance of Delay

Delay is a most important factor in the determination of volume warrants. From an economic viewpoint the type of traffic control device that is preferred is the one that results in the minimum delay to motorists. Total or overall delay is the type of delay which has the greatest significance when comparing two types of intersection control (7). Total delay encompasses any delay as caused by the existence of traffic control devices and interaction with other vehicles. An undelayed straight-thru vehicle will pass thru the intersection area at its desired speed. An undelayed turning vehicle will decelerate to a safe turning speed and then regain its desired velocity. Any travel time in addition to these requirements is considered a delay.

In order to relate delays observed at various levels of volume, the figure of merit used was average delay per vehicle. It was realized, however, that the intersection may be operated such that the average delay per vehicle is small, but the average delay per side-street vehicle is excessive. To perceive this situation the average delays per vehicle for each street were also considered.

Most field studies of intersection control have been based on stopped delay, because total delay is a most difficult quantity to measure. To permit comparison with field studies and utilization in economic studies, stopped delay was included as an additional output of the simulation model. A complete economic study would include not only the cost of time resulting from delay, but also the cost of motor vehicle operation. Different operating costs are associated with acceleration and deceleration as compared to stopped operation, and the inclusion of both total and stopped delay facilitates the determination of these costs.

CHAPTER II

DEVELOPMENT OF THE SIMULATION MODEL

Mode of Representation

Modes Previously Used

There are various methods which may be used to represent the flow of traffic within the computer. The first traffic simulations employed a physical notation (18, 21). Binary "1's" were used to represent vehicles and "0's" were used to indicate the spaces between vehicles. Groups of memory cells were figuratively placed end to end to represent the roadway. Algebraic manipulations caused the "1's" to change position, thereby simulating the flow of traffic. With this mode of representation the vehicles must occupy only certain specified locations (bit positions) along the roadway and individual vehicles have no identity as such.

The memorandum notation utilizes an entire word to represent a vehicle. Various parts of the word are used for such individual characteristics as its time of entry into the system, its desired velocity, et cetera. These parts may be extracted and interpreted as desired. This method is more versatile in that each vehicle's characteristics are identifiable as it moves thru the system. This makes it possible to compute the delays associated with each individual vehicle.

Most simulation programs which have used the memorandum notation have considered the roadway as being composed of a series of unit blocks (55).

These blocks represent the various positions which a vehicle can occupy. Each block is one lane wide and has a length which is equivalent to some fraction or multiple of the unit vehicle length. Thus a vehicle may occupy only a limited number of discrete positions. Velocity and acceleration are step functions of the unit block and the time increment of scanning. In other words, the only velocities possible are zero or some integer number of blocks per time increment. This procedure is adequate for some models, but offers severe restrictions when realistic total delays are desired. This lack of flexibility can be offset to some extent by decreasing the time increment between successive processings; however, this greatly increases the computational work required.

A third method of representation has been called a mathematical notation (18). This form of representation is similar to the memorandum notation, except that, in addition to its other characteristics, each vehicle is associated with its own position indicator. Its position is therefore continuous within the accuracy of the computer. At any time a vehicle's new position can be computed simply by adding its velocity (in units related to the time increment) to its previous position coordinate. Spacings between vehicles are available from their respective coordinates and the vehicle length.

A fully mathematical notation has generally been avoided since it requires a more complicated logic. Maneuvers, such as turns, which must be accomplished at a specified location are more difficult when the vehicle may occupy any position at the start of the maneuver. Furthermore, the mathematical processing of vehicles is more complex; thereby increasing the computer time required. On the other hand, the elimination of

limitations on the position increment will allow some increase in the size of the time increment for the same model accuracy.

The Adopted Mode

The mode of representation that was employed is a variation of the mathematical notation. Because an algebraic compiler was selected for the coding of the program, the entire representation had to be in an algebraic format. Moreover, since bit manipulation could not be performed within the scope of the compiler, the various vehicle characteristics could not be coded within the same word. One word had to be used for each characteristic. As a vehicle was then composed of several computer words, it became cumbersome to shift the vehicle for its relative position changes in the system. Movement was accomplished, in effect, by making the roadway "flow" past the vehicle.

The entire roadway system was represented by a three-dimensioned mathematical array. The length dimension corresponded to relative position along the roadway, the vertical dimension accommodated all the information or characteristics of each particular vehicle, and the width dimension represented the several traffic lanes.

Because the vehicles did not move within the array, a very long array would have been needed to handle all the traffic within a study period. Thus the memory capacity of the computer would soon have been exceeded. To circumvent this problem the concept of a "circular array" was utilized. The ends of the array were mathematically connected to provide a roadway which was sufficient in length to handle all of the traffic within the study section. Two items of information were kept in special registers for each traffic lane: the index position of the lead vehicle and the

number of vehicles in the lane. Knowing this information enabled the extraction of the characteristics for any vehicle by stating its relative position with respect to the lead car. Each vehicle maintained its own record of its absolute position, or X coordinate. When a vehicle left a lane, the lead index was shifted to the vehicle immediately behind, and the lane count was reduced by one. When a vehicle entered a lane, its characteristics were placed in the position immediately after the last vehicle, and the lane count was increased by one. It was unnecessary to erase the vehicle characteristics when a vehicle left since the computer stored the new information "on top of" any residual data.

Selection of the Time Increment

In actuality all of the drivers of vehicles within the roadway system are continually and simultaneously making decisions and modifying their behavior. The computer, however, can make only one simple logical choice at a time. In order to control all the occurrences at any given instant, it must process all decisions sequentially. In other words, it must process each decision for every car, for each vehicle in every lane, and for each lane within the system. It must do this in accordance with a prescribed sequence for each instant of time to be considered. The time parameter must therefore be incremental.

The selection of a suitable time increment is most important. If the time increment chosen is too large, it will not be possible to simulate all the events that may occur. On the other hand, if the increment is too small, many additional computations will be required for each event. This will result in additional computer time, thereby increasing the cost of running the problem on the computer.

The increment selected must be no smaller than the smallest event to be simulated. The time for all other events must be some multiple of the time increment. This requirement will apply to such items as the traffic controller settings, acceptable gaps for crossing, reaction times, et cetera.

In most simulations a critical factor is the minimum headway for vehicles. That is, since vehicles may enter the system only at each time increment, their minimum time spacing will be equal to, or some multiple of, this increment. A method was developed for this study which isolated vehicle generation from the time increment. The only requirement was that the minimum intervehicular headway and the time increment be some multiple of each other.

A time increment of one second between successive scans of the system was selected as adequately meeting the above criteria.

The Mathematics of Vehicle Behavior

Velocity and Acceleration Characteristics

It was assumed that all vehicles would attempt to travel at an average velocity $\bar{V}$. A value of 30 miles per hour or 44 feet per second was selected as this average velocity. Units of feet and seconds were used throughout this study for the sake of simplicity.

A uniform rate of speed change was also assumed under free flowing conditions. Although observed rates of acceleration are not quite uniform, the uniform case supplies an adequate approximation of the real case.

From a study of intersection performance, Greenshields set forth the concept that different forms of speed change exist (24). A chronotropic

acceleration is one where delay is independent of the time lost in speed change; such as a vehicle stopping for a red light. Regardless of the time lost in stopping, the vehicle is still delayed until the light turns green. Functional speed change occurs when the loss of time is dependent on the rate of speed change; for example, a bus stopping to discharge passengers. Sometimes the driver is not aware of which situation exists; such as when stopping for a stop sign. At other times a combination of circumstances will exist. It was postulated that vehicles will be operated in such a manner as to minimize their delays. Therefore, the values selected for speed changes were representative of the functional type.

Obviously all free-flow acceleration is functional. It was assumed that all vehicles would attempt to utilize an acceleration rate $\bar{A}$ of 3 feet per second per second (23, 43, 49). It was recognized, however, that higher rates of acceleration are used in crossing maneuvers when vehicles are under the pressure of opposing traffic flows. This behavior pattern was accommodated for vehicles accelerating from a stopped or near stopped condition at stop signs and for left turn maneuvers. In such cases vehicles must accelerate rapidly to take advantage of available gaps in the traffic stream. For this case accelerations of 6, 5, and 4 feet per second per second were used for the first three seconds respectively, and an acceleration of 3 feet per second per second was used thereafter.

Studies have shown that deceleration rates of 8 to 9 feet per second per second are comfortable while rates of up to 16 feet per second per second can be used without severe discomfort (27, 53). Typical deceleration rates are approximately twice the value of typical acceleration rates (4). Under free flowing conditions the average deceleration rate $\bar{D}$ which

all vehicles attempted to use was assumed to be 6 feet per second per second. However, when drivers are presented with the amber signal, much higher rates may be expected. For this situation a deceleration rate of up to 12 feet per second per second was utilized (12, 37).

In the simulation model velocity and rates of acceleration and deceleration were sometimes affected by the presence of other vehicles within the system. In no case, however, was $\bar{V}$ or $\bar{A}$ exceeded.

Car-Following Procedure

In recent years there has been much interest in the development of car-following models. Newell and Greenberg have used physical analogies based on the kinetic theory of gases and on fluid dynamics (36, 22). Research involving actual field studies and theoretical investigations has been reported by Pipes, Chandler, Herman, Montroll, Potts, Rothery, Gazis, Kometani, and Sasaki (39, 9, 28, 14, 33). Most of these studies are concerned with the capacity or near capacity situation, where cars are following each other as closely as possible. They attempt to relate the spacings between successive vehicles to such factors as the velocity and acceleration of the lead vehicle and the velocity and reaction time of the following vehicle.

For this research problem a car-following model was needed which would be applicable for a wide range of traffic volumes including well-below capacity conditions. Such a model was developed along practical lines which yielded relatively realistic results insofar as delays were concerned.

The derivation of this car-following relationship was based on the premise that vehicles do not collide, and that they are operated in such a manner as to provide for safety. The margin for safety, however, may

be extremely small. This premise is justified by the fact that the number of accidents is infinitesimal as compared with the number of opportunities for the occurrence of accidents.

Derivation of the Spacing Equation. Vehicles stopped in a queue are at some average minimum spacing which includes the vehicle length and a clear space. This average minimum spacing P is measured from the front bumper of the lead vehicle to the front bumper of the following vehicle. Field studies have shown that P has a value of approximately 22 feet (46, 24, 5).

When vehicles are moving at the same speed, the minimum desired spacing S (measured from front to front of adjacent vehicles) has been shown to be linearly related to velocity. One study resulted in the equation

$$S \geq P + 1.09 V ;$$

where S and P are in feet and V is velocity in feet per second. One conclusion of this study was that the minimum clear spacing was equal to the product of brake reaction time and velocity, plus a few feet (24). Other equations that have been proposed yield somewhat similar spacings (49, 10).

The relationship that was chosen for the uniform velocity case was

$$S \geq P + V .$$

This equation is substantiated by the practical consideration by braking behavior. Consider the example of two vehicles which are traveling at equal velocities and at minimum spacing, and which have similar braking capabilities. If the preceding vehicle stops, and if a brake reaction time of one second is assumed for the following vehicle, then both vehicles will come to rest with S equal to P .

Next consider the situation where the following vehicle is traveling at a higher speed than the preceding vehicle. Let the preceding vehicle (as noted by primed values) be at speed V_1' at time t_1 , then decelerate uniformly to speed V_2' at t_2 , and continue at this speed until time t_3 . The distance traveled during this maneuver is X' . The following vehicle is at a higher initial speed V_1 at time t_1 and decelerates to speed $V_2 = V_2'$ at time t_3 . This vehicle travels a distance X during the time t_1 to t_3 . The following vehicle is to be at its minimum desired spacing S_1 at the start of the maneuver and at a similar spacing S_2 at the conclusion of its deceleration. The relationships are shown diagrammatically in Figure 1.

Using the basic laws of motion for uniform deceleration, and letting D represent the rate of deceleration,

$$X = \frac{1}{2D} (V_1'^2 - V_2'^2) , \text{ and} \quad \text{eq. 1*}$$

$$X' = \frac{1}{2D} (V_1'^2 - V_2'^2) + V_2' (t_3 - t_2) . \quad \text{eq. 2}$$

$$\text{However; } t_3 - t_1 = \frac{1}{D} (V_1 - V_2') , \text{ and} \quad \text{eq. 3}$$

$$t_2 - t_1 = \frac{1}{D} (V_1' - V_2') . \quad \text{eq. 4}$$

Using equation 3 and 4 one finds that

$$t_3 - t_2 = \frac{1}{D} (V_1 - V_1') .$$

Substituting this value in equation 2 gives the following result:

* Equations are numbered consecutively thruout the text.

FIGURE 1. FACTORS INVOLVED IN THE SPACING RELATIONSHIP

FIGURE 2. DIAGRAM OF THE SPACING RESTRICTION

$$X' = \frac{1}{2D} (V_1'^2 - V_2'^2) + (V_2' / D)(V_1 - V_1') . \quad \text{eq. 5}$$

Since at time t_3 the two vehicles are at the minimum spacing and at equal velocities,

$$S_2 = P + V_2' . \quad \text{eq. 6}$$

From Figure 1 it can be seen that

$$S_1 = S_2 + X - X' . \quad \text{eq. 7}$$

Substituting the values obtained in equations 1, 5, and 6 into equation 7,

$$\begin{aligned} S_1 &= P + V_2' + \frac{1}{2D} (V_1'^2 - V_2'^2) - \frac{1}{2D} (V_1'^2 - V_2'^2) \\ &\quad - (V_2'/D)(V_1 - V_1') . \end{aligned} \quad \text{eq. 8}$$

By expanding and collecting terms equation 8 reduces to

$$\begin{aligned} S_1 &= P + V_2' + \frac{1}{2D} (V_1'^2 - V_1'^2) + \frac{1}{D} (V_1' V_2') \\ &\quad - \frac{1}{D} (V_1 V_2') . \end{aligned} \quad \text{eq. 9}$$

Let case I be the situation that occurs when the lead vehicle stops (i.e. when $V_2' = 0$). Equation 9 then becomes

$$S_1 = P + \frac{1}{2D} (V_1'^2 - V_1'^2) . \quad \text{eq. 10}$$

Let case II be the situation that results when the lead vehicle maintains a constant speed throughout the maneuver (i.e. $V_1' = V_2'$). Then equation 9 reduces to

$$S_1 = P + V_1' + \frac{1}{2D} (V_1 - V_1')^2 . \quad \text{eq. 11}$$

Two additional situations exist: (a) when both vehicles are at equal velocities, and (b) when the lead vehicle is stopped throughout the maneuver. These are merely special cases of case II.

The spacing equation was based on case II with the one change that the V_1' term was replaced by V_1 . This provided a slight margin of safety when the following vehicle was traveling at the higher velocity. The spacing equation thus became

$$S = P + V_1 + \frac{1}{2D} (V_1 - V_1')^2 \quad . \quad \text{eq. 12}$$

It can be shown that this equation provides a reasonable factor of safety for case I which is the more critical, but less common, situation. Case II may be considered safe if it provides a spacing that is at least equal to that of case I.

Comparing the adopted spacing equation 12 with the spacing required by case I, equation 10, it is to be proven that

$$P + V + \frac{1}{2D} (V - V')^2 \geq P + \frac{1}{2D} (V^2 - V'^2) \quad . \quad \text{eq. 13}$$

By expanding and cancelling terms this equation reduces to

$$D \geq V' - (V'^2/V) \quad . \quad \text{eq. 14}$$

If the value of D used is at least as great as that shown, then case I is adequately provided for. It may be seen in equation 14 that D will be largest when V is maximum. Setting V equal to 44 and differentiating,

$$\frac{dD}{dV'} = 1 - \frac{V'}{22} \quad . \quad \text{eq. 15}$$

Setting equation 15 equal to zero and solving for V' , one finds that D is a maximum when V' equals 22 feet per second and when V equals 44 feet per second. By substituting these values in equation 14,

$$D = 22 - (22^2/44) = 11 \text{ ft/sec}^2 .$$

This deceleration is still within the reasonable range of deceleration rates. This high rate of deceleration is required only in the unusual case where the following vehicle is traveling at $\bar{V}$ and approaching the preceding vehicle which has a velocity of $\bar{V}/2$, and at the instant when the following vehicle starts to slow to maintain its required spacing, the preceding vehicle also starts decelerating.

Since the computer program processes vehicles sequentially by proceeding down the lane backwards, the preceding vehicle has already been relocated at the time the following vehicle is processed. The decision of which variation of the spacing equation is applicable is therefore based on the current velocity of the preceding vehicle. Thus the generalized spacing equation is

$$S \geq P + V_t + \frac{1}{2D} (V_t - V'_t)^2 (Q) ; \quad \text{eq. 16}$$

where Q is defined as

$$Q = 1 \text{ when } V_{t-1} > V'_t , \text{ and}$$

$$Q = 0 \text{ when } V_{t-1} \leq V'_t .$$

The subscripts refer to increments of time. When the preceding vehicle is at a higher velocity, acceleration limitations become significant, and spacing is seldom critical.

The Spacing Restriction. Spacing is merely one of several restrictions that limit vehicle movement. When spacing is critical, speed is adjusted so that at the end of each time increment a vehicle's position with respect to the preceding vehicle is no closer than desired. By using

this restriction the rate of deceleration is not specified directly and may vary over some range. Ordinarily the deceleration rate will not exceed the value D used in the spacing equation.

To derive the spacing restriction let ZS equal the distance which the following vehicle travels during one time increment. Again, using subscripts to refer to time and primes for the preceding vehicle, the movement during one increment of time is as shown in Figure 2.

Assuming a uniform rate of acceleration during each time increment and using a time increment equal to unity (one second), the basic equation for movement in the model is

$$Z = \frac{1}{2} (v_{t-1} - v_t) \quad . \quad \text{eq. 17}$$

It can be seen in Figure 2 that

$$ZS = X_t' - X_{t-1} - S \quad . \quad \text{eq. 18}$$

First, taking the case where $v_{t-1} > v_t'$, the appropriate spacing condition is selected from equation 16. Substituting this value for S in equation 18 yields

$$ZS = X_t' - X_{t-1} - P - v_t - (1/2\bar{D})(v_t - v_t')^2 \quad .$$

Replacing v_t by the value obtained from equation 17 results in

$$\begin{aligned} ZS = X_t' - X_{t-1} - P - 2ZS + v_{t-1} - (1/2\bar{D})(2ZS - v_{t-1} \\ - v_t')^2 \quad . \end{aligned}$$

Expanding and collecting terms,

$$\begin{aligned} ZS^2 \left[\frac{2}{\bar{D}} \right] + ZS \left[3 - (2/\bar{D})(v_{t-1}) - (2/\bar{D})(v_t') \right] \\ - X_t' + X_{t-1} + P - v_{t-1} + (1/\bar{D})(v_{t-1})(v_t') \end{aligned}$$

$$+ (1/2\bar{D})(V_{t-1}^2) + (1/2\bar{D})(V_t'^2) = 0 .$$

By using the quadratic formula and selecting the significant root, one obtains

$$ZS = \frac{1}{2} V_{t-1} + \frac{1}{2} V_t' - \frac{3\bar{D}}{4} + \left[\frac{9\bar{D}^2}{16} - \frac{\bar{D}}{4} V_{t-1} - \frac{3\bar{D}}{4} V_t' + \frac{\bar{D}}{2} (X_t' - X_{t-1} - P) \right]^{1/2} ; \quad \text{eq. 19}$$

$$\text{when } V_{t-1} > V_t' .$$

Next take the case where $V_{t-1} \leq V_t'$. Again, using equations 16 and 18

$$ZS = X_t' - X_{t-1} - P - V_t .$$

Substituting for V_t the value obtained from equation 17, and solving for ZS gives

$$ZS = \frac{1}{3} \left[X_t' - X_{t-1} - P + V_{t-1} \right] ; \quad \text{eq. 20}$$

$$\text{when } V_{t-1} \leq V_t' .$$

The Acceleration Restriction. Another restriction involved with vehicle behavior is based on acceleration. When free to do so, a vehicle will continue to accelerate at $\bar{A}$ until the maximum permissible velocity $\bar{V}$ is attained. Let ZA be the distance that a vehicle travels in one time increment based on the acceleration restriction. Considering the time increment as unity and using the relationship indicated in equation 17,

$$ZA = \frac{1}{2} \left[V_{t-1} + (V_{t-1} + \bar{A}) \right] ; \quad \text{eq. 21}$$

$$\text{where } (V_{t-1} + \bar{A}) \text{ must be } \leq \bar{V} .$$

Slowing Procedure

In addition to the car-following criteria, a vehicle must also adjust its behavior in accordance with the requirements of traffic controls and the limitations associated with turning maneuvers.

The Stopping Restriction. When decelerating for a traffic control device, such as a traffic signal or stop sign, the vehicle adjusts its speed for each time increment. Let ZD be the distance traveled during a time increment based on the stopping restriction. Let x be the distance between the vehicle and the stopping point at time $t-1$. Using the basic motion equations based on uniform acceleration,

$$V_t^2 = 2D (x - ZD) \quad . \quad \text{eq. 22}$$

By solving equation 22 for V_t and substituting this value in equation 17, one obtains

$$ZD = \frac{1}{2} V_{t-1} + \frac{1}{2} \left[2D (x - ZD) \right]^{1/2} \quad .$$

Transposing terms and squaring each side of this equation, the result is

$$ZD^2 + ZD \left[\frac{D}{2} - V_{t-1} \right] + \left[\frac{1}{4} V_{t-1}^2 - 3x \right] = 0 \quad .$$

By using the quadratic formula to solve for ZD and selecting the significant root,

$$ZD = \frac{1}{2} V_{t-1} - \frac{D}{4} + \left[\frac{D^2}{16} - \frac{D}{4} V_{t-1} + \frac{D}{2} x \right]^{1/2} \quad . \quad \text{eq. 23}$$

The Turning Restriction. During the turning maneuver it is assumed that a free flowing vehicle will decelerate uniformly up to a point during the turn which is called the "turn point". Once past the turn point

the vehicle is free to accelerate normally. Let v be the maximum velocity permitted at the turn point, and let x be the distance from the turn point at time $t-1$. ZT is the distance which the vehicle will travel in one time increment in accordance with the turning restriction.

The basic law of motion for uniform acceleration applicable to this situation is

$$V_t^2 - 2\bar{D} (x - ZT) = v^2 . \quad \text{eq. 24}$$

Substituting the value for V_t obtained from equation 24 in equation 17,

$$ZT = \frac{1}{2} V_{t-1} + \frac{1}{2} \left[v^2 + 2\bar{D} (x - ZT) \right]^{1/2} .$$

By transposing terms and squaring each side of the equation, it is found that

$$ZT^2 + ZT \left[\frac{\bar{D}}{2} - V_{t-1} \right] + \left[\frac{1}{4} V_{t-1}^2 - \frac{1}{4} v^2 - \frac{\bar{D}}{2} x \right] = 0 .$$

Solving this equation by the quadratic formula and selecting the significant root, the result is

$$ZT = \frac{1}{2} V_{t-1} - \frac{\bar{D}}{4} + \left[\frac{\bar{D}^2}{16} + \frac{v^2}{4} - \frac{\bar{D}}{4} V_{t-1} + \frac{\bar{D}}{2} x \right]^{1/2} . \quad \text{eq. 25}$$

Equation 25 is only applicable when the vehicle does not proceed beyond the turn point during the given time increment. When $ZT > x$, a different solution is indicated. It is convenient to first consider whether or not the maximum velocity permitted at the turn point can be exceeded. Based on acceleration capabilities the maximum velocity possible at the turn point is given by the equation

$$V_{\max} = \left[V_{t-1}^2 + 2 \bar{A} x \right]^{1/2} . \quad \text{eq. 26}$$

If $V_{\max} < v$, then the turning restriction is not applicable. When $V_{\max} > v$, the alternate solution for ZT is required.

In the latter situation let $(1-T)$ be the time required for the vehicle to reach the turn point. The velocity at the turn point will be equal to v , and the time required is given by the distance divided by the mean velocity. That is,

$$1 - T = \frac{2x}{V_{t-1} + v} \quad . \quad \text{eq. 27}$$

The time available for acceleration after passing the turn point is then given by T , and

$$ZT = x + v T + \frac{1}{2} \bar{A} T^2 \quad . \quad \text{eq. 28}$$

For this one instance a special computation of V_t is required, as the change in velocity is not at a uniform rate during the previous time increment. The applicable equation is

$$V_t = v + \bar{A} T \quad . \quad \text{eq. 29}$$

The turn point is located at some point approximately midway thru the turning maneuver. It has been shown that turning vehicles with a relatively high initial velocity start decelerating at some point prior to turning and start to regain speed at some point during the turn (13). Vehicles with a low initial speed, however, may accelerate thruout a major portion of or even the entire turning maneuver. A mid-turn location for the turn point would have this effect. From the standpoint of delay, its location is not critical.

Turning speeds depend to some extent on the direction of turn. There is a tendency to use a slower turning speed for right turns than for left

turns due to the shorter turning radius available. The relative lack of interference for right turns, however, may have the opposite effect. Equal turning speeds were therefore assumed for both the left and right turn maneuvers. The maximum velocity at the turn point has been observed to be in the neighborhood of 15 feet per second (13, 16, 41); therefore this value was utilized.

The Generation of Vehicles

Because it was assumed that the intersection is somewhat isolated from the effects of adjacent traffic controls, the arrival of vehicles at the intersection was essentially random. Two possibilities existed for the determination of arrivals. First, actual field data could have been utilized. This procedure has the two-fold disadvantage that the securing of such unbiased data over the full range of traffic volumes required would be a tedious undertaking, and that the supplying of this information to the program is most inefficient. The external communication speed of the computer is very slow as compared with its internal computational ability. The preferred method was to program the computer so that it could calculate its own vehicle arrivals. This was done by supplying it with a suitable mathematical distribution and a method of securing random numbers.

Random Number Generation

Although a table of random numbers could have been supplied, the use of a pseudo-random number generator was much preferred. Many thousands of such numbers were required. A pseudo-random number is one for which each number is determined uniquely from the preceding number by some

computational scheme. This procedure had the important advantage that the series could be reset at will. This was essential in order to provide the same traffic at the intersection while testing it under variations in traffic control. The use of identical traffic eliminated the variability in delays as caused by the traffic pattern itself.

The pseudo-random number generation method used is known as the multiplicative congruential method, the particular formulation having been proposed by Taussky and Todd (47). Let R_0 be the initial random number selected. Subsequent numbers are generated according to the formula

$$R_m = \rho \cdot R_{m-1} \pmod{b^n} ,$$

where ρ is a suitable multiplier, b is the number base and n is the number of digits in the word size of the computer used*. The particular values used were R_0 (the initial number) = 1, 3, or 5 and $\rho = 2^{15}$. As is the case with all known methods for the generation of pseudo-random numbers, this method produces numbers that become cyclic. When using the stated parameters, the sequence repeats itself after approximately 2^{33} numbers.

Distributions Previously Used

Much has been written concerning the apparent randomness of vehicle arrivals at a point in the roadway. As early as 1936 Adams compared observations on vehicle arrivals to values obtained from the poisson distribution and obtained good agreement at relatively low traffic volumes (1). Since that time the poisson distribution has been extensively employed in many theories concerning vehicular traffic.

The poisson theory is based on the random placement of discrete points of a line. The automotive vehicle, however, occupies a finite length of

* $b = 2$ and $n = 35$ for the IBM 7090 Computer.

roadway. Thus the actual behavior deviates considerably from the theoretical at higher traffic volumes. At capacity, moreover, arrivals may approach a uniform spacing, and the theory is inappropriate.

When the poisson theory is applied to the distribution of time spacings between adjacent vehicles rather than being used as a counting distribution, an exponential distribution results (17). The exponential distribution is continuous as is the physical phenomena it represents. To compensate for the fact that there is some minimum non-zero headway (time spacing) which can exist between successive vehicles, Gerlough has proposed the shifted exponential distribution. In this distribution the exponential curve is translated a small distance away from the origin along the time axis (19).

Another complication is the so called platooning effect of vehicular traffic. At any but the lowest traffic volumes, vehicles are not completely free to select their own positions in the roadway unless the opportunity to pass is continuously available. For the same traffic volumes more platooning occurs on two-lane roads than on multi-lane roads due to the greater passing restrictions. While the distribution of vehicles on four-lane roads is approximately poisson for a wide range of traffic volumes, the distribution on two-lane roads has been shown to deviate considerably from such a pattern (25).

A most promising method of accounting for this platooning effect was first proposed by Schuh1 (44). He pointed out that a traffic stream can be composed of a combination of free-flowing and constrained vehicles each of which conforms to a poisson-like behavior. The distribution of headways which is based on this premise is called a composite exponential

distribution and compares favorably with data from field observations. Research is in progress to determine the several parameters of this distribution (31).

Because the computer can attempt the generation of vehicles only at certain increments of time, the resultant distribution of headways will be discrete rather than continuous. A discrete distribution which has been used in some traffic simulations is binomial in nature (21, 52). The binomial distribution is known to closely approximate the poisson when the probability of an occurrence is small. The probability of an arrival at each time increment is determined by the traffic volume desired. This probability is simply compared to a random fraction at each time increment. If the random fraction is smaller than the probability, a vehicle is considered to have arrived at that instant. On the other hand, the use of an exponential distribution is more complex and time consuming, as it involves a solution based on a successive approximation or Monte Carlo approach (19).

Derivation of the Distribution Used

The distribution which was developed is a modified binomial distribution in which two different levels of probability are employed. This distribution retains the computational ease of the binomial distribution, but incorporates a contagious or platooning effect and provides for the existence of some minimum headway. Its derivation is based on the premise that if vehicles tend to travel in bunches, the probability of an arrival at each time increment is no longer constant. Two probabilities of an arrival are used. It is hypothesized that a platoon exists when vehicles are traveling at or below a certain headway and ceases to exist when this

specified headway is exceeded. That is to say; the occurrence of a recent arrival enhances the probability of an arrival at the present instant. Likewise; if the previous arrival was some time ago, the probability of an arrival at this instant is diminished.

It will first be necessary to define the several terms used in the derivation. These terms and their associated symbols are as follows:

h = headway or the time spacing between the front of adjacent vehicles as they pass a given point on the roadway.

$\bar{h}$ = the mean of all headways.

e = the minimum headway permitted.

r = the maximum headway for which the probability of an arrival is enhanced.

n = any value of h .

p = the probability of an arrival at any time increment, assuming a uniform probability of arrivals.

q = the probability of no arrival at any time increment, assuming a uniform probability of arrivals = $1 - p$.

p_a = the enhanced probability of an arrival at a time increment when $e \leq h \leq r$.

$q_a = 1 - p_a$.

p_b = the diminished probability of an arrival at a time increment when $h > r$.

$q_b = 1 - p_b$.

K = the fraction of all headways which are $\leq r$.

By assuming a uniform probability of an arrival at each time increment the basic probability equation may be obtained. The probability of

a headway $\geq h$ is the product of the probabilities that no vehicle has arrived at each time increment since the last arrival of a vehicle. That is;

$$P(h \geq n) = q^{n-1} .$$

Thus;

$$P(h = n) = q^{n-1} - q^n .$$

In order that the traffic volume remain at the level specified, it is necessary to compensate for the fact that headways less than e are rejected. The area under the probability curve must be the same both before and after truncation. This means that after truncation of the small headways, each ordinate must be multiplied by a factor of

$$\frac{1}{1 - P(h < e)} = \frac{1}{1 - [1 - q_a^{e-1}]} = \frac{1}{q_a^{e-1}} ;$$

where $P(h < e)$ is the probability before truncation of a headway less than the minimum value desired. The general expressions for the probabilities of arrivals can now be formulated.

When $e \leq h \leq r$,

$$P(h = n) = \frac{1}{q_a^{e-1}} [q_a^{n-1} - q_a^n] ;$$

$$\text{or,} \quad P(h = n) = q_a^{n-e} - q_a^{n-e+1} . \quad \text{eq. 30}$$

Likewise;

$$P(h > r) = \frac{1}{q_a^{e-1}} \cdot q_a^r = q_a^{r-e+1} . \quad \text{eq. 31}$$

Therefore; when $H > r$,

$$P(h = n) = q_a^{r-e+1} (q_b^{n-r-1} - q_b^{n-r}) . \quad \text{eq. 32}$$

The value of q_a may be obtained directly from equation 31. By definition

$$q_a^{r-e+1} = 1 - K \quad . \quad \text{eq. 33}$$

Solving for q_a and rewriting in terms of p_a ,

$$p_a = 1 - (1 - K)^{\frac{1}{r-e+1}} \quad . \quad \text{eq. 34}$$

For uniform probability the general expression for the weighted mean of all headways is given by

$$\sum_{n=1}^{\infty} \left[(q^{n-1} - q^n)(n) \right] \quad .$$

For the proposed distribution the product of headways $\leq r$ and their respective probabilities is

$$\sum_{n=e}^r \left[(q_a^{n-e} - q_a^{n-e+1})(n) \right] \quad ,$$

and the mean headway $> r$ multiplied by the probability of its occurrence is

$$q_a^{r-e+1} \left[r + \frac{1}{p_b} \right] \quad .$$

Therefore;

$$\bar{h} = \sum_{n=e}^r \left[(q_a^{n-e} - q_a^{n-e+1})(n) \right] + q_a^{r-e+1} \left[r + \frac{1}{p_b} \right] \quad . \quad \text{eq. 35}$$

By expanding equation 35 it is found that

$$\begin{aligned} \bar{h} = & (e) - (e) q_a + (e+1) q_a - (e+1) q_a^2 \\ & + \dots + (r-1) q_a^{r-e-1} - (r-1) q_a^{r-e} \end{aligned}$$

$$\begin{aligned}
& + (r) q_a^{r-e} - (r) q_a^{r-e+1} + (r) q_a^{r-e+1} \\
& + \left(\frac{1}{p_b}\right) q_a^{r-e+1} .
\end{aligned}$$

Concelling and collecting terms,

$$\bar{h} = e + \sum_{n=1}^{r-e} q_a^n + \left(\frac{1}{p_b}\right) q_a^{r-e+1} .$$

Therefore;

$$p_b = \frac{q_a^{r-e+1}}{\bar{h} - e - \sum_{n=1}^{r-e} q_a^n} ,$$

and substituting in the numerator the expression obtained in equation 33,

$$p_b = \frac{1 - K}{\bar{h} - e - \sum_{n=1}^{r-e} (1 - p_a)^n} . \quad \text{eq. 36}$$

Selection of the Distribution Parameters

Gresnshields has reported that when comparing observed data on vehicle spacings with theoretical (poisson) values, the field data resulted in an excess of spacings below 200 feet in length and a deficit of spacings greater than 200 feet (25)*. Car-following research has indicated that the correlation between a vehicle's behavior and the behavior of the preceeding vehicle decreases rapidly when the distance between the two vehicles exceeds 200 feet (29). Minimum headways vary from 2 seconds down to a low of about 1/2 second. The average minimum headway has been found to be about 1 1/2 seconds (24). This selection is substantiated by capacity studies where the maximum possible capacities observed have approached

* 200 feet = 4.55 seconds at a velocity of 44 feet per second.

2400 vehicles per hour per lane, which corresponds to an average headway of 1 1/2 seconds.

Several factors are involved in the selection of the time increment of vehicle generation. Because a discrete distribution was used to represent headways which are of a continuous nature, the smaller the increment, the better the approximation. The time increment of generation must also bear a relationship to the headway parameters selected and to the time increment of scanning. A 1/2 second time increment was used for vehicle generation. This means that at a speed of 44 feet per second all spacings were some multiple of 22 feet. The minimum headway selected was 1 1/2 seconds, and the maximum headway for which the probability of an arrival was enhanced was 4 1/2 seconds.

The equations for the computation of the two probabilities therefore reduced to

$$p_a = 1 - (1 - K)^{\frac{1}{7}}, \quad \text{eq. 34a*}$$

and

$$p_b = \frac{1 - K}{\frac{7200}{F} - 3 - \sum_{n=1}^6 (1 - p_a)^n}, \quad \text{eq. 36a}$$

where F is the volume of traffic specified in vehicles per hour and time is in units of 1/2 seconds for vehicle generation.

The parameter K is a function of both traffic volume and roadway classification. Because the distribution used permitted headways only in increments of 1/2 second, empirical values of headways which are $\leq 4 \frac{3}{4}$ seconds were included in the values of K. Figure 3 shows curves of K versus traffic volume for two-lane and four-lane rural roads. These

* This notation means that equation 34a was obtained directly from equation 34 by fixing the values of certain parameters.

FIGURE 3. FRACTION OF SHORT HEADWAYS VERSUS TRAFFIC VOLUME

curves are based on empirical data presented in the Highway Capacity Manual (10). For the four-lane case the values of K are almost identical with theoretical values as determined from the poisson distribution.

This theoretical equation is

$$P(h = n) \leq 1 - e^{-\frac{nF}{3600}},$$

where headway is in seconds and F is the traffic volume in vehicles per hour (17). By substituting $4 \frac{3}{4}$ seconds for n, one obtains the equation

$$K = 1 - e^{-0.00132F} \quad \text{eq. 37}$$

Equation 37 was assumed to be equally applicable to four-lane rural roads and four-lane urban streets.

Additional information was desired with respect to the platooning effect on two-lane urban streets. Headways were measured at two such locations. Both these streets were two-lane, two-way streets with parking on one side. Adjacent cross streets were controlled with stop signs; the studied street being designated as a thru street. The nearest signalized intersections were approximately one-half mile distant, and the streets were typical of these in an urban intermediate area. Average travel speeds were very close to 44 feet per second at both locations.

The values of K were determined for 44 different samples each of 15 minutes duration. These points are shown on Figure 3. A negative exponential curve was fit to the field data by the method of least squares*. The curve was forced thru the origin as is required by the physical significance of the relationship. This type of curve was selected because its shape is consistent with the data and because it has the desired property of closely

* The fit was made to the transformed equation, $\ln(1 - K) = -C(F)$; where C is the constant that was computed.

following the curve for four-lane roads as the traffic volume approaches zero. The equation of this curve for two-lane urban streets is

$$K = 1 - e^{-0.00155F} \quad \text{eq. 38}$$

Equation 38 is probably not valid beyond the range of traffic volumes shown as there is reason to believe that the curves for both two and four-lane roads should approach each other as capacity is reached. A comparison of the two curves for two-lane roads indicates that there is less platooning of vehicles on two-lane urban streets as compared with two-lane rural roads.

Figure 4 compares the distribution of headways as computed by the modified binomial distribution with the results of field observations on a two-lane urban street. Good agreement is obtained. Figure 5 compares the modified binomial distribution with field data presented in the Highway Capacity Manual for two and four-lane rural roads (10). The poisson distribution is also shown. A good fit is indicated for the derived distribution, and similar results are obtained at other volume levels. Note that the modified binomial distribution deviates most from the empirical data at the smallest headways. This discrepancy is caused by the fact that the empirical data contains minimum headways, whereas the derived distribution is based on average minimum headways. The poisson distribution provides a good fit for four-lane roads. The modified binomial distribution is still preferred for this case, however, because it truncates the less than minimum headways, then compensates for this truncation by increasing the number of small headways.

FIGURE 4. HEADWAY DISTRIBUTION FOR A TWO-LANE URBAN STREET

FIGURE 5. HEADWAY DISTRIBUTION FOR RURAL ROADS

Backlogging and Entering Procedure

When a vehicle is generated, it was considered to have arrived. The time of arrival of a vehicle was defined as the time that it would have reached a given point in the roadway had it experienced no delay and is designated as TOA. It can be seen that arrival is independent of intersection conflicts and the effect of traffic control devices. The point at which arrival occurs is termed the beginning of the lane and is designated as X_0 . Ordinarily a long approach lane would be needed if the effect of the backup of traffic is not to be felt at the beginning of the lane. Such a long approach lane would result in an added computational load because many additional vehicles would be included in the system.

To eliminate the necessity for a long approach lane a backlog list was used. When a vehicle was generated, it was placed directly in the backlog and designated by its time of arrival. Its turning maneuver, if any, was determined binomially using a pseudo-random number. Its time of arrival and turn data were stored in a circular array similar to the lane array previously described. This backlog file provided the additional function of separating the generation time increment from the scanning time increment.

Entering was defined as the process of leaving the backlog and starting down the approach lane. Vehicles were entered in such a manner as to minimize their potential delay. Since the acceleration rate used was less than the deceleration rate employed, vehicles were entered at the maximum velocity.

The beginning of the lane was located sufficiently far back from the stop line so that the turning and stopping restrictions were not applicable.

Thus there were only two factors which affected the entering movement. Let ZE represent the distance traveled by a vehicle during one scan time increment while entering. Based on the spacing relationship given as equation 16, .

$$ZE_1 = X'_t - X_0 - P - \bar{V} - \frac{1}{2D} (\bar{V} - v'_t)^2 . \quad \text{eq. 37}$$

The second consideration is how far could the vehicle have traveled since its time of arrival. That is,

$$ZE_2 = \bar{V} (t - \text{TOA}) \quad \text{eq. 38}$$

where t refers to the clock time at this instant. The critical ZE is the smaller of the two as obtained by equations 37 and 38. Negative values of ZE merely mean that the vehicle remains in the backlog.

The backlog was inspected at each scanning time increment to determine whether the first vehicle listed could enter. It can be seen that vehicles were entered in the same position that they would have occupied had the scanning time increment been equal to the generation increment.

Description of the Intersection

Physical Description

The intersection studied was a four-legged right-angled intersection of a high-volume major arterial with a lower-volume minor arterial street. Hereafter, these streets are called the main street or MS and the side street or SS respectively. The main street had four traveled lanes 11 feet wide, with parking prohibited. The side street had four 10 foot lanes with parking permitted; thereby providing but two travel lanes. If the side

street volume is low, this same configuration is applicable when parking is prohibited for at low traffic volumes a multi-lane side street approach is utilized as if it has but one travel lane. This layout also approximates a rural intersection where the side street is but 20 feet wide and a larger curb radius is employed.

Figure 6 is a diagram of the intersection. The stop line was located 12 feet back from the extensions of the curb lines. For the purpose of notation the approaches were labeled by the four points of the compass, N, S, E, and W, and the main street was considered to be oriented in a north-south direction. The symbols $\emptyset$ and I are used to refer to the main-street outside and inside lanes, respectively.

The near stop line for all approaches was designated as station 2000 feet. The beginning of the lane was a program variable with a minimum of zero feet. The end of the lane was located 350 feet beyond the far stop line for each maneuver. These maneuvers were left turn, straight thru, and right turn, abbreviated as LT, ST, and RT, respectively.

Release points were established where the scanning of vehicles was no longer required. These points occurred at locations where a vehicle no longer blocked either following vehicles making different maneuvers, or vehicles from the opposing approach. For example: when an east-approach right-turn vehicle reached its release point (which was 33 feet beyond the stop line), a following straight-thru or left-turn vehicle was free to proceed. Likewise, it did not conflict with a west-approach left-turn vehicle. In Figure 6 the arrowheads denote the release points for two approaches of the intersection. The complete lane stationing is included in Table 1.

FIGURE 6. DIAGRAM OF THE INTERSECTION

TABLE 1
STATIONING OF THE INTERSECTION

<u>Movement</u>	<u>Release Point (feet)</u>	<u>Distance Between Stop Lines (feet)</u>	<u>End of Lane (feet)</u>
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Main Street

Left Turn	2070	61	2411
Straight Thru	2041	64	2414
Right Turn	2041	33	2383

Side Street

Left Turn	2057	61	2411
Straight Thru	2034	68	2418
Right Turn	2034	33	2383

Beginning of Lane	Variable (≥ 0 feet)
Near Stop Line	2000 feet
Turn Point	2016 feet
Left Turn Wait Point	2016 feet (2032 feet for SS hold)
End of Lane	350 feet from far Stop Line

Rules of Operation

Because no device yet conceived by man can duplicate all the characteristics of man, the vehicle operator, certain simplifications had to be imposed in the simulation. Moreover, the excellence of the simulation is not measured by how closely each segment compares with the real situation, but rather by the degree to which the conclusions drawn from the model are true in reality. These simplifications should be of such an order that the problem can be solved efficiently, yet over simplification makes the results meaningless. The intent, therefore, was to rule out both the unusual and insignificant behavior patterns, and maintain the typical behavior which was characteristic of the vast majority of vehicles and their operators.

Towards this end certain general rules were established for the formulation of the model. Vehicle behavior was postulated as follows:

1. Vehicles enter the system in accordance with a prescribed random distribution.
2. Turning maneuvers are made in accordance with the desires of each vehicle as determined randomly at the time when it enters the system .
3. Vehicles travel in such a manner as to minimize their delays.
4. The maximum velocity is fixed at 44 feet per second.
5. Free flowing acceleration is at a uniform rate of 3 feet per second per second, except that in a few special instances a higher initial rate is used.
6. Free flowing deceleration is at a uniform deceleration rate of 6 feet per second per second. For stopping at an amber traffic signal, rates of 6 to 12 feet per second per second may be used.

7. All vehicles are approximately 17 feet long and when stopped have a fixed minimum spacing of 22 feet.
8. The position of vehicles within their lane is given by the location of their front bumper.
9. Pedestrian interference is negligible and therefore neglected.
10. For the main street all right turns are made from the outside lanes, and all left turns are made from the inside lanes.
11. Passing is permitted for second- and third-in-line straight-thru main-street vehicles when the lead vehicle is slowing for a turn.
12. The turning maneuvers of approaching vehicles are not indicated to opposing traffic until they reach the extension of the near curb lines.
13. In situations of equal advantage vehicles from the south or west approaches give way to vehicles on the north and east approaches, respectively.
14. Turning vehicles must not exceed a velocity of 15 feet per second at the turn point (a point located 16 feet beyond the near stop line.)
15. Vehicles react to preceding vehicles and to traffic controls in accordance to the behavior equations previously derived and summarized in Appendix A.
16. Merging and crossing maneuvers are made in accordance with fixed gap-acceptance criteria.
17. Vehicles follow the preceding vehicle only until such time as the preceding vehicle reaches the release point.
18. Vehicles are released as soon as their movement is independent

of the intersection. The time for the vehicle to reach the end of its lane is then computed and added to its travel time.

19. When the intersection is operating under signal control, there is a location called the "left turn hold position". One vehicle from a side street approach can wait for an acceptable turning gap at this location without obstructing any side street maneuvers other than a following left turn.
20. Left turn vehicles will not proceed past a point 16 feet beyond the near stop line (32 feet for vehicles in the left turn hold position) until they can be released thru an acceptable gap in the opposing traffic stream.
21. When the intersection is operating under two-way stop control, all side street vehicles give way to all main street vehicles. Furthermore, no delays are incurred by main street vehicles due to the presence of side street traffic.
22. No vehicles travel backward, collide, or breakdown.

The detailed application of these general rules is explained in the flow charts for the simulation program.

Description of the Traffic Controller

Operation of the Controller

Semi-traffic-actuated control is applicable to intersections of a heavy volume or high speed road with a lightly traveled minor road. Traffic actuation of the signal is by means of detectors placed on the side street only. Detectors used may be of many types; including pressure-sensitive, magnetic, and radar devices. Basic operation is the same

regardless of the type of detector employed. The signal is normally green on the main street, changing to the side street only as a result of detector actuation. In some older installations the side street green is of fixed duration, but in the preferred type it is proportioned to the side street volume of traffic with some maximum limit. Upon expiration of the required or maximum side street interval, the green signal automatically reverts to the main street where it remains for a predetermined minimum interval. This type of control provides for a minimum of disturbance to main street traffic at the intersection.

Controller Adjustment Features

The traffic controller is the electro-mechanical device which responds to vehicle actuation and in turn sets the proper aspects of the traffic signal. The more common type of semi-traffic-actuated controller has six adjustable time intervals. A description of each of these intervals and the limits of adjustment follow (35).

Main Street Minimum Green (10 to 90 seconds). This interval determines the minimum time for which the green light must be shown on the main street. Transfer of right-of-way to the side street may start immediately once this interval is timed out. If an actuation is received before the end of this interval, the transfer of the right-of-way is delayed until the interval has expired.

Main Street Amber (up to 10 seconds). This interval determines the clearance time on the main street following the main-street green. It is set at a value that will permit moving traffic to come safely to a halt or clear the intersection. Selection of the interval is determined by the expected speed of vehicles on the main street and the width of the side street.

Side Street Initial Green (2 to 12 seconds). This interval allows time for standing vehicles to get into motion. It should be adjusted to a time which, added to an extension interval, will permit a solid line of cars between the detector and the stop line to move through the intersection.

Side Street Extension Green (2 to 12 seconds). The minimum side street green period consists of the initial interval plus one extension. If there is a line of vehicles crossing the detector after the initial interval has expired, each actuation will cancel out the unexpired remainder of the previous extension interval and initiate a new extension interval. Thus it can be seen that the extension interval represents the time spacing between vehicles approaching the green signal in excess of which it is desired that the right-of-way be yielded to waiting cross traffic. The extension interval should be set so that a vehicle which has actuated the detector will, if traveling at a speed normal for the street, pass through the intersection before losing right-of-way.

Side Street Maximum Green (10 to 60 seconds). This interval limits the continued resetting of the extension interval by heavy traffic on the side street and terminates the green signal, causing right-of-way to be transferred to the main street. In such cases a memory feature in the controller returns the green signal to the side street upon the completion of the main street minimum green interval without the necessity of further actuation. When traffic becomes very heavy on both streets, the signal operates, in effect, as a fixed-time signal. Under conditions of heavy traffic the side street maximum green interval and the main street minimum green interval should be selected to give the proper proportions of the green signal to each street.

Side Street Amber (up to 10 seconds). This interval determines the clearance time on the side street following the side-street green. Selection of the interval is determined by the expected speed of vehicles on the side street and the width of the main street.

Performance Characteristics

The Effect of the Behavior Equations

The vehicle behavior equations were previously derived in general terms. In order to assess these equations it is first necessary to substitute the particular values of the variables utilized. The applicable substitutions and the resultant specific behavior equations are listed in Appendix B.

The effect of these equations is to fix the relationships that must exist with respect to position and velocity. The relationship between change in position Z and velocity for each increment of time is fixed by the assumption of uniform acceleration during that time increment. This interdependence of Z and V is expressed in equation 17. Two sequences of solution exist, as either Z or V may be determined first. The prior solution of Z was employed because the program logic was more dependent on position than on velocity.

At each time increment the vehicle determined its Z from each of the applicable behavior equations. Restrictions to movement were based on spacing, acceleration, turning, and stopping. The critical Z was the smallest one computed. Once this Z was selected, the vehicles position and velocity were readily computed. It should be noted that each of these behavior equations did not establish a specific behavior pattern,

but merely placed an outer bounds on behavior. Thus the turning restriction did not force all vehicles within a certain zone to decelerate at a specified rate. It simply stated that for each position there was a velocity that could not be exceeded. In application a vehicle could actually be accelerating in conformance with this restriction.

Free flowing acceleration and deceleration were essentially uniform and at specified rates. Other speed changes were not fixed directly. They could vary over a specified range, and could be non-uniform from one time increment to the next.

Starting Performance

The behavior equations were based on the performance characteristics of individual vehicles. In order to assure their adequacy, the behavior of a traffic stream in the model should be compared with field observations of traffic flow.

Consider a line of vehicles stopped at minimum spacing at a red traffic signal. When the light turns green, the lead vehicle must react to the signal change and then start to move. Likewise, each successive vehicle must react in turn to the preceding vehicle before getting under way. This reaction time has been observed to be approximately one second per vehicle when pedestrian interference is negligible (24). The initial acceleration rate is in the range of 5 feet per second per second, but this rate decreases materially after the first few seconds (4, 24).

In the model, however, a different situation existed. When the first-in-line vehicle was free to move, it accelerated uniformly at 3 feet per second per second. Once the lead vehicle had moved all other vehicles were free to move sequentially in accordance with the spacing restriction.

Each vehicle, therefore, experienced an instantaneous creeping that decreased in magnitude for positions further away from the stop line. This creeping effect was such that it compensated for the high initial acceleration of the real vehicle. If actual starting in the model is defined as occurring when a vehicle attains a velocity of a few feet per second, then the equivalent reaction times for successive vehicles was very nearly one second per vehicle. Despite initial deviations, the model starting performance gave similar eventual results insofar as delay is concerned.

Extensive field studies have been conducted to determine queue starting headways. Greenshield's well publicized values for passenger cars at urban intersections are 3.8 seconds for the first-in-line car with subsequent values ranging down to 2.2 seconds for the fifth car, and a constant of 2.1 seconds per car thereafter (24). These values are the time intervals after the green signal for each subsequent car in the queue to enter the intersection (pass beyond the extension of the near curb line). Bartle, Skoro, and Gerlough conducted similar tests at signalized intersections and obtained a mean value of 3.83 seconds for the first car to enter the intersection (3). Other research studies have yielded similar results (11).

Figure 7 depicts the queue starting headways for the intersection model. Using a one second reaction time for the first-in-line vehicle, it can be seen that it required 3.8 seconds for it to enter the intersection. Subsequent headways decreased to about 2.1 seconds for the fourth vehicle. By the time the twentieth vehicle entered the intersection, it was traveling at a velocity close to $\bar{V}$ and the minimum intervehicular headway of 1.5 seconds existed.

FIGURE 7. QUEUE STARTING HEADWAYS

Reaction Time

Perception-reaction time requirements were not included as a program variable. This characteristic of behavior is recognized, however, and was indirectly included in several applicable situations.

In the model vehicles instantaneously reacted to certain events, such as the changes in traffic signal aspects. The model traffic signal was set so that each aspect was displayed after a delay which was equal to the reaction time required for the real signal. Considering that the reaction time to all aspects is the same, the signal timing was unaffected. The model signal phasing was considered to have a one second lag as compared to the real signal.

As derived the car-following equations neglect reaction time. Some reaction delay obviously exist in the real situation, and research has been performed in order to determine its magnitude (9). It has also been observed that the reaction time may be zero in some cases. Second-in-line vehicles often react directly to a traffic signal change, and following vehicles may react directly to the speed changes of the vehicle in front of the preceding vehicle (24). The inclusion of a reaction lag in the car-following equations would have added realism, but would not have had an appreciable effect on delay. It has already been shown that the starting performance for following cars provided delays that are essentially equivalent to observed behavior.

Theoretical studies have demonstrated that a reaction lag can cause instability (9). The result of this instability would be an amplification of speed changes by following vehicles that may reach a resonant condition. Such behavior does occasionally occur in nature as is evidenced by some

chain-type rear-end collisions. This type of behavior was undesirable in the model because it is an uncommon occurrence. Observations on model vehicle behavior using the car-following equations indicated that velocity oscillations were damped for following vehicles.

CHAPTER III

PROGRAMMING THE SIMULATION MODEL

Flow Charting

Flow Charting Procedure

The basic programming tool is the flow chart. It consists of a schematic representation of the model showing the sequence of operations, the logical choices available, and the pattern of loops. Flow charts are presented in detail, as they provide the easiest and most complete method of displaying the functioning of the entire program.

Four levels of flow charts were required for the entire program. The hierarchy of these various levels was as follows: The complete programming of the model is called the Master Program. The Master Program consists of several individual programs. The programs in turn are divided into routines, which may be further subdivided into subroutines. It should be noted that the terms used for the various levels of programming are not always defined as used herein. For the purposes of labeling, the programs are designated by Roman numerals. Upper case letters with or without Arabic numeral suffixes are used for routines, and lower case letters denote subroutines. For example; "III W b" refers to Subroutine b of Routine W of Program III.

The Master Program

The flow chart for the Master Program is shown as Figure 8. This chart points out the relationships between the four programs. Program I reads in the problem specifications and sets up the computer for the running of each problem. The simulated traffic signal controller is contained in Program II. Program III simulates the intersection and the traffic flow therein. Program IV contains the simulated real time clock and handles the computation and display of results.

The Lane Scan Program

It was originally planned to handle the simulation of the intersection under stop-sign control and signal control as two separate projects. It soon became obvious that many portions of the programs were common to both types of control, and they were incorporated into a single program. Further study indicated that programming economy could also be achieved by making the same program elements handle all six approach lanes. Figure 9 is a flow chart for the Lane Scan Program III*. Most of the logic shown in this flow chart is the switching necessary to permit this single program to handle all six approach lanes under either of two types of traffic control.

Figures 10 thru 29 are flow charts of the various routines of Program III and are presented in order of occurrence.

The Lane Setup Routine III A1, shown as Figure 10, initializes the program for the scanning of each particular lane. Lanes are scanned in the following order: north outside, north inside, south outside, south inside, east, and west. Once the proper lane is selected, the various opposing approaches are noted; that is, the indexes of the opposite approach,

* In this and in succeeding flow charts numbers are shown at the upper right hand corners of the boxes. These numbers refer to the beginning statement numbers given in Appendix H and are used to cross reference the flow charts and the code listing.

FIGURE 8. MASTER FLOW CHART

FIGURE 9. LANE SCAN PROGRAM III

FIGURE 10. LANE SETUP ROUTINE III A1

FIGURE 11. VEHICLE SETUP ROUTINE III A2

the approach on the right, and the approach on the left are recorded. Next, the settings for the M switches are selected. These switches are all set identically to any of four positions, depending upon which street is to be scanned and whether the control mode is signal or stop sign.

Figure 11 is a flow chart of the Vehicle Setup Routine III A2. This routine sets up the procedure whereby each vehicle within the lane is processed. For each time increment scanning starts with the lead vehicle and proceeds sequentially to the last vehicle in the lane. Upon entering this routine initially, the register containing the number of vehicles in the lane is examined. If the lane is empty, the scanning process is bypassed and control is transferred to the vehicle Generation Routine III W. In this case dummy values of X' and V' are established which will permit a generated vehicle to enter the lane. When entering from III A1, the vehicle index is set to the lead vehicle. When entering from III S, the index of the next vehicle in line is used. Switch M and its associated logic is used in conjunction with the Passing Routine III P. When a main street vehicle moves from an outside lane into an inside lane, it has already been processed during that time increment. Such a vehicle is flagged by setting its deceleration register to a negative value. This condition is observed in the Vehicle Setup Routine and processing is deleted for that time increment. Before proceeding to III B large dummy values of various Z 's are established. As many vehicles will not be effected by all the behavior restrictions, the irrelevant Z 's will thus be ineffective.

The Spacing Bypass Routine III C1, shown as Figure 12, provides for a special case applicable only to side-street vehicles when operating under signal control. In this one instance a straight-thru or right-turn

FIGURE 12. SPACING BYPASS ROUTINE III C1

FIGURE 13. SIGNAL STOPPING RESTRICTION ROUTINE III E1

second-in-line vehicle is not required to follow a lead vehicle which is in the left-turn hold position. All other non-lead vehicles must behave in accordance with the spacing restriction.

The stopping restriction is handled by Routine III E1, Figure 13, when the traffic signal is employed. A vehicle that is the first to stop at an amber signal will have been "tagged" in another routine. Therefore, only tagged vehicles are processed by this routine. Subsequent vehicles that stop at the amber or red signal do so in accordance with the car following criteria. A separate ZD switch is used for the main street and the side street. For each street this switch is set to position 1 at the start of the amber phase and to position 2 at the start of the green phase. When the signal turns green the tag is removed. The stopping restriction is still applicable during this time increment because the vehicle is being processed to determine its position at this instant. The value of the deceleration rate used in the computation of ZD was computed during a previous time increment by the Tagging Routine III H.

The stopping restriction is handled by Routine III E2 for stop-sign control. A deceleration rate of 6 feet per second per second is always used in the computation of ZD at a stop sign.

Figure 14 shows the flow chart for the Turning Restriction Routine III F. Note that ZT is computed only for vehicles that will be affected by this restriction. Furthermore, stopping vehicles bypass this routine completely, because stopping is a more severe restriction than slowing for a turn. ZT is first computed by the regular equation. The new position of the vehicle is then computed based on this value of Z. If the vehicle moves past the turn point, the alternate equation is employed for the

FIGURE 14. TURNING RESTRICTION ROUTINE III F

determination of ZT. Switch MZT is set to position 2 to indicate that a special value of V_t has been computed for a vehicle passing the turn point.

The Car Processing Routine III G is included as Figure 15. The new X coordinate and velocity for the current clock time are computed in accordance with the relevant behavior restrictions. If the velocity is less than 4.5 feet per second, the pertinent stopped delay counter is incremented. A different counter is used for each lane and each turning movement. Finally, this vehicle's X and V are recorded as the preceding vehicle's characteristics for the next vehicle to be processed.

Vehicle behavior when confronted by an amber traffic signal is taken care of in the Tagging Routine III H, shown as Figure 16. A three-position tag switch is provided for each approach lane. This switch is set by the traffic signal controller to position 1 at the start of the amber phase and to position 2 at the start of the green phase. In addition, this switch may be reset by the routine itself. When the traffic signal is green, no action is taken. When the signal changes to amber, the routine checks each vehicle to determine which one will be the first to stop. The criterion used is that the vehicle must be able to stop at the stop line with a uniform rate of deceleration which does not exceed 12 feet per second per second. If the required deceleration rate is less than 6 feet per second per second, a value of 6 is substituted for the computed deceleration rate. When a vehicle meets this criterion, it is tagged and its applicable rate of deceleration is recorded. If no vehicle is found which can stop within the acceptable deceleration range or if the lane is empty, a procedure is established whereby the next vehicle that enters the lane will be tagged. Tagging attempts are terminated once a suitable vehicle is tagged or when the signal turns green.

FIGURE 15. VEHICLE PROCESSING ROUTINE III G

FIGURE 16. TAGGING ROUTINE III H

After the vehicle has been repositioned for the current time increment, it is necessary to determine whether it is able to be released. The Main Street Release Checking Routine III J1 is shown as Figure 17. The first prerequisite for release is that the vehicle be first in line. If a straight-thru or right-turn vehicle has reached the release point, control is then transferred to the appropriate release routine. If a left-turn vehicle is in a position to intercept the opposing traffic stream, control is transferred to a decision routine. When the vehicle is not in a position to be released, its passing potential is examined. Passing opportunities are provided for second and third position straight-thru vehicles during the green phase.

The Side Street Release Checking Routine III J2, Figure 18, is similar to the first portion of the corresponding main street routine. One difference is that it provides for the fact that a second-in-line side-street vehicle may be released. This movement is possible due to the existence of the side-street left-turn hold position.

Special considerations are involved when a vehicle must cross an opposing stream of traffic. First, the crossing vehicle examines the position of other vehicles within the intersection area, as defined by the extensions of the curb lines. The presence of a vehicle within this area may block the desired movement. Once the blocking vehicle has been released it is no longer considered to be an obstacle. Although in fact it may still physically obstruct the movement, it does not hamper the decision process. Furthermore, by the time the crossing vehicle actually reaches the point of conflict, the released vehicle will have moved past this point. It is assumed that once a vehicle enters the intersection area, its

FIGURE 17. MAIN STREET RELEASE CHECKING ROUTINE III J1

FIGURE 18. SIDE STREET RELEASE CHECKING ROUTINE III J2

path thru the intersection becomes obvious. On the other hand, a vehicle which has not reached the intersection area is as yet uncommitted. The crossing vehicle must assume that the approaching vehicle can make any acceptable turning maneuver.

The logic sequence that the crossing vehicle performs is now established. The following questions are asked for each opposing approach:

1. Are there any vehicles in the opposing approach lane? (Vehicles which have passed the release point are automatically excluded.)
2. What is the effect of any vehicles that are now within the intersection area?
3. Is there sufficient time to cross before a vehicle from the opposing approach lane will enter the intersection, assuming that it will make the critical maneuver? (Vehicles stopping at an amber traffic signal do not conflict with a left-turning vehicle.)

To determine whether an acceptable gap exists in the opposing traffic stream, the time for the opposing vehicle to reach the intersection area is computed. This computation is based on the assumption that the vehicle continues moving at its present velocity. The distance between the edge of the intersection area and the point of physical contact provides a factor of safety. This safety factor will permit some acceleration of the approaching vehicle. The time for the crossing vehicle to reach its release point is then computed. This clearance time is based on the crossing vehicle accelerating in accordance with the applicable behavior equations. It is recognized that the crossing vehicle will undergo a high initial acceleration from a stopped or near stopped condition. The clearance time is also computed using this higher acceleration as described on page 12 . The shorter of the two clearance times is used.

The left-turning procedure is described in Figure 19, the Main-Street Left-Turn Decision Routine III K1. For main street left turns the crossing vehicle must examine both the opposing inside and outside lanes for potential conflicts. The available crossing time is computed as determined by each conflicting vehicle located. The shortest time found is selected as the critical one. When the time required is equal to or less than the time available, the left-turning vehicle proceeds. If an available gap does not exist, and if the vehicle has passed the left-turn wait point, it is moved back to this point and stopped.

In the real situation decisions are not made at a single point. The left-turning vehicle will continually examine the opposing traffic stream as it approaches the intersection and adjust its velocity accordingly. Such behavior is complex and difficult to simulate. The procedure employed in the model is not realistic, but it yields similar results. The loss of advantage due to a complete stop is offset by the higher initial starting acceleration. High decelerations will be experienced by following vehicles. In actuality, lesser rates of deceleration would be required over a longer distance from the intersection. This difference has a minor effect on the delays to following vehicles, because they are blocked by the left-turning vehicle. If, as is often the case, the left-turning vehicle must stop in the real situation, the simulation results are equivalent.

Similar procedures are employed in the Side-Street Left-Turn Decision Routine III K2 shown as Figure 20. In this case, a blocked turning vehicle may proceed to the left-turn hold point when it is unoccupied.

The main-street release routines are III L1 and N1, and the side-street release routines are III L2 and N2. The side-street routines are utilized

FIGURE 19. MAIN STREET LEFT TURN DECISION ROUTINE III K1

FIGURE 20. SIDE STREET LEFT TURN DECISION ROUTINE III K2

only when the intersection is operating under signal control. The procedure employed in all these routines is similar and is shown in Figure 21. For the straight-thru and right-turn routines the vehicle will have already reached the release point. The time to reach the end of the lane is computed by using the vehicle's present position and velocity.

The computations for the left turn release routines are handled differently. If the time to reach the release point, as previously computed in the decision routine, is the maximum value, the time to reach the end of the lane is based on the higher initial acceleration rates. When the time to reach the release point is less than the maximum, the computations are handled in the same manner as for the other turning maneuvers.

The time to reach the end of the lane is then added to the existing travel time as determined by the difference between the clock time and the time of arrival. To obtain the delay, the travel time as required for an unimpeded free-flowing vehicle is subtracted from the actual travel time. This delay is then added to the appropriate delay counter; a different one being used for each turning movement and for each lane. Finally, various housekeeping functions are performed. These consist of adjusting the counter for the number of vehicles in the lane and the register which holds the index of the lead vehicle.

Passing is accommodated in the model for main-street vehicles under conditions of moderate traffic volume. Preliminary conditions for lane changing are specified in the Main-Street Release Checking Routine III J1. Passing is attempted only when a vehicle is preceded by a turning lead vehicle. Furthermore, only the second or third position vehicle may pass. This provision will accommodate the vast majority of cases. Because the

FIGURE 21. FLOW CHART FOR TYPICAL RELEASE ROUTINE

percentage of turning vehicles is small, the probability of a queue of three or more blocked turning vehicles is remote. A more liberalized passing procedure could readily be provided, but at the expense of increased computational effort. The procedure used fulfills the primary purpose of decreasing the sensitivity of delay to lane distribution and of providing more realistic values of delay.

The Passing Routine III P is shown as Figure 22. The prospective passing vehicle examines the adjacent lane for an acceptable gap. Two conditions must be met. If an adjacent lane vehicle precedes the gap, it must conform to the spacing restriction for the passing vehicle. Secondly, if an adjacent lane vehicle follows the gap, it must have a potential time of at least 3 seconds to a point 22 feet behind the front of the passing vehicle. In computing this time the conflicting vehicle is assumed to maintain its present velocity. The MQ switch is used to set a negative deceleration rate when the passing vehicle originates from an outside lane. This indicator is used in Routine III A2 to assure that the vehicle is not processed twice during the same time increment. The MP switch indicates the position into which the passing vehicle is moving. The MPASS switch, set in Routine III J1, indicates the position from which the passing vehicle originated. The mode of representation necessitates that adjacent vehicles have sequential lane indexes; therefore, considerable housekeeping is performed in shifting vehicles within the circular arrays which represent the lanes.

Figure 23 is a flow chart of the Stop Sign Decision Routine III Q. If the side street vehicle is less than 3 feet from the stop line, this routine is utilized. Thus a vehicle may be released with a velocity as high as 6 feet per second. This provision accommodates the fact that some vehicles at a stop sign will proceed without making a full stop.

FIGURE 22. PASSING ROUTINE III P

Certain vehicles, such as main-street left-turning vehicles, may still occupy the intersection area even though they have been removed from the lane arrays. In order that these vehicles may have the proper effect on side-street traffic, blocking registers are employed. A separate register is used for each side street approach and for each turning movement. The registers contain the earliest clock time at which the various side-street vehicles may proceed.

The gap selection procedure employed by this routine is similar to that previously described for the left-turn decision routines. Opposing vehicles within the intersection area may prevent the release of side-street vehicles. Vehicles within the intersection area are considered to be committed to their desired travel path. The time needed for approaching vehicles to reach the extension of the near curb lines is determined by assuming that the vehicle continues at its present velocity.

The critical lag is the smallest time lag that a crossing vehicle will accept. This quantity is an input variable. If the available time for crossing is equal to or greater than the critical lag, the side street vehicle is released. The critical lag required for straight-thru and left-turning vehicles has been found to be similar. Right-turning vehicles will accept a shorter time lag due to the merging nature of this maneuver. Raff found that the critical lag for right-turning vehicles is about 80 percent of that for the other maneuvers. Greenshields observed that this value was approximately 68.4 percent. A compromise value of 75 percent of the critical lag was used for right-turning vehicles in the model.

The Stop Sign Release Routine III R is shown as Figure 24. All vehicles are considered to be stopped at the stop line at the time of release. A

FIGURE 24. STOP SIGN RELEASE ROUTINE III R

vehicle that is actually behind the stop sign when released will experience approximately the same delay as the stopped vehicle. The advantage of its initial velocity is offset by the greater travel distance and reduced initial acceleration. The released vehicle is assumed to utilize a high rate of initial acceleration as described on page 12. Delay computations are performed in a manner similar to that employed for the other release routines. The values of the delay for each released vehicle are stored in a special file which is later examined to select the 85th percentile delay.

A side-street vehicle released from the stop line may block vehicles from the opposing approach until it clears the intersection area. The blocking time is dependent upon the turning maneuvers of the blocking and the blocked vehicles. As each vehicle is released, the blocking registers for the opposite approach are set. The appropriate blocking time is added to the clock time. If the resultant time is later than the time presently contained in the blocking register, the register is reset to the new value. Housekeeping functions are then performed to update the lane array counter and lead index.

The earliest time of release of a subsequent vehicle at the stop sign is controlled by the car-following equations. The following vehicle may not be released until it has reached a position which is less than 3 feet from the stop line. Various delays will be experienced by the following vehicle depending upon the position-velocity combinations that exist for both vehicles. If both vehicles are stopped at a minimum spacing at the time that the first vehicle is released, a time of 4 seconds is required for the following vehicle to move into the release position. Likewise, if the following vehicle is in the process of decelerating when the first

vehicle is released, at least 4 seconds are required before the following vehicle can be released.

The Blocking Routine III T performs the blocking functions necessitated by the release of main-street left-turning vehicles. This routine, shown as Figure 25, is bypassed when the intersection is operating under signal control. Side-street vehicles located to the left of the main-street approach are delayed for the actual clearance time required for the main-street vehicle. This time is computed in the Main-Street Left-Turn Decision Routine III K1. Side-street vehicles located to the right of the main-street approach are delayed for one second less than this required clearance time.

The Detector Routine III U is shown as Figure 26. The position of the detector for each side-street approach is an input variable. When a side-street vehicle passes the detector position, a switch is set. This switch is located in the Controller Program II.

The generation of vehicles is accomplished by the Generation Routine III W. Ordinarily generation is attempted twice each time increment; thereby providing for headways in steps of $1/2$ second. As shown in Figure 27, two switches are used to provide for the minimum permissible headway. The action of these switches is such that once a vehicle is generated, a subsequent generation will not be attempted for $1\ 1/2$ seconds.

Separate subroutines are used to generate random fractions for the main street and the side street. The time of arrival of the last vehicle generated is compared to the clock time to determine which probability of an arrival is applicable. If the random fraction is smaller than the probability level selected, a vehicle arrives. Its time of arrival is recorded as the clock time or as the clock time plus $1/2$ second, whichever is applicable.

FIGURE 25. BLOCKING ROUTINE III T

FIGURE 26. DETECTOR ROUTINE III U

FIGURE 27. VEHICLE GENERATION ROUTINE III W

The backlogging procedure is shown in Figure 28. A new random fraction is generated for the determination of turning movements. A small random number signifies a right turn, while a large random number indicates a left turn. Intermediate values mean that the vehicle will go straight thru. The vehicle's time of arrival and turn indication are then stored in the circular array representing the backlog.

The Entering Routine III W c is shown as Figure 29. Entering is attempted once each time increment. When a vehicle enters, its time of arrival and turn indication are transferred from the backlog array to the lane array. Its position coordinate is determined at this time, and its velocity is set to 44 feet per second.

This one Generation Routine is used for all six approaches. This is possible because switch positions, previous arrival times, and backlog information are stored separately for each lane.

The Traffic Controller Program

The Traffic Controller Program II is shown in Figure 30. Signal phases are adjusted in accordance with the demands of side-street traffic as determined by the detector switch. Traffic controllers commonly exhibit a response lag upon actuation. The magnitude of this lag varies, depending upon the design of the particular controller and upon the position of the timing drum at the instant of detector actuation. The simulated controller exhibits a time lag upon actuation which may vary from zero to one second. The magnitude of the time lag depends on the relationship of the instant of detection to the one second time increment.

The detector switch is used at two places in the program. Once the main street minimum green interval is timed out, the switch labeled II C

FIGURE 28. BACKLOGGING SUBROUTINE III W b

FIGURE 29. ENTERING SUBROUTINE III W c

FIGURE 30. TRAFFIC CONTROLLER PROGRAM II

is used to initiate a new side-street green phase. Detector switch II M is used to reset a new extension interval during the side-street green phase. In addition to the action of the Lane Scan Program, the detector switch may also be set by the controller itself in Routine II R. This accomplishes the memory feature whereby a new side-street green phase will be initiated if the side-street maximum green interval is timed out before the completion of an extension green interval. Once the detector switch is actuated, it will remain in that position until action is taken by the controller. Actuation is cancelled when Routine II P is reached.

The correspondence between signal phasing for the two streets is shown in Table 2. Also shown are the codes employed by a signal indicator register. This indicator is used by Programs II and III to determine which aspects are displayed during a time increment.

The setting of signal aspects is performed in Routines II D, F, H, and S. These routines set the signal indicator, the interval timers, and the appropriate tagging and ZD switches in the Lane Scan Program. A separate timer is used for each of the five signal phases as shown in Table 2. These timing registers contain the clock time when the signal aspects should be changed to conform with the requirements of the next phase. As an example, the following steps are performed in changing the signal to main-street red and side-street green (Routine II F):

1. Set the signal indicator to 3.
2. Set the side-street-initial-green timer to clock time plus the side-street-initial-green interval.
3. Set the side-street-extension-green timer to clock time plus the side-street-initial-green interval plus the side-street-extension-green interval.

TABLE 2
TRAFFIC SIGNAL PHASES

Main Street Phase	Side Street Phase	Signal Indicator
Green	Red	1
Amber	Red	2
Red	Green	3
Red	Green (Extension)	4
Red	Amber	5

4. Set the side-street-maximum-green timer to clock time plus the side-street-maximum-green interval.
5. Set the side-street ZD switch in Routine III E1 to position 2.
6. Set the tagging switches for the two side-street lanes in Routine III H to position 2.

The Input and Initialization Program

The Input and Initialization Program I is shown as Figure 31. For the initial problem, or upon completion of a previous problem, control is first transferred to Routine II A. This routine reads in the specifications for the next problem to be run.

Routine I B is the Initialization Routine. It computes quantities, such as arrival probabilities, which are constants for this particular problem. All switches are set to their initial positions and counters are set to zero. Blocking registers and previous arrival times are set to large negative values to nullify their initial effect. The traffic signal is set to main-street green with the main-street-minimum-green interval timed out.

Routine I C displays the problem specifications as a portion of the output data. Routine I H zeroes all the registers which record delays and which count the number of vehicles generated and released. Routines I C and I H combined will perform a complete initialization.

Because the intersection is initially devoid of traffic, some time is necessary to load the system with vehicles and reach a statistical steady-state condition. This time is called the transient time and is an input variable. Data collected during the transient time is not statistically significant and must be disregarded. After the transient time has expired, Routine I H is re-entered, and a partial reset takes place. This resets all values that are used in the computation of delays.

FIGURE 31. INPUT AND INITIALIZATION PROGRAM I

Several different reset modes are available. If additional data are needed at some later time for a given list of problem specifications, a different set of vehicle arrivals would be desired. Three different choices exist in selecting random numbers. The switches labeled I E and I D may be set to initiate either of two different series of random numbers, or to continue the selection of numbers from the previous series.

Two other modes must be specified by the input specifications. The control mode is used to designate whether the intersection is to be operated under semi-traffic-actuated-signal control, or two-way-stop control. The production mode designates the output information that is to be displayed. Two formats of output are available for production runs, and several formats may be utilized for check-out purposes. Appendix F describes in detail the functioning of the three operation modes.

In order to obtain data during the running of a problem, a sample size (in units of time) may be designated. At the end of each sample time, results are displayed. The length of time that the problem runs is fixed by the number of samples and the sample size. A maximum backlog size may be specified, which is a useful device when high volumes are input. If this backlog limit is exceeded, Routine I J will cause the current data to be summarized and the remainder of the problem to be deleted. The variables that must be included as input are listed in Table 3. The input format is described in detail in Appendix E.

The Summary and Display Program

Figure 32 depicts the procedures followed by the Summary and Display Program IV. Routine IV A adds one time increment to the simulated real time clock. Switch MØ is initialized in position 1. Ordinarily the

TABLE 3
INPUT INFORMATION

Description of Variables	Number of Variables Involved
Run number	1
Control mode	1
Production mode	1
Reset mode	1
Backlog limit	1
Transient time	1
Sample time	1
Number of samples	1
Beginning of lanes for each street	2
Position of detectors on each side-street approach	2
Critical lag for each side-street approach	2
Traffic volume for each lane	6
Fraction of small headways (K) for each lane	6
Fraction of right and left turns for each lane	12
Traffic signal controller intervals	6

FIGURE 32. SUMMARY AND DISPLAY PROGRAM IV

remainder of the program is then bypassed, as control is transferred to Routine I J and scanning is continued. When the transient time is over, switch MØ is set to position 2 so that Routine IV E is utilized. The output time is initialized as the clock time which will exist at the end of the first sample. As each sample is processed the output time is increased by Routine IV M.

When an output time is reached, Routine IV G summarizes the data collected during the sample time and transfers these results to the output medium. Routine IV N computes the information required for the run summary. This summary is usually displayed immediately following the output data for the last sample. An alternate output format is available by means of the production mode switch shown as Routine IV J. When this switch is in position 10, the information included in the run summary will be displayed after each sample.

The sample data include the total and stopped delays and the number of vehicles generated and released. This information is displayed by turning movements for each lane. These registers were zeroed after the completion of the transient time and give cumulative values thereafter. The numbers of vehicles currently in each lane and each backlog are also shown. The average delay per vehicle encountered during the sample time is computed. This computation is based on the delay for all vehicles during that time.

The run summary computes the mean of the average sample delays and the standard deviation for this mean. Likewise, the overall average delay per vehicle is found. This figure is determined by using the total values of delay and released vehicles recorded since the expiration of the transient time. The actual values of traffic volume, directional distribution,

and percent of turns are also computed for each street. For stop sign control the 85th percentile total delay for side-street vehicles is located. This is accomplished by ranking in ascending order the individual values of delay, and then selecting the value which is 85 percent of the way thru the list. Table 4 lists all items of information that are included as output.

Coding

Coding Procedure

The program is coded in the IBM 709/7090 FORTRAN language (30). The FORTRAN (FORMula TRANslation) system accepts a source program written in a language that closely resembles the ordinary language of mathematics. The system uses the computer to convert this mathematical language into a machine language, which is actually used in running the problem. The source program with explanatory information is included in the appendices. It is not the intention to describe the coding process fully. A person familiar with the FORTRAN system will be able to follow the source program with the aid of the associated tables and flow charts. There are several points of interest, however, concerning the manner by which the simulation is converted into an algebraic format.

The approach lanes are represented by a three dimensioned circular array with dimensions of 6, 100, and 5. The first subscript denotes the particular lane. The second subscript refers to the relative position within the lane. Vehicles are stored in order starting with the lead vehicle, and they do not ordinarily change position*. Two separate arrays are used to keep track of the index of the lead vehicle and the number of

* Vehicles shift positions within the lane arrays only for passing maneuvers.

TABLE 4
OUTPUT INFORMATION

Description	Number of Items Involved
Problem Specifications (All items included in Table 3)	—
Results for Each Sample	
Cumulative number of vehicles generated	14 *
Cumulative number of vehicles released	14 *
Number of vehicles currently in lanes	6
Number of vehicles currently in backlogs	6
Cumulative total delay	14 *
Cumulative stopped delay	14 *
Average total delay per vehicle in sample	3 †
Average stopped delay per vehicle in sample	3 †
Run Summary	
Mean of average total delay per vehicle for samples	3 †
Mean of average stopped delay per vehicle for samples	3 †
Variability of sample averages of total delay	3 †
Variability of sample averages of stopped delay	3 †
Overall average total delay per vehicle for run	3 †
Overall average stopped delay per vehicle for run	3 †
Actual volume of traffic in vehicles per hour	3 +
Actual percent of directional distribution	2 +
Actual percent of right turns	2 +
Actual percent of left turns	2 +
85th percentile total delay on side street for stop-sign control	1

* By lane and by turning movement

† For main street, side street, and both streets

+ For main street and side street

vehicles in each lane. This information is updated each time a vehicle enters or is released from a lane. The 100 index positions are sufficient to store a solid line of stopped vehicles when the beginning of the lane is designated as $X = 0.0$ feet.

When index position 100 is reached, the next position behind it is given as index position 1; thereby providing the continuous circular feature of the lane array. Three special functions are used to simplify the computation of these indexes. The first function computes the index of the following vehicle, given the index of the vehicle in question. A second function computes the index of the next vehicle to enter the lane. The third function computes the index for any position, based on the index of the lead vehicle and the position number. As an example of how this function works, consider the following example. It is desired to find the index of the fourth vehicle when the lead vehicle is at index number 39. The index is computed as $39 + 4 - 1 = 42$. If the lead vehicle were at index number 99, however, the value would be computed as $99 + 4 - 1 = 102$. Since the result is greater than 100, the function reduces the result by 100; thus obtaining $102 - 100 = 2$. By using these special functions for referring to indexes, the programmer is able to treat the array as if it were an endless loop.

The third subscript for the lane array refers to the vehicle characteristics. The values stored represent the time of arrival, turning movement, X coordinate, velocity, and deceleration rate. The turn indicator is set to a negative, zero, or positive value to signify left turn, straight thru, or right turn, respectively. The deceleration rate stored is that computed by the Tagging Routine as the rate required to stop at the traffic signal.

If the deceleration rate is zero, the car is not tagged. A vehicle's deceleration register is also used for two special purposes which do not occur concurrently with stopping for the amber signal. A negative deceleration rate for a main-street vehicle signifies that the vehicle has passed from an outside lane to an inside lane during the current time increment. For a side-street vehicle a negative deceleration rate indicates that the vehicle occupies the left-turn hold position.

The backlog file is likewise represented by a three dimensioned circular array, but with dimensions of 6, 100, and 2. The subscripts have the same meaning as in the lane array, except that only the first two vehicle characteristics are stored. Since the same number of index positions are used, the special index functions are applicable to the backlog array. The 100 vehicle positions should accommodate the most severe traffic jam. If the backlog is filled to capacity, however a special indication is included in the output. In addition to this feature a backlog limit may be specified which will delete the remainder of the problem when the limit is exceeded.

Appendix C contains a list of all variables used in the coding with their corresponding meaning. Appendix D indicates the dimensions and the significance of subscripts for the subscripted variables (arrays).

The entire input for a particular problem can be contained in two IBM cards. Appendix E specifies the procedure for preparing the input cards. The significance of the input modes and the various settings available are explained in Appendix F. There are many variables that are fixed in the program, such as the maximum acceptable rate of deceleration at an amber traffic signal. The FORTRAN language facilitates the location of these

variables in the code. Even though the program would have to be recompiled, it is a simple matter to alter the values of such variables.

The FORTRAN system permits a program to be coded in various units consisting of one main program and several subprograms. Each subprogram is a separate entity which may be called into action by the main program or another subprogram. The use of these subprograms simplifies coding in that an identical procedure may be employed at several different places merely by calling in the appropriate subprogram. Furthermore, this division into smaller units simplifies the checking out of the program.

Programs I and IV were both coded such that they comprise the main program. Programs II and III were each coded as subprograms. Many routines were also coded separately. For example, the computation of probabilities, delays, and the various Z's are all performed in subprograms. The random number subroutines had to be coded separately. The procedure for obtaining these numbers requires that only the lower ordered bits of a product are to be used. This bit manipulation is beyond the scope of the FORTRAN language. This one portion of the program was coded in the FAP (FORTRAN Assembly Program) language and was incorporated in the program as a FORTRAN FUNCTION Subprogram. Appendix G describes the 21 different program units used in coding the simulation model.

The FORTRAN code listing is included as Appendix H. Coding tricks were avoided to facilitate the reading of the source program. The flow charts and the code listing are completely cross referenced. Comment cards are used to head each programming unit and the same program and routine notation is employed in each. To simplify the location of FORTRAN statements, statement numbers are assigned in order of magnitude for each

programming unit. The starting statement number is shown at the upper right-hand corner of each block in the flow charts. The routine notation plus the statement numbers provide complete correspondence between each element of the flow charts and the code listing.

The simulation was programmed for an IBM 7090 computer with 32,000 words of core storage. The program, as written, requires 15,271 words of core storage of which 668 words are used by special debugging routines. The lane and backlog arrays use 4200 words and the file for side-street delays with stop-sign control uses 4000 words of storage. By reducing the length of the approach lanes and the backlog lists and reducing and/or eliminating the delay file and debugging routines, the program could be run on a computer with but 8000 words of core storage.

Debugging Provisions

Five subprograms are included in the code listing which are not described in the flow charts. These routines display additional information that may be desired when checking out the program. These routines are available as options thru the production mode settings. Appendix F lists the various combinations possible.

Debugging Routine A is used to check out the initialization procedure. This routine is entered by a switch located immediately after Routine I H. This routine displays the values of various counters and variables as they exist after initialization.

Debugging Routine B provides additional information about the Traffic Controller Program II. It is entered thru a switch placed immediately after this program. The values of the interval timers, the signal indicator, and the detector switch are displayed.

Debugging Routine C is available each time a vehicle is processed during a time increment. It is entered thru a switch at the beginning of Routine III S. It displays the items needed in computing the vehicle characteristics at each time increment.

Debugging Routine D is used to check out the Vehicle Generation Routine, and its entrance switch is located at the end of Routine III W. All pertinent information regarding generation, backloging, and entering is displayed.

Debugging Routine E indicates in detail the manner in which each vehicle flows thru the model. It is entered thru a switch at the beginning of Routine III X. At the end of each time increment the vehicle characteristics are displayed for each vehicle in every lane.

The regular output procedure also provides a most useful debugging tool. A sample size of one second may be specified to display all the normal output information at the end of each time increment. The transient time feature may be utilized so that this information is supplied only after the intersection is loaded with vehicles.

CHAPTER IV

RUNNING THE SIMULATION PROGRAM

Selection of the Intersection Parameters

It is difficult to make a general comparison of two types of traffic control at intersections. Even for a particular intersection, traffic patterns vary throughout the day. Furthermore, there is often a wide operational latitude possible for a specific control type. The variables involved may be classified in three categories; geometric factors, traffic factors, and control factors.

The geometric design of the intersection was fixed by using typical dimensions and characteristics for the class of intersection being studied. It was then necessary to determine the values of the remaining variables in order to accomplish a direct comparison of the effect of the two types of traffic control.

Traffic Factors

Some traffic factors, such as velocities, rates of acceleration, and vehicle size, were incorporated in the behavior equations. The magnitude of these quantities was dependent in part on the composition of traffic. A single vehicle type was used to approximate the mixed vehicles in the traffic stream. This average vehicle had properties that were essentially similar to those of passenger cars, except for a slight reduction in acceleration capability to account for the presence of trucks. Other traffic

factors include such items as directional distribution, lane distribution, and the frequency of turns. Although it would have been desirable to investigate the individual effect of each of these items, the computer time required to simulate the intersection under the complete range of possible conditions was well beyond the scope of this project.

For urban streets in intermediate areas the typical proportion of traffic flowing in the major direction has been found to be 60 percent of the total street volume (2). Therefore, the directional distribution was fixed at a 60 percent - 40 percent value.

For rural highways lane distribution is a function of traffic volume. At low volumes the major portion of traffic will utilize the outside lane. On four-lane rural highways the proportion of traffic in the outside lane has been found to vary from 88 percent at very low volumes to 40 percent as capacity is approached (10). Wagner and May presented data for the lane distribution on a heavily traveled four-lane urban expressway. Their value for the proportion of traffic in the outside lane was approximately 57 percent throughout the range of volumes observed (51). Equivalent information for urban streets is lacking. The proportion of turns and the proximity of intersections undoubtedly has a significant effect on lane selection.

Field studies were conducted by the author on two urban arterial streets in West Lafayette, Indiana. These were both four-lane streets with parking prohibited. Two 15 minute recording traffic counters were placed side by side; one with the road tube covering both lanes going in one direction, and the other tube covering only the outside lane. The hoses were cut off 2 1/2 feet short of the lane lines so that vehicles straddling two lanes were distributed equally to both counts. The data obtained

indicated that, at traffic volumes below capacity, lane distribution remained relatively constant. Even at extremely low volumes a significant number of vehicles selected the inside lane. A lane distribution with 60 percent of the vehicles using the outside lane was consistent with these observations. This value was therefore used throughout the range of volumes employed in the simulation. Because passing was accommodated for main street vehicles, delay was not sensitive to lane distribution.

The percentage of turns commonly used for urban intersections is 10 percent for each turning direction (10). This value is typical for the intersection of two similar streets. The simulated intersection was composed of two streets of different character. The proportion of vehicles turning from the main street into the side street would usually be less than the proportion of turning vehicles entering the main street. The percentage of turns may differ for each approach and may even be a function of traffic volume. The percentage of turns was fixed in the simulation, however, and typical values were chosen as 7 percent for the main street and 14 percent for the side street. That is 7 percent of the traffic entering the intersection from each approach of the main street turned left, and another 7 percent turned right. For the main street all right-turning vehicles used the outside lane, and all left-turning vehicles used the inside lane. Due to the lane distribution factor, a higher percentage of vehicles in the inside lane turned as compared with the outside lane.

The remaining traffic factors were the traffic volumes on the two intersecting streets. These volumes could not be fixed as they are the fundamental variables with which delay is associated.

Stop Sign Factors

In his study of vehicle performance at urban two-way stop signs, Raff developed the concept of a "critical lag". This critical lag is defined as the lag which has the property that the number of accepted lags shorter than it is the same as the number of rejected lags longer than it. A lag is in turn defined as the time interval between the arrival of a side-street vehicle at the intersection and the arrival of the next main-street vehicle. A main-street vehicle is considered to have arrived when it enters the area bounded by the extension of the curb lines. A side-street vehicle arrives when it reaches its lowest speed; or, if it is following behind another side-street vehicle, it arrives when the preceding vehicle enters the intersection area (40).

The critical lag is the single value used to represent the pattern of acceptance and rejection of lags. The four intersections studied by Raff yielded values for the critical lag of 4.6, 4.7, 5.9, and 6.0 seconds. The higher values were observed at intersections which correspond more closely to the intersection under study. Of all the factors affecting the critical lag the most significant was found to be sight distance; that is, shorter lags are associated with poorer sight distances. The sight distances for the two intersections with the shorter lags were typical for downtown areas, while the sight distances at the other two intersections were more typical of intermediate areas.

In Greenshields study a different quantity was used to evaluate performance at a stop sign. Greenshields' "minimum acceptable time gap" is defined as that gap which will be accepted by more than 50 percent of the drivers. This time gap is measured as the time required for the main-street

vehicle approaching from the left to reach the point of conflict. The point of conflict is in turn described as the intersection of the center lines of the two vehicle paths (24). Since the distance to this point is greater than the distance to the intersection area, a slightly larger value will be expected for Greenshields' "gap" as compared with Raff's "lag". Greenshields' quantity was observed to be 6.1 seconds and is 0.2 seconds longer on the average than the critical lag for similar intersections.

A recent study by Bissel resulted in a probability distribution for gap acceptance at stop signs. The median value for straight-thru vehicles was 5.8 seconds with the 15 and 85 percentiles at 3.9 and 8.5 seconds respectively. The median value for left-turning vehicles was about 0.4 seconds greater (8). Neither Raff nor Greenshields segregated left-turns since the differences between left-turning and straight-thru vehicles were found to be very small.

Raff's terminology and definitions were employed in this study as they are more rigorous. A value of 5.8 seconds was used as the typical critical lag for stop signs. A second value of 4.8 seconds was used to indicate the effect of changing this quantity. The single values were considered representative of the actual distributions of acceptable lags. It should be noted that in most field studies the lag is measured as it occurs after the fact. In both the model and in reality the lag can only be estimated by the driver before the maneuver takes place.

Traffic Signal Factors

There are seven basic variables involved in semi-traffic-actuated-signal control. These are the six adjustable intervals employed by the controller and the location of the side-street detectors. The two amber

interval settings should be based on geometric and traffic factors. The most widely used amber interval is 3 seconds long. It has been shown, both theoretically and in field studies, that this short clearance time may result in a "dilemma zone" of considerable length (15, 37). In other words, there is a portion of the approach lane in which a vehicle can neither safely stop, nor clear the intersection before the expiration of the amber interval. Corresponding behavior took place in the model. In such cases where the model vehicle could not stop within the acceptable limits of deceleration, the vehicle automatically continued thru the intersection. Even though it may not have cleared before the start of the opposing green interval, it cleared in sufficient time to avoid physical contact. Inasmuch as the 3 second clearance interval is prevalent, both amber intervals were fixed at this value.

Of the five remaining variables three are inter-dependent. The side-street-initial-green interval plus one extension interval combine to provide the minimum side-street-green time. This minimum green time must be of sufficient duration to clear a queue of vehicles occupying the space between the stop line and the detector. Pedestrian considerations may also bear on the minimum green. This time should accommodate pedestrians crossing the main street. Using a walking speed of $3\frac{1}{2}$ feet per second and allowing a 5 second leeway, a desirable minimum green time is 18 seconds.

Optimal controller settings, with respect to delay, are dependent upon traffic volumes. If delay on the main street is to be minimized, the detector should be placed near the stop line and short side-street initial and extension intervals used. If delay on the side street is to be minimized, the detector should be placed at some distance from the stop line. Then

an approaching side-street vehicle may clear without even decelerating. Ordinarily, settings cannot be changed when volumes vary, and compromise values must be used. Because traffic volume on the main street is most always greater, the delay to main-street vehicles is usually critical.

Two sets of signal variables were used; one with the detectors placed at 150 feet, and one with the detectors 21 feet from the stop lines. These settings provide for the cases where pedestrians must be considered and where pedestrian movements are negligible. They also correspond to attempts to minimize side-street delay and minimize main-street delay. The effect of intermediate detector locations can be estimated by interpolation of the resultant delays.

When the detector is placed approximately 150 feet from the stop line, the side-street initial and extension-green intervals should be set at 13 and 5 seconds respectively. About 7 vehicles may be stopped between the stop line and the detector. As determined by the behavior equation, $17 \frac{1}{2}$ seconds is needed to move a queue of 7 vehicles such that the front of the seventh vehicle is 17 feet beyond the extension of the far curb line. This behavior is illustrated as the time to reach a position where $X = 2073$ feet in Figure 7. An eighth vehicle may also clear by using one-half of the amber interval. A ninth vehicle in the queue would cross the detector during the fourteenth second of green, thereby gaining an additional 5 second extension interval. All subsequent vehicles would similarly be cleared up to the time at which the side-street-maximum-green interval has expired.

The side-street-extension interval should be of sufficient duration to clear a vehicle approaching a green signal once it has actuated the detector. An interval of 5 seconds is adequate with but occasional use

of a portion of the amber interval. Furthermore, the 5 second interval accommodates the maximum platoon headway of $4 \frac{1}{2}$ seconds which was assumed in the arrival distribution.

Once the main-street-minimum-green interval has expired, these settings require an approaching side-street vehicle to slow to approximately 24 feet per second before receiving the green aspect. The settings closely correspond to the values recommended in the Manual of Uniform Traffic Control Devices (35).

When the detector is placed 21 feet from the stop line, the side-street initial and extension-green intervals should be 2 and 4 seconds respectively. A second-in-line vehicle would thus cross the detector 3 seconds after the start of the green aspect, thereby resetting the extension interval. All subsequent vehicles in a queue may similarly be cleared. A side-street vehicle approaching a red aspect would normally reach a complete stop and then wait for one second before receiving the right-of-way.

Minimum delays have been found to occur when the main-street-minimum-green interval is relatively short as more flexibility is provided in that the controller can react quickly to side-street actuation. On the other hand, the side-street-maximum green was found to have only a minor effect on delay (6). The nature of this interval is such that it is rarely timed out. The interval will be used fully only when it is actually required. Practical values for these two intervals are in the range of 30 seconds. These values would provide for reasonable cycling of the right-of-way as capacity conditions are approached.

The two sets of traffic signal variables that were used are shown in Table 5. It should be noted that the model detector is actuated by the

TABLE 5
TRAFFIC SIGNAL VARIABLES USED

Variable	Distance Between Detector and Stop Line	
	150 ft	21 ft
Main-street minimum green	30 sec	30 sec
Main-street amber	3 sec	3 sec
Side-street initial green	13 sec	2 sec
Side-street extension green	5 sec	4 sec
Side-street maximum green	30 sec	30 sec
Side-street amber	3 sec	3 sec
Station of model detector	1853 ft	1982 ft

front bumper of a vehicle, whereas the real detector is more often actuated by the front tires. The model detector was therefore placed 3 feet closer to the stop line than the corresponding nominal position.

Preliminary Runs

Checking the Program

Once the program was debugged several runs were made using production mode 4. This alternate provided, in a readable format, detailed information on the behavior of each vehicle during each time increment. The use of this information resulted in several refinements in the program. Extensive testing of the intersection in this manner assured that the program was properly written and that the action of the vehicles was reasonable and realistic.

Field validation of the model was well beyond the scope of this study. Such validation is a most difficult undertaking even when unlimited resources are available. It was hoped that the model could be checked against some of the delay studies reported in the traffic engineering literature. In each case, however, certain necessary information was lacking in these studies. In some cases the delay data were measured over a period of several hours, and the variations in traffic volume thruout the study period were not recorded. In other cases such items as traffic distribution and turning movements were not observed. The basic problem in validation is simply that information of the type readily obtained from the model is extremely difficult to measure in the field.

The merit of the model, therefore, must be judged by the manner in which it was constructed. The traffic characteristics on which it was

based are those that have been extensively studied and found to be similar at different locations. These characteristics included velocity, acceleration, spacing, gap acceptance, et cetera.

Insofar as possible identical models were used to represent the intersection as operating under the two types of traffic control. The effects of certain possible inaccuracies in delays as determined for the two control types were thus significantly reduced. That is, differences in delay could be realistic even though the absolute values of delay may have been somewhat distorted. The use of model comparison also permitted such variables as parking interference, pedestrian movements, and intersection geometry to be eliminated as direct considerations.

Selection of Approach Length

Runs were also made to test the effect of changing the length of approach lanes. These lanes had to be of sufficient length to permit an entering vehicle to stabilize its behavior before reaching any of the critical points in the lane. These critical locations were the point where vehicles began decelerating for a stop, the location of the detectors, and the furthest point investigated by a vehicle crossing the traffic stream as it searched for an acceptable gap. A beginning of lane coordinate, X_0 , of 1650 feet adequately met these requirements. This provided an approach lane of 350 feet prior to the location of the stop lines.

The beginning of the lane also affects vehicle behavior in that it fixes the relative time within a time increment that a free-flowing vehicle reaches the various critical points in the lane. To assure a comparison in which the only variable was the length of lane, two X_0 's were selected

which differed by a multiple of 44 feet*. Two runs were made with X_0 's of 22 feet and 1650 feet. Care was taken to assure that the identical traffic was used for each run. No significant difference in total delay was observed for these runs. One should note, however, that stopped delay is recorded only for vehicles within the lane. Stopped delay would be underestimated in a situation where a long line of stopped vehicles filled the approach lanes and the backlog contained additional vehicles. An X_0 of 1650 feet was used for all production runs.

Selection of Running Time

Additional preliminary runs were made to investigate the variability of the delay data. A 90 minute run was made for each of the two types of control using 30 samples of 3 minutes each. Various groupings of the sample data were tried, and the standard deviation of the sample means was used as an index of the variability. Control by traffic signal resulted in considerably less variability than stop sign control. For either case the additional data obtained beyond one hours running time had little effect on the average delay. A one hour run consisting of 8 samples of 7.5 minutes each was selected for all production runs. This plan provided a reasonable compromise between sample size and number of samples. A 5 minute transient time was used for all production runs.

Procedure for Production Runs

Most of the production runs were made using the regular random number series option of the program. This assured that the identical traffic was generated when the two different control devices were tested at the same

* 44 feet is the distance traversed by a free-flowing vehicle during a one second time increment.

volume levels. Furthermore, since a separate series of random numbers was used to generate vehicles for each street, the volume level of one street could be varied without affecting the traffic pattern on the other street. It was desirable that the volume levels for each street remained fixed to accurately locate the points of equal delay.

As both the generation of vehicles and the selection of turning maneuvers were done randomly, the actual traffic characteristics deviated from the ones specified. Minor variations also occurred when identical traffic patterns were generated. This latter variation was caused by slight differences in the pattern of vehicle release at the beginning and end of the one hour run. As these differences were small, the characteristics were averaged for each street and for each volume level. The average traffic characteristics are listed in Table 6.

The backlog limit was arbitrarily set at 20 vehicles. When this backlog was exceeded there were usually 8 to 10 vehicles occupying the distance between the beginning of the lane and the stop line. In each case when a run was terminated due to the exceeding of the backlog limit, it was obvious that the possible capacity of the approach was exceeded.

Computer runs were made in several shifts. The results of one run enabled a more intelligent selection of specifications for subsequent runs. In some cases this procedure reduced the number of volume combinations required for subsequent runs, because it was known which combinations were likely to be critical.

Two average delays were computed by the program. The first was the average of the sample means and the second was the overall average delay. Since the number of vehicles released during each sample varied, the values

TABLE 6
VALUES OF ACTUAL TRAFFIC CHARACTERISTICS

Traffic Volume Vehicles per hour		Actual Traffic Characteristics in Percent		
Specified	Actual	Directional Distribution	Right Turns	Left Turns

REGULAR RANDOM NUMBER SERIES

Side Street

42	43	51.8	24.0	11.5
84	84	58.1	17.7	9.6
125	125	54.8	14.2	10.4
250	251	58.8	13.2	14.0
375	363	60.8	13.0	13.2
500	522	60.7	13.0	12.8

Main Street

125	113	60.2	7.1	4.4
250	252	58.8	7.5	8.3
500	531	61.0	6.0	5.8
750	789	59.9	8.1	8.9
1000	1018	59.3	7.5	7.0
1250	1283	59.8	7.0	7.4
1500	1489	58.9	7.4	6.7

ALTERNATE RANDOM NUMBER SERIES

Side Street

42	44	55.0	16.6	11.4
84	72	56.5	15.3	9.6
125	116	65.1	16.5	12.5
250	249	56.0	14.9	12.7
375	363	62.2	15.9	15.3
500	-	58.8	15.6	13.5

Main Street

125	136	62.5	9.6	3.7
250	257	62.5	8.2	6.6
500	513	57.9	7.4	7.6
750	766	60.1	8.2	6.8
1000	1035	60.8	7.1	6.6
1250	1296	61.0	6.9	7.3
1500	1519	60.4	7.1	7.4

differed for the two quantities. The differences were minor, but the overall average delay was the one used in the analysis and is shown in the tables in Chapter V.

The possibility existed of underestimating average total delay as capacity was approached. Since total delay was computed and recorded only at the time of a vehicle's release, the delays to vehicles still in the system were unmeasured. Such a situation could be detected, however, by examining the number of vehicles in the lanes, the size of the backlogs, and noting a drop in the rate at which vehicles were released.

The Efficiency of the Model

With the recent tremendous advances in computer technology, the efficiency of the simulation model is rapidly becoming unimportant. The model may be classified as the periodic scanning type, where each vehicle is processed during each time increment. Models of the event scanning type have been used. In this type, processing is bypassed except when an event occurs which necessitates some action of the vehicle. The reduction in scanning time thus achieved, however, is in good part offset by the additional logic employed. The behavior equations used in this model, moreover, are such that continual processing is required.

The real time to computer time ratio achieved by the program is 45 to 1. This means that one hours traffic can be simulated in about 1 1/3 minutes on the computer. At regular commercial rates this corresponds to approximately 15.50 dollars of computer time.

A possible criticism of the model is that it is too realistic. Such a belief reflects more on the efficiency of the model than on the validity

of the results. The principle employed was to use the more realistic approach when the effect of an alternate course of action was unknown. It was recognized, however, that excessive attempts for realism may be detrimental. For example, it may be hypothesized that there is some impatience factor that modifies a driver's gap acceptance pattern at a stop sign. If the magnitude of this factor and the manner in which it operates has not been determined in the field, its inclusion in the model may well give less accurate results than would be obtained by its omission.

CHAPTER V

RESULTS AND DISCUSSION

Results for Two-Way Stop Control

The average total delay that resulted when the intersection was operated under stop-sign control is shown in Tables 7, 8, and 9. In analysing this data it was first advantageous to consider the two streets separately. The delay to main-street traffic is due only to the interaction between main-street vehicles and is completely independent of the traffic on the side street. The major factor contributing to this delay is left-turning vehicles. Delays also occur when straight-thru vehicles are forced to slow down behind turning vehicles. It should be noted that when two turning vehicles are traveling at minimum headway, the second vehicle will be delayed. Due to the spacing restriction, the minimum headway increases as velocity is reduced. The average total delay per main-street vehicle is shown as a function of main-street volume in Figure 33. Even though the values of these delays are small, they become a significant portion of the total delay when the main-street volume is considerably greater than side-street volume.

The delay data for side-street vehicles contained a fair amount of scatter, but trends were clearly evident. When the data were plotted, an exponential relationship was indicated. By fixing the side-street volume and plotting the natural logarithm of delay versus main-street volume, an

TABLE 7
 DELAY AT TWO-WAY STOP
 WITH CRITICAL LAG OF 5.8 SECONDS

		Average Total Delay per Vehicle in Seconds					
Main-Street Volume	Street	Side-Street Volume in Vehicles per Hour					
		43	84	125	251	363	522
113	Both	2.9	4.1	5.4	7.6		
	Side	10.6	9.9	10.2	11.0		
	*	13.2	10.7	12.2	14.2		
252	Both	1.8	2.9	4.0	6.3	8.2	
	Side	11.7	11.5	11.7	12.5	13.8	
	*	15.7	14.7	14.7	16.7	20.2	
531	Both	1.2	2.7	3.9	7.5	13.6	40.8
	Side	15.8	20.1	20.3	23.2	33.4	82.0
	*	20.7	33.2	28.3	35.3	59.2	149.2
789	Both	1.4	2.8	3.6	12.2	38.0	
	Side	21.9	27.5	25.0	49.5	120.8	≠
	*	31.7	36.7	39.7	94.2	227.7	
1018	Both	1.4	3.2	6.3	58.7		
	Side	28.4	38.7	55.6	332.5	≠	≠
	*	39.7	61.2	93.2	534.2		
1283	Both	2.0	4.7	11.7			
	Side	47.2	68.5	121.9	≠	≠	≠
	*	76.2	114.2	212.7			
1489	Both	3.6	25.0				
	Side	104.9	451.7				
	*	201.7	929.2				

* 85th percentile value of total delay per side-street vehicle.

≠ The possible capacity of the side-street approaches was exceeded.

TABLE 8

DELAY AT TWO-WAY STOP WITH CRITICAL LAG OF
5.8 SECONDS USING ALTERNATE RANDOM NUMBER SERIES

Average Total Delay per Vehicle in Seconds							
Main-Street Volume	Street	Side-Street Volume in Vehicles per Hour					
		44	72	116	249	363	500
136	Both		3.3				
	Side		9.6				
	*		10.7				
257	Both		2.4			8.0	
	Side		10.7			13.6	
	*		14.2			18.2	
513	Both		1.9	2.9	6.5	9.4	
	Side		14.3	15.3	19.9	22.5	≠
	*		22.2	23.2	31.7	36.7	
766	Both	1.2	1.8	3.0	9.1	24.0	
	Side	18.8	19.3	21.2	36.4	76.4	
	*	30.7	30.7	31.6	59.2	154.2	
1035	Both	1.5	2.7	4.4	37.5		
	Side	29.5	36.7	40.5	202.2		
	*	54.2	59.7	66.7	528.7		
1296	Both	2.6	4.2	8.2			
	Side	65.6	74.8	98.5			
	*	125.7	135.7	236.2			
1519	Both	4.4	6.7				
	Side	132.4	137.4				
	*	239.2	336.2				

* 85th percentile value of total delay per side-street vehicle.

≠ The possible capacity of the side-street approaches was exceeded.

TABLE 9
 DELAY AT TWO-WAY STOP
 WITH CRITICAL LAG OF 4.8 SECONDS

Average Total Delay per Vehicle in Seconds							
Main-Street Volume	Street	Side-Street Volume in Vehicles per Hour					
		43	84	125	251	363	522
0	Both	9.1	9.0	9.0	9.3	9.7	10.0
	Side	9.1	9.0	9.0	9.3	9.7	10.0
	*	9.2	9.2	9.2	9.2	10.7	11.7
252	Both	1.7	2.7	3.8	6.0	7.6	
	Side	11.3	10.9	11.1	11.9	12.8	
	*	13.7	12.7	13.7	16.2	18.2	
531	Both	1.1	2.0	3.0	5.5	9.3	17.1
	Side	13.6	14.5	15.5	17.1	22.8	34.4
	*	20.7	20.7	22.7	27.7	39.2	60.2
789	Both	1.1	2.1	3.1	8.0	14.3	
	Side	17.5	19.4	21.5	31.9	44.5	≠
	*	24.7	27.7	29.2	50.2	74.7	
1018	Both	1.3	2.5	4.1	18.0		
	Side	25.3	30.2	35.5	88.9	≠	
	*	35.7	41.2	48.7	192.7		
1283	Both	1.9	3.6	6.6			
	Side	42.3	50.7	67.0	≠		
	*	58.7	82.2	110.7			
1489	Both	2.1	3.9				
	Side	50.8	62.0				
	*	93.2	134.2				

* 85th percentile value of total delay per side-street vehicle.

≠ The possible capacity of the side-street approaches was exceeded.

FIGURE 33. AVERAGE TOTAL DELAY PER MAIN-STREET VEHICLE — TWO-WAY STOP SIGN

interesting relationship was obtained. Subtracting a constant amount from each delay resulted in relatively straight lines. Similar results were obtained when main-street volume was fixed and side-street volume was varied.

The constant amount of delay which exists for each side-street vehicle is the time lost in deceleration and acceleration. In the model the magnitude of this portion of delay is known for free-flowing vehicles. It amounts to 8.67 seconds for vehicles which are generated at an even second and 9.17 seconds for vehicles generated on the half second. As the probabilities are equal for the two cases, a mean value of 8.9 seconds was used. The concept of a "wait" was then defined as the total delay per side-street vehicle minus 8.9 seconds. It is the wait and not the total delay which is directly identifiable by the vehicle operator.

Stopped delay might have been used in place of wait, but it neglects some delays that occur in waiting. For example, when the lead vehicle is released from a queue at the stop line, following vehicles may exceed a 4.5 feet per second velocity (used to define stopped delay) as they change position in the queue. Stopped delay thus tends to underestimate waiting time.

In order to place the origin corresponding to zero waiting time on the graphs, the quantity "wait plus one second" was used. Figure 34 shows the relationship between wait plus one second and traffic volume. The lines shown are drawn directly thru the data points, and the linear trend is clearly shown. Other sets of data indicate a similar relationship.

The major portion of the variability in the delays that was observed under stop-sign control occurred on the side-street. The standard deviation of the sample means increased as the value of the delay increased.

FIGURE 34. THE RELATIONSHIP BETWEEN AVERAGE WAIT PER SIDE-STREET VEHICLE AND TRAFFIC VOLUME — TWO-WAY STOP SIGN

The standard deviation for the average total delay per side-street vehicle generally varied between 7 and 50 seconds. Because the variability in side-street delays was greater than desired, it was decided to check the results against an independent set of data. The alternate random number series option in the program was used to obtain data based on different main-street and side-street traffic. These results likewise contained a fair amount of scatter, yet comparison of the two sets of data revealed that the results were quite similar. In spite of the variation between the short time samples, the overall delay characteristics of the one hour runs were essentially reproducible.

Regression analysis was used in an attempt to determine an equation for the side-street wait. The relationships investigated were of the form

$$\text{wait} = e^{f(F_m, F_s)} - 1 ,$$

where the exponent is some linear function of both main-street volume (F_m) and side-street volume (F_s). No linear equation was found which satisfactorily fit the data thruout its range. It is believed that an equation exists, but it is undoubtedly a more complex relationship than those studied. It is interesting to note, however, that for the equations investigated the regression coefficients for the two independent sets of data were very similar.

Data were collected for the delay to side-street vehicles when the main-street volume was zero. These data, shown in Table 9, have no practical significance other than indicating the boundary conditions for the delay versus volume relationship. This side-street delay is due entirely to the interaction of side-street vehicles and is essentially independent of the critical lag.

Figure 34 shows the actual data points for a critical lag of 5.8 seconds when the alternate random number series was used. Figure 35 shows the corresponding information for the regular random number series. A visual fit to both sets of data is shown in Figure 35. Straight lines were assumed in constructing this fit. To a minor extent the data points were weighted by using additional information available from the computer output. Such items as actual traffic characteristics, size of backlogs, and variability were considered. Figure 36 shows a similar fit for the average side-street wait when the critical lag was 4.8 seconds. One should not extrapolate these curves for higher main-street volumes. The relationships shown hold true only when the capacity of the side-street approaches is not exceeded. When capacity is exceeded, delay is associated with the additional variable of time, and the given curves will underestimate the average wait.

The average total delay per side-street vehicle was recomputed by adding 8.9 seconds to the values obtained from the smoothed curves for the average side-street wait. A new average total delay per main-street vehicle was also found by using the smoothed curve shown in Figure 33. A new value for the average total delay per vehicle for all vehicles was then computed based on this information and the known traffic volumes for each street. This computation was performed by using the weighted mean concept.

A significant advantage of this smoothing process was that it tended to eliminate the variations due to the individual traffic patterns and the deviation of the traffic characteristics from the specified mean values. The adjusted values of average total delay per vehicle are shown in Figures 37 and 38 for critical lags of 5.8 and 4.8 seconds respectively. As curves are drawn directly thru the adjusted data points, the uniform shape of the

FIGURE 35. AVERAGE WAIT PER SIDE-STREET VEHICLE —
TWO-WAY STOP SIGN WITH A CRITICAL LAG OF 5.8 SECONDS

FIGURE 36. AVERAGE WAIT PER SIDE-STREET VEHICLE —
TWO-WAY STOP SIGN WITH A CRITICAL LAG OF 4.8 SECONDS

FIGURE 37. AVERAGE TOTAL DELAY PER VEHICLE FOR ALL VEHICLES
— TWO-WAY STOP SIGN WITH A CRITICAL LAG OF 5.8 SECONDS

FIGURE 38. AVERAGE TOTAL DELAY PER VEHICLE FOR ALL VEHICLES
— TWO-WAY STOP SIGN WITH A CRITICAL LAG OF 4.8 SECONDS

curves demonstrates the efficiency of the smoothing process. The adjusted curves are nevertheless shown to be a reasonable fit to the original data points.

Results for Semi-Traffic-Actuated Signal Control

The average total delay that occurred when the intersection was operated under actuated-signal control is shown in Tables 10 and 11. The standard deviation of the sample means rarely exceeded a few seconds for the average delay per vehicle. As the variability of the data was small, the data were used directly. One property of semi-traffic-actuated control is that the average delay per side-street vehicle is independent of the volume of traffic on the main street. This property is clearly shown in the data.

Curves for the average total delay per vehicle for the two detector locations are shown as Figures 39 and 40. The individual data points are also shown. The drawing of smooth curves thru these points again reduces the variability in the data as caused by the individual traffic patterns and the deviation of the traffic characteristics from the specified values.

The Development of Volume Warrants

The first consideration in establishing the warrants was minimizing the average total delay for all vehicles. By superimposing the delay curves for one traffic control type on the curves for the other control type, the points of equal delay were determined. These points were then plotted as a function of the traffic volumes on the two streets, and the line of equal delay was drawn. The various combinations of the two critical lags and two detector locations, as shown in Figures 37 thru 40, yielded four lines of equal delay. These lines are shown in Figure 41. Lines of equal delay for

TABLE 10

DELAY AT SEMI-TRAFFIC-ACTUATED SIGNAL
WITH DETECTOR 150 FEET FROM STOP LINE

Average Total Delay per Vehicle in Seconds							
Main-Street Volume	Street	Side-Street Volume in Vehicles per Hour					
		43	84	125	251	363	522
113	Both	4.8	8.9	9.1	13.6		
	Main	3.8	5.9	6.1	8.0		
252	Both	4.5	8.1	8.4	12.7	12.7	
	Main	4.0	6.5	6.7	9.3	8.1	
531	Both	4.2	7.1	8.0	11.2	12.0	12.8
	Main	4.0	6.2	7.1	8.8	9.3	9.2
789	Both	4.9	8.0	8.4	10.7	11.4	12.8
	Main	4.8	7.5	7.8	8.9	9.3	10.4
1018	Both	4.3	7.3	8.4	11.3	11.9	12.8
	Main	4.2	6.8	8.0	10.1	10.5	10.8
1283	Both	6.2	9.1	10.2	12.1	12.7	13.4
	Main	6.2	8.8	10.0	11.3	11.7	12.1
All	Side	7.3	13.1	11.8	16.2	15.9	16.6

TABLE 11

DELAY AT SEMI-TRAFFIC-ACTUATED SIGNAL
WITH DETECTOR 21 FEET FROM STOP LINE

Average Total Delay per Vehicle in Seconds							
Main-Street Volume	Street	Side-Street Volume in Vehicles per Hour					
		43	84	125	251	363	522
113	Both	4.3			14.8		
	Main	1.1			4.1		
252	Both			8.7		14.6	
	Main			2.6		5.9	
531	Both	2.2			9.3	11.7	13.4
	Main	1.4			4.5	5.8	7.3
789	Both			5.9	8.1	10.8	
	Main			3.4	4.4	6.2	
1018	Both	2.3	4.1				
	Main	1.9	3.0				
1283	Both			6.3	8.0		
	Main			4.9	5.7		
1489	Both	2.8	4.5				
	Main	2.5	3.8				
All	Side	12.3	17.9	20.6	19.6	20.6	19.7

FIGURE 39. AVERAGE TOTAL DELAY PER VEHICLE FOR ALL VEHICLES
— ACTUATED SIGNAL WITH DETECTOR 150 FEET FROM STOP LINE

FIGURE 40. AVERAGE TOTAL DELAY PER VEHICLE FOR ALL VEHICLES
— ACTUATED SIGNAL WITH DETECTOR 21 FEET FROM STOP LINE

FIGURE 41. WARRANT DIAGRAM BASED ON MINIMIZING THE AVERAGE TOTAL DELAY PER VEHICLE FOR ALL VEHICLES

other critical lags and detector locations may be estimated by interpolation.

By entering Figure 41 with known main-street and side-street volumes, the intercept of the two volume lines is found. The point of intersection may then be related to a line of equal delay. If the point lies above the appropriate line, then the average total delay per vehicle is less for actuated signal control. Conversely, if the point lies below the line, delay is less for two-way stop control. When the point falls on or close to the line, local conditions and other factors may prevail. When the point falls some distance from the line, one of the control devices is superior from the standpoint of minimizing overall delay. The advantage of stop-sign control over actuated-signal control varies for different volume combinations, with the maximum reduction in average total delay being 6 to 7 seconds per vehicle.

A second, yet equally important, consideration is that delay should not be excessive for either street. Both of the control types studied usually operate in such a manner that the delays to side-street traffic are greater than the delays to main-street traffic, and the delay per side-street vehicle under stop-sign control is the critical factor. The second warrant diagram is shown as Figure 42. This diagram shows for stop-sign control the average wait per side-street vehicle as a function of the traffic volume on the two streets.

For a critical lag of 5.8 seconds curves for average waits of 30, 60, and 90 seconds are shown. For a critical lag of 4.8 seconds curves for average waits of 30 and 60 seconds are drawn. The average wait that is acceptable on the side street may be a function of side-street volume. With smaller

FIGURE 42. WARRANT DIAGRAM BASED ON THE DELAY TO SIDE-STREET VEHICLES FOR TWO-WAY STOP SIGN

side-street volumes greater waits may be considered reasonable. The curves shown were obtained directly from the information contained in Figures 35 and 36. The values of the 85th percentile wait remained relatively constant for each average wait and are also shown in Figure 42.

The Application of the Volume Warrants

The procedure for using the warrant diagrams is as follows. Enter the first warrant diagram, Figure 41, with the traffic volumes for the two streets. Using the appropriate line of equal delay determine which control type will minimize delay. If the decision is not clearly indicated, judgment must be exercised. If two-way-stop control is indicated, the second warrant diagram should be consulted. Using Figure 42 find the average wait that will occur on the side street. If this wait is considered to be excessive, then stop-sign control should not be used. The magnitude of the difference in delay for the two control types should be obtained by referring to Figures 37 thru 40.

One must keep in mind that these warrant curves were developed using specific traffic characteristics. The actual characteristics that occurred were as follows:

Directional Distribution = 59%
 Right turns on side-street = 14%*
 Left turns on side-street = 12%*
 Right turns on main-street = 7%*
 Left turns on main-street = 7%*

Other traffic factors such as the approach speed were also fixed. Moreover, the geometric factors were specified, and certain of the traffic controller

* The percent of turns is given as the percentage of the approach volume.

settings were arbitrarily selected. If the warrants are used with care, however, the results should be indicative of the behavior of the general class of intersection.

As traffic volumes vary thruout the day, the problem naturally arises concerning which traffic volumes to use. If the critical factor is the wait on the side-street under stop-sign control, then the highest volumes anticipated should be considered. This procedure will assure that the two-way stop will remain operational, and that the capacity of the side-street approaches will not be exceeded.

A rigorous approach to minimizing total delay would entail use of the hourly variation in traffic volumes thruout a typical day. The day may then be divided into several periods for which the volume characteristics remain relatively constant. Figures 37 thru 40 may be used to determine the average delay per vehicle for each period. The average delay per vehicle for the entire day may then be computed by weighting each period delay by the number of vehicles using the intersection during that period. By performing this computation for each control type, the difference in average delay for the typical day is readily found.

Although the investigation of delays at pretimed traffic signals was not included in this study, the results obtained are applicable in part to pretimed signals. Except in unusual circumstances, the delays due to pretimed signals are greater than the delays due to actuated signals. Actuation reduces the allocation of the right-of-way to approaches where it is not required. Therefore, if two-way-stop control can be shown to be preferable from the standpoint of delay to semi-traffic-actuated control, then it will be preferred in all likelihood to pretimed signal control.

An additional application of the delay information is concerned with the flashing operation of traffic signals. When a traffic signal is set to flash a red light on the side street and an amber light on the main street, the signal is operationally equivalent to a two-way stop. While it is generally believed that the delays caused by actuated control are small enough that flashing operation is not warranted, the data obtained in this study indicates otherwise for some volume combinations. Again using the assumption that delays at pretimed signals are greater than at actuated signals, the delay data may also be used to indicate when flashing operation of pretimed signals will be advantageous.

Discussion

It should be emphasized that the volume warrants developed in this study are not complete within themselves. They are based solely on the considerations of delay. Although delay is perhaps the major factor, in the final analysis many other factors should be considered. These factors include the differences in accident potential, the types of traffic control used at adjacent intersections, pedestrian movements, and local conditions.

The delay data are directly applicable to the particular type of intersection studied when the geometric, traffic, and control factors are similar to those used in the study. Extrapolation of these data should be done with caution.

Even though two-way-stop control may be shown to reduce overall delays at high volumes, hazardous conditions may exist. The impatience of drivers may cause side-street vehicles to accept dangerously small gaps in the main-street traffic stream. Furthermore, the motorists acceptability of delay

should be considered. It has been stated that motorists may be more willing to accept longer delays at a signal than shorter delays at a stop sign (48). This willingness stems from the fact that the signal provides a certainty of right-of-way, whereas the stop sign does not.

It is of interest to compare the warrants developed in this study to the warrants presented in the Manual on Uniform Traffic Control Devices (35). No specific volume warrants are given for actuated-signal control, but such warrants are given for pretimed signals. Two types of warrants are given, and for each the minimum volume warrant is satisfied when:

"- - - for each of any 8 hours of an average day the traffic volumes given (in tables) exist on the major street and on the higher-volume minor-street approach to the intersection. The major-street and the minor-street volumes are for the same 8 hours. During those 8 hours the direction of higher volume on the minor street may be on one approach during some hours and on the opposite approach during other hours."

By applying a 60 percent - 40 percent directional distribution to the side-street, the "minimum vehicular warrant" becomes 600 and 250 vehicles per hour on the main street and side street respectively. Likewise, the "interruption of continuous traffic warrant" is 900 and 125 vehicles per hour for the two streets. Because for each of 8 hours these volumes must be equalled or exceeded the average volume during this period will be higher than the minimum. These volume figures therefore, are not directly comparable to the warrant diagrams presented herein.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The digital simulation model performed in the desired manner and provided comprehensive delay information that would be most difficult to obtain by more conventional methods.
2. The volume warrants developed in this study for type of intersection control are directly applicable to intersections of the class studied when they are operating within the range of conditions considered. The trends in the delay data are of general interest, moreover, and should contribute to the understanding of the effect of type of traffic control on delay at all intersections.
3. When the intersection was operated under two-way stop-sign control, the following conclusions were drawn from the results:
 - a. Unless an average wait in excess of 30 seconds per vehicle is acceptable on the side street, the critical factor in determining the adequacy of stop-sign control will generally be the delay to side-street vehicles. The interruption of continuous traffic will then be the primary justification for abandoning the two-way stop in favor of a higher type of control.
 - b. The average wait per side-street vehicle is quite sensitive to

the gap acceptance criteria employed by the motorists.

4. The following conclusions were reached in regards to semi-traffic-actuated signal control:
 - a. For many volume combinations that occur during portions of the day, the overall delay to all vehicles would be materially reduced by placing traffic signals on flashing operation.
 - b. For normal volume distributions (the majority of traffic on the main street) the average delay per vehicle for all vehicles is lowest when the detectors are placed close to the side-street stop lines.

Recommendations for Further Study

The computer program used in this study is capable of performing much additional research in its present form. The following items are specifically recommended for further investigation:

1. The effect of varying the percent of turns.
2. The effect of varying the directional distribution.
3. The effect of different settings for the main-street minimum-green interval.
4. The delay characteristics of T intersections.

With a few minor changes in the program the following additional items could be investigated:

1. The delay characteristics of pretimed and volume-density traffic signals.
2. The effect of different lane configurations.
3. The effect of commercial vehicles.

It is recommended that further study be performed towards the development of an equation that would fit the surfaces depicted by Figures 35 and 36. This equation would give the average wait on the side-street for two-way-stop control as a function of main-street volume and side-street volume. Such an empirical relationship would take into account the interaction between vehicles on the same street and on the intersecting street.

One must not think that the advances in simulation techniques will mitigate the importance of field studies. The author knows of no better way to appreciate the present inadequacy of knowledge in the traffic field than by attempting to develop a simulation model. The models can be no better than the information on which they are based. The need for continuing field studies to obtain the information requisite for our understanding of the dynamic traffic process is emphatically stressed.

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APPENDIX

APPENDIX A

GLOSSARY OF SYMBOLS

<u>Symbol</u>	<u>Meaning</u>
$\bar{A}$	Free-flowing or maximum rate of acceleration
D	Actual rate of deceleration
$\bar{D}$	Free-flowing deceleration rate
e	The minimum headway permitted
F	Traffic volume
h	Headway or time spacing between vehicle arrivals
$\bar{h}$	The mean headway
I	Inside lane on main street
K	The fraction of all headways $\leq r$ ($4 \frac{3}{4}$ sec)
LT	Left turn
MS	Main street
n	Any value of h
$\emptyset$	Outside lane on main street
p	The probability of an arrival, assuming uniform probability
P_a	The probability of an arrival when $e \leq h \leq r$
P_b	The probability of an arrival when $h > r$
$P(y)$	The probability of "y" occurring
q	The probability of no arrival, assuming uniform probability
q_a	The probability of no arrival when $e \leq h \leq r$
q_b	The probability of no arrival when $h > r$
Q	Constant based on ΔV in spacing relationship
r	The maximum headway for which the probability of an arrival is enhanced
RT	Right turn
S	Distance between the front of adjacent vehicles
SS	Side street
ST	Straight thru
t	Clock time
T	Time remaining in time increment after passing turn point
TOA	Time of arrival

APPENDIX A (continued)

<u>Symbol</u>	<u>Meaning</u>
v	The maximum velocity permitted at the turn point
V	Velocity
$\bar{V}$	Free-flowing or maximum velocity
$V_{\max}$	The maximum velocity possible at the turn point
x	The distance between a vehicle and some given point
X	Longitudinal coordinate of vehicle along lane
X_0	Coordinate of the beginning of the lane
Z	Distance traveled during one time increment
ZA	Z based on the acceleration restriction
ZD	Z based on the stopping restriction
ZE	Z based on entering restrictions
ZE_1	Z when entering based on spacing
ZE_2	Z when entering based on time available
ZS	Z based on the spacing restriction
ZT	Z based on the turning restriction

Primes refer to the preceding vehicle

Subscripts with t refer to time

APPENDIX B

SUMMARY OF BEHAVIOR EQUATIONS

Values of Parameters Used

Free-flowing acceleration,	$\bar{A} = 3 \text{ ft/sec}^2$
Free-flowing deceleration,	$\bar{D} = 6 \text{ ft/sec}^2$
Free-flowing velocity,	$\bar{V} = 44 \text{ ft/sec}$
Stop line,	$X = 2000 \text{ ft}$
Turn point,	$X = 2016 \text{ ft}$
Minimum vehicular spacing,	$P = 22 \text{ ft}$

Spacing Equation

$$S \geq 22 + V_t + \frac{1}{12} (V_t - V_t')^2 \cdot Q \quad \text{eq. 16a}$$

where Q is defined as

$Q = 1$ when $V_{t-1} > V_t'$

$Q = 0$ when $V_{t-1} \leq V_t'$

Spacing Restriction

$$ZS = \frac{1}{2} (V_{t-1} + V_t') - 4.5 + \left[20.25 - 1.5 V_{t-1} - 4.5 V_t' + 3 (X_t' - X_{t-1} - 22) \right]^{1/2} \quad \text{eq. 19a}$$

when $V_{t-1} > V_t'$

$$ZS = \frac{1}{3} \left[X_t' - X_{t-1} - 22 + V_{t-1} \right] \quad \text{eq. 20a}$$

when $V_{t-1} \leq V_t'$

Acceleration Restriction

$$ZA = \frac{1}{2} \left[V_{t-1} + (V_{t-1} + 3) \right] \quad \text{eq. 21a}$$

APPENDIX B (continued)

where $(V_{t-1} + 3)$ may not be > 44

Stopping Restriction

$$ZD = \frac{1}{2} V_{t-1} - \frac{D}{4} + \left[\frac{D^2}{16} - \frac{D}{4} V_{t-1} + \frac{D}{2} (2000 - X_{t-1}) \right]^{1/2} \quad \text{eq. 23}$$

when $6 < D \leq 12$

$$ZD = \frac{1}{2} V_{t-1} - 1.5 + \left[2.25 - 1.5 V_{t-1} + 3 (2000 - X_{t-1}) \right]^{1/2} \quad \text{eq. 23a}$$

when $D \leq 6$

Turning Restriction

$$ZT = \frac{1}{2} V_{t-1} - 1.5 + \left[58.5 - 1.5 V_{t-1} + 3 (2016 - X_{t-1}) \right]^{1/2} \quad \text{eq. 25a}$$

when $ZT \leq 2016 - X_{t-1}$

Otherwise, compute $V_{\max}$ at turn point

$$V_{\max} = \left[V_{t-1}^2 + 6 (2016 - X_{t-1}) \right]^{1/2} \quad \text{eq. 26a}$$

If $V_{\max} < 15$, then ZT is not applicable

If $V_{\max} \geq 15$, then:

$$T = 1 - \frac{2 (2016 - X_{t-1})}{V_{t-1} + 15} \quad \text{eq. 27a}$$

$$ZT = (2016 - X_{t-1}) + 15T + 1.5T^2 \quad \text{eq. 28a}$$

$$V_t = 15 + 3T \quad \text{eq. 29a}$$

APPENDIX B (continued)

Vehicle Processing

Z = the smallest of the Z 's which are applicable (ZS , ZA , ZD , or ZT)

where Z must be ≥ 0

$$X_t = X_{t-1} + Z$$

$$V_t = 2Z - V_{t-1}$$

where V_t must be ≥ 0

Entering Procedure

$$ZE_1 = X_t' - X_0 - 66 - \frac{1}{12} (44 - V_t')^2 \quad \text{eq. 37a}$$

$$ZE_2 = 44 (t - TOA) \quad \text{eq. 38a}$$

ZE = the smaller of ZE_1 and ZE_2

APPENDIX C

DICTIONARY OF FORTRAN VARIABLES

<u>Variable Name</u>	<u>Meaning</u>
* ARRAY	Data storage for vehicles in lanes
* AVE	Average delay per vehicle during sample time
* AVEAVE	Mean of average delays per vehicle
B	A temporary value
* BLOCK	Earliest clock time for release from stop sign
* BRAY	Data storage for vehicles in backlog
BT	A temporary value (time interval)
* CARS	Cumulative number of cars released
* CLAG	Critical lag for release from stop sign
CLOCK	Simulated clock time
CONTRO	Subprogram name
D	Rate of deceleration
* DELAY	Total delay encountered by released cars
DIST	Direction distribution of traffic
DREQ	Deceleration rate for vehicle stopping at amber
* FILE	List of individual total delays for SS vehicles at stop sign
FJCNT	Floating point value of JCOUNT
* FRTURN	Fraction of turns for lanes
GEN	Subprogram name
I	Subscript indicating lane
IADJ	Subscript for adjacent lane in same direction (MS)
INDSIG	Register indicating traffic signal aspects displayed
IO	Subscript for opposite approach
IOL	Subscript for the left-hand approach
IOR	Subscript for the right-hand approach
J	Subscript - general
J85	Subscript of 85th percentile value in FILE
JCOUNT	Number of values stored in FILE
+ K__	Subscript - general

* These variables are arrays. See Appendix D for array specifications.

+ Underlined blank spaces indicate that other symbols may be used in these positions.

APPENDIX C (continued)

<u>Variable Name</u>	<u>Meaning</u>
L	Subscript indicating vehicle index in lane
* LEAD	Index of lead vehicle in lane
LDE	Index of lead vehicle for Passing Routine
LED	Index of lead vehicle at start of each lane scan
LNEXT	Subprogram name
LNKENT	Subprogram name
* LOC	Index of next vehicle to enter lane
LXPOS	Subprogram name
M	Switch used in Lane Scan Program
MDET	Switch representing traffic signal detector
* MGEN	Switches in Generation Routine
MO	Switch used in Summary and Display Program
MODEC	Traffic control mode
MODEP	Production mode
MODER	Reset mode
MOUT	Switch used in conjunction with production mode 10
MP	Switch indicating new position of passing car
MPASS	Switch indicating previous position of passing car
MQ	Switch indicating previous lane of passing car
* MTAG	Switch used in Tagging Routine
MZD	Switch used in ZD Routine
MZDEW	Value of ZD switch for side street
MZDNS	Value of ZD switch for main street
MZT	Switch for special V_t in Vehicle Processing Routine
N	Current sample number
N1	Counter used to accumulate the value of V_1
N2	Counter used to accumulate the value of V_2
NCARS	Counter used to accumulate the value of CARS
* NDELAY	Stopped delay
NLT	Counter used to accumulate the value of VLT
NRT	Counter used to accumulate the value of VRT
NSEC	Counter used to accumulate a value of SEC
* NUM	Number of vehicles currently in lanes or backlogs
* NUMIN	Counter for vehicles generated
NUMMAX	Backlog limit
* NUMOUT	Counter for vehicles released
NUSAM	Number of samples specified
* OAVE	Overall mean delay per vehicle
OUTIME	Next time that results are to be displayed

APPENDIX C (continued)

<u>Variable Name</u>	<u>Meaning</u>
P85	85th percentile total delay for SS vehicle at stop sign
* PCARS	Previous value of CARS
PCLT	Percent of left turns
PCRT	Percent of right turns
* PREV	Time of arrival of the last car which arrived
* PROB	The probability of vehicle arrivals
* PSEC	Previous value of SEC
QA	q _a
+ R_	The value for which the square root is desired
+ R_2	$\sqrt{R_-}$
+ RAND_	Subprogram names
RATE	Actual traffic volume in vehicles per hour for street
RN1	Random number used to determine vehicle arrivals
RN2	Random number used to determine turns
RUNNU	Number of problem being processed
S	Spacing based on spacing restriction
SAMPLE	Size of sample in units of seconds
SCAN	Subprogram name
* SEC	Cumulative delay
+ SET_	Subprogram names
* SIGCNT	Traffic signal controller interval timers
* SIGNAL	Traffic signal controller intervals specified
* STDDEV	Standard deviation of sample average delays
* SUM	Σ (sample average delays)
* SUM2	Σ (sample average delays) ²
TL2	Time after clock time that vehicle generation is attempted
+ TA	Time available for crossing or merging
TAVAIL	Critical time available for crossing or merging
TIME	Subprogram name
TNEED	Time needed for crossing or merging
TOA	Time of arrival for current vehicle
TRANS	Transient time
TURN	Turn indicator for current vehicle
* TXEND	Travel time for an undelayed vehicle
TXLT	Delay constant for LT vehicle at stop sign
TXRT	Delay constant for RT vehicle at stop sign
TXST	Delay constant for ST vehicle at stop sign

APPENDIX C (continued)

<u>Variable Name</u>	<u>Meaning</u>
V	Velocity of current vehicle (V_{t-1})
V1	No. of vehicles released in one direction
V2	No. of vehicles released in the direction opposite to V1
V2057	Velocity at X = 2057
V2070	Velocity at X = 2070
VLT	No. of LT vehicles released for street
VMXTP	Velocity at turn point based on accelerating capability
VNOW	Velocity of current vehicle (V_t)
* VOLK	Probability of arrival at small headways (K)
* VOLUME	Traffic volume specified
VP	Velocity of preceding vehicle (V_t')
VRT	No. of RT vehicles released for street
VTURN	Special V_t computed by ZT Routine
W	Dummy variable
X	X coordinate of current vehicle (X_{t-1})
* XDET	X coordinate of traffic signal detector
* XEND	X coordinate of the end of the lane
XNOW	X coordinate of current vehicle (X_t)
XOEW	X coordinate of beginning of SS lanes
XONS	X coordinate of beginning of MS lanes
XP	X of preceding vehicle (X_t)
Z	Critical Z
ZA	Z based on acceleration restriction
ZACCEL	Subprogram name
ZD	Z based on stopping restriction
ZDECEL	Subprogram name
+ ZE_	Z based on entering restrictions
ZENTER	Subprogram name
ZS	Z based on spacing restriction
ZSPACE	Subprogram name
ZT	Z based on turning restriction
ZTURN	Subprogram name

APPENDIX D
SPECIFICATIONS FOR FORTRAN ARRAYS

Name	Dimensions	Subscript Meaning*
ARRAY	6, 100, 5	I, L, M
AVE	2, 3	D, H
AVEAVE	2, 3	D, H
BLOCK	2, 3	F, J
BRAY	6, 100, 2	I, L, M
CARS	3	H
CLAG	2, 2	F, C
DELAY	6, 3	I, J
FILE	4000	-
FRTURN	6, 2	I, K
LEAD	6, 2	I, A
LOC	6	I
MGEN	6, 2	I, E
MTAG	6	I
NDELAY	6, 3	I, J
NUM	6, 2	I, A
NUMIN	6, 3	I, J
NUMOUT	6, 3	I, J
OAVE	2, 3	D, H
PCARS	3	H
PREV	6	I
PROB	6, 2	I, B
PSEC	2, 3	D, H
SEC	2, 3	D, H
SIGCNT	6	N
SIGNAL	6	N
STDDEV	2, 3	D, H
SUM	2, 3	D, H
SUM2	2, 3	D, H

APPENDIX D (continued)

Name	Dimensions	Subscript Meaning
TXEND	2, 3	G, J
VOLK	6	I
VOLUME	6	I
XDET	2	F
XEND	2, 3	G, J

* Key to Subscript Meaning

<u>Subscript</u>	<u>Meaning</u>
A	1 = lane array, 2 = backlog array
B	1 = p_a , 2 = p_b
C	1 = critical lag, 2 = $3/4 \cdot$ critical lag
D	1 = total delay, 2 = stopped delay
E	1 = switch GEN1, 2 = switch GEN2
F	1 = east approach, 2 = west approach
G	1 = main street, 2 = side street
H	1 = main street, 2 = side street, 3 = both streets
I	Lanes: 1 = NØ, 2 = NI, 3 = SØ, 4 = SI, 5 = E, 6 = W
J	Turns: 1 = LT, 2 = ST, 3 = RT
K	Turns: 1 = RT, 2 = LT
L	Index for vehicle in lane or backlog (1 thru 100)
M	Vehicle characteristics: 1 = TOA, 2 = TURN, 3 = X, 4 = V, 5 = DREQ
N	Traffic signal intervals: 1 = MS min. green, 2 = MS amber, 3 = SS init. green, 4 = SS ext. green, 5 = SS max. green, 6 = SS amber

APPENDIX E
INPUT SPECIFICATIONS

Column Numbers	Variable	Variable Name	Field Specification
<u>Card Number ONE</u>			
1 - 8	Run number	RUNNU	F8.2
9 - 10	Control mode	MODEC	I2
11 - 12	Production mode	MODEP	I2
13 - 14	Reset mode	MODER	I2
15 - 18	Transient time (sec)	TRANS	F4.0
19 - 22	Sample time (sec)	SAMPLE	F4.0
23 - 24	Number of samples	NUSAM	I2
25 - 26	Backlog limit	NUMMAX	I2
27 - 30	X_0 of main street (ft)	XONS	F4.0
31 - 34	X_0 of side street (ft)	XOEW	F4.0
35 - 38	X of east detector (ft)	XDET(1)	F4.0
39 - 42	X of west detector (ft)	XDET(2)	F4.0
43 - 45	Critical lag east (sec)	CLAG(1, 1)	F3.2
46 - 48	Critical lag west (sec)	CLAG(2, 1)	F3.2
49 - 52	K for NØ lane	VOLK(1)	F4.4
53 - 56	" " NI "	VOLK(2)	F4.4
57 - 60	" " SØ "	VOLK(3)	F4.4
61 - 64	" " SI "	VOLK(4)	F4.4
65 - 68	" " E "	VOLK(5)	F4.4
69 - 72	" " W "	VOLK(6)	F4.4
<u>Card Number TWO</u>			
1 - 4	Volume for NØ lane (veh/hr)	VOLUME(1)	F4.0
5 - 8	" " NI "	VOLUME(2)	F4.0
9 - 12	" " SØ "	VOLUME(3)	F4.0
13 - 16	" " SI "	VOLUME(4)	F4.0
17 - 20	" " E "	VOLUME(5)	F4.0
21 - 24	" " W "	VOLUME(6)	F4.0
25 - 27	Fraction of RT, NØ lane*	FRTURN(1, 1)	F3.3
28 - 30	" " LT, " "	FRTURN(1, 2)	F3.3
31 - 33	" " RT, NI "	FRTURN(2, 1)	F3.3

* The turning fraction is given as a fraction of the lane volume.

APPENDIX E (continued)

Column Numbers	Variable	Variable Name	Field Specification
34 - 36	Fraction of LT, NI lane	FRTURN(2, 2)	F3.3
37 - 39	" " RT, SØ "	FRTURN(3, 1)	F3.3
40 - 42	" " LT, " "	FRTURN(3, 2)	F3.3
43 - 45	" " RT, SI "	FRTURN(4, 1)	F3.3
46 - 48	" " LT, " "	FRTURN(4, 2)	F3.3
49 - 51	" " RT, E "	FRTURN(5, 1)	F3.3
52 - 54	" " LT, " "	FRTURN(5, 2)	F3.3
55 - 57	" " RT, W "	FRTURN(6, 1)	F3.3
58 - 60	" " LT, " "	FRTURN(6, 2)	F3.3
61 - 62	MS minimum green (sec)	SIGNAL(1)	F2.0
63 - 64	MS amber "	SIGNAL(2)	F2.0
65 - 66	SS initial green "	SIGNAL(3)	F2.0
67 - 68	SS extension green "	SIGNAL(4)	F2.0
69 - 70	SS maximum green "	SIGNAL(5)	F2.0
71 - 72	SS amber "	SIGNAL(6)	F2.0

APPENDIX F

KEY TO OPERATION MODES

CONTROL MODE (MODEC)

<u>Setting</u>	<u>Traffic Control</u>
1	Semi-traffic-actuated signal
2	Two-way stop

PRODUCTION MODE (MODEP)

<u>Setting</u>	<u>Additional Data Displayed</u>	<u>Debugging Routines Used</u>
0	None (normal production data only)	-
1	Initialized values	A
2	Controller data	B
3	Controller and lane data	B & E
4	Lane data	C
5	Lane and Vehicle data	C & E
6	Vehicle data	C
7	(Not used)	-
8	Generation and lane data	D & E
9	Generation data	D
10	Run summary after each sample	-

RESET MODE (MODER)

<u>Setting</u>	<u>For Transient Time</u>	<u>For Run Time</u>
1	Regular series reset	Regular series reset
2	" " "	Regular series continued
3	" " "	Alternate series reset
4	Previous series continued	Regular series reset
5	" " "	Previous series continued
6	" " "	Alternate series reset
7	Alternate series reset	Regular series reset
8	" " "	Alternate series continued
9	" " "	Alternate series reset

APPENDIX G

CODING SUBDIVISION OF THE PROGRAM

Program Type	Code Name	Action
FORTRAN Program	MAIN	Master Program; contains Programs I and IV
FORTRAN SUBROUTINE	COMP	Compute the probabilities of arrivals
Subprograms	CONTRO	Contains Program II
	SCAN	Contains Program III
	TIME	Computes total delay
	GEN	Generates, backlogs, and enters vehicles
	ZTURN	Computes ZT
	DEBUGA	Displays initialized variables
	DEBUGB	Displays traffic controller variables
	DEBUGC	Displays data on each vehicle as processed
FORTRAN FUNCTION	DEBUGD	Displays data on vehicle generation
	DEBUGE	Displays vehicle data for each time increment
	ZSPACE	Computes ZS
	ZACCEL	Computes ZA
	ZDECEL	Computes ZD
	ZENTER	Computes ZE
	LXPOS	Gives index for vehicle in any position
Subprograms	LNEXT	Gives index of next vehicle in lane
	LNSENT	Gives index of next vehicle to enter
FAP	RAND	Generates random numbers for main street
FUNCTION	RANDS	Generates random numbers for side street
Subprograms	SET*	Resets random number series in RAND
	SETS*	Resets random number series in RANDS

* These names are merely alternate entrances to subprograms RAND and RANDS.

APPENDIX H
FORTRAN CODE LISTING

```

*      LIST
*      LABEL
CMAIN  MAIN PROGRAM          (CONTAINS PROGRAMS I AND IV)
C      SIMULATION OF VEHICULAR TRAFFIC AT AN INTERSECTION, BY R. M. LEWIS
C
C      OCOMMON  CLOCK, ARAY, BRAY, LEAD, NUM, PREV, MGEN, FRTURN, PROB,
1      NUMIN, XONS, XOEW, RN1, RN2, MODEP, MODEC, NUMOUT, DELAY,
2      NDELAY, BLOCK, MDET, MTAG, MZDNS, MZDEW, INDSIG, SIGNAL, XDET,
3      CLAG, TXLT, TXST, TXRT, TXEND, XEND, JCOUNT, FILE
C
C      ODIMENSION  ARAY(6,100,5), BRAY(6,100,2), LEAD(6,2), NUM(6,2),
1      PREV(6), MGEN(6,2), FRTURN(6,2), PROB(6,2), NUMIN(6,3),
2      NUMOUT(6,3), DELAY(6,3), NDELAY(6,3), BLOCK(2,3), MTAG(6),
3      SIGNAL(6), XDET(2), CLAG(2,2), TXEND(2,3), XEND(2,3), FILE(4000)
C
C      ODIMENSION  VOLUME(6), VOLK(6), OAVE(2,6), SIGCNT(6), SEC(2,3),
1      PSEC(2,3), CARS(3), PCARS(3), AVE(2,3), SUM(2,3), SUM2(2,3),
2      AVEAVE(2,3), STDDEV(2,3)
C
C      OFREQUENCY  200(9,0,1), 220(9,1,1), 225(9,1,1), 411(1,9),
1      412(9,1,0), 415(9,1,0), 208(9,1,1)
C
C      PROGRAM 1  -  INPUT AND INITIALIZATION PROGRAM
C
C      READ IN SPECIFICATIONS          I A
100READ INPUT TAPE 7, 11, RUNNU, MODEC, MODEP, MODER, TRANS, SAMPLE,
1      NUSAM, NUMMAX, XONS, XOEW, XDET, CLAG(1,1), CLAG(2,1), VOLK
11 FORMAT (F8.2, 3I2, 2F4.0, 2I2, 2F4.0, 2F4.0, 2F3.2, 6F4.4)
130READ INPUT TAPE 7, 14, VOLUME, ((FRTURN(I,J), J = 1,2), I = 1,6),
1      SIGNAL
14 FORMAT (6F4.0, 12F3.3, 6F2.0)
C
C      INITIALIZATION ROUTINE          I B
C
16 MZDNS = 2
   MZDEW = 1
   DO 18 K = 1,4
18 MTAG(K) = 2
   MTAG(5) = 1
   MTAG(6) = 1
   MDET = 1
   DO 20 K2 = 1,2
   DO 20 K1 = 1,6
20 MGEN(K1,K2) = 1
22 CALL COMP (VOLUME, VOLK, PROB)
   CLAG(1,2) = 0.75 * CLAG(1,1)
   CLAG(2,2) = 0.75 * CLAG(2,1)
   XEND(1,1) = 2411.0
   XEND(1,2) = 2414.0
   XEND(1,3) = 2383.0

```

```

XEND(2,1) = 2411.0
XEND(2,2) = 2418.0
XEND(2,3) = 2383.0
TXEND(1,1) = (2411.0 - XONS)/44.0 + 4.77840909
TXEND(1,2) = (2414.0 - XONS)/44.0
TXEND(1,3) = (2383.0 - XONS)/44.0 + 4.77840909
TXEND(2,1) = (2411.0 - XOEW)/44.0 + 4.77840909
TXEND(2,2) = (2418.0 - XOEW)/44.0
TXEND(2,3) = (2383.0 - XOEW)/44.0 + 4.77840909
TXLT = (2411.0 - XOEW) / 44.0 - 14.9696970
TXST = (2418.0 - XOEW) / 44.0 - 15.1287879
TXRT = (2383.0 - XOEW) / 44.0 - 14.3333333
30 DO 32 I = 1,2
   DO 32 J = 1,3
32 BLOCK(1,J) = -10000.0
   DO 34 I = 1,6
34 PREV(I) = -10000.0
   INDSIG = 1
   SIGCNT(1) = -10000.0
   DO 38 K = 1,2
   DO 38 I = 1,6
   NUM(I,K) = 0
38 LEAD(I,K) = 1
40 MO = 1
   MOUT = 1
   N = 0
   OUTIME = SAMPLE
   DO 41 J = 1,3
41 PCARS(J) = 0.0
   DO 42 K = 1,2
   DO 42 J = 1,3
42 PSEC(K,J) = 0.0
   DO 45 K = 1,2
   DO 45 J = 1,3
   SUM(K,J) = 0.0
45 SUM2(K,J) = 0.0
   CLOCK = 0.0 - TRANS
C
C           DISPLAY INPUT SPECIFICATIONS   I C
46 WRITE OUTPUT TAPE 6, 99
   WRITE OUTPUT TAPE 6, 100, RUNNU
   GO TO (47, 48),MODEC
47 WRITE OUTPUT TAPE 6, 101, MODEP, MODER
   GO TO 49
48 WRITE OUTPUT TAPE 6, 102, MODEP, MODER
49 WRITE OUTPUT TAPE 6, 103
   WRITE OUTPUT TAPE 6, 104, (VOLUME(1), I = 1,6)
   WRITE OUTPUT TAPE 6, 105, (VOLK(1), I = 1,6)
   WRITE OUTPUT TAPE 6, 106, (FRTURN(1,1), I = 1,6)
   WRITE OUTPUT TAPE 6, 107, (FRTURN(1,2), I = 1,6)
   WRITE OUTPUT TAPE 6, 108
   OWRITE OUTPUT TAPE 6, 109, XONS, XOEW, XDET(1), XDET(2),
1   CLAG(1,1), CLAG(2,1)
   WRITE OUTPUT TAPE 6, 110
   WRITE OUTPUT TAPE 6, 111, (SIGNAL(1), I = 1,6)
   WRITE OUTPUT TAPE 6, 112, TRANS, SAMPLE, NUSAM, NUMMAX
C
C           RESET MODE - SWITCHES           I D + E
   GO TO (60,60,60,80,80,80,70,70,70),MODER
50 GO TO (60,80,70,60,80,70,60,80,70),MODER
C
C           SET REG. RANDOM NO. SERIES       I F
60 W = SET(1)

```

```

W = SETS(3)
GO TO 80

```

```

C
C          SET ALT. RANDOM NO. SERIES      I G

```

```

70 W = SET(5)
W = SETS(5)
GO TO 80

```

```

C
C          PARTIAL RESET ROUTINE          I H

```

```

80 DO 85 I = 1,6
DO 85 J = 1,3
  NUMIN(1,J) = 0
  NUMOUT(1,J) = 0
  NDELAY(1,J) = 0
85 DELAY(1,J) = 0.0
  JCOUNT = 0
GO TO 200

```

```

C
C          FORMAT FOR PRINTING OF RUN SPECIFICATIONS

```

```

99CFORMAT(1H1,34X,43HSIMULATION OF VEHICULAR TRAFFIC AT AN INTER,
1 7HSECTION)
1000FORMAT(35X,11HRUN NUMBER ,F9.2,14X,16HRUSSELL M. LEWIS,
1 //50X,20HINPUT SPECIFICATIONS)
1010FORMAT(44H CONTROL MODE = SEMI-TRAFFIC-ACTUATED SIGNAL,22X,
1 17HPRODUCTION MODE =,13,17X,12HRESET MODE =,13)
1020FORMAT(29H CONTROL MODE = TWO-WAY STOP ,37X,
1 17HPRODUCTION MODE =,13,17X,12HRESET MODE =,13)
1030FORMAT(29X,43HNORTH OUTSIDE NORTH INSIDE SOUTH OUTSIDE,3X,
1 12HSOUTH INSIDE,7X,4HEAST,11X,4HWEST)
104 FORMAT(25H TRAFFIC VOLUME /LANE/HR., F13.0,5F15.0)
105 FORMAT(24H PROB. OF SMALL HEADWAYS, 6F15.4)
106 FORMAT(24H FRACTION OF RIGHT TURNS, 6F15.4)
107 FORMAT(24H FRACTION OF LEFT TURNS , 6F15.4)
1080FORMAT(7X, 11HXO NS LANES,8X,11HXO EW LANES,7X,14HX OF DET. EAST,
1 5X,14HX OF DET. WEST,5X,14HCRIT. LAG EAST,5X,
2 14HCRIT. LAG WEST)
109 FORMAT(1F15.0, 3F19.0, 2F18.2)
1100FORMAT(30H SIGNAL TIMING MS MIN. GREEN, 7X, 8HMS AMBER,
1 6X,47HSS INIT. GREEN SS EXT. GREEN SS MAX. GREEN,
2 7X, 8HSS AMBER)
111 FORMAT(8X, 6F17.0)
1120FORMAT(17H TRANSIENT TIME =, F5.0, 12X, 13HSAMPLE TIME =,
1 F5.0, 12X, 19HNUMBER OF SAMPLES =, 13, 16X,
2 14HMAX. BACKLOG =, 13////)

```

```

C
C
C          HEART OF MAIN PROGRAM

```

```

200 IF (MODEP - 1) 207, 205, 207
2050CALL DEBUGA (MZDNS, MZDEW, MTAG, MGEN, CLAG, PROB,
1 TXEND, TXLT, TXST, TXRT, BLOCK, PREV, INDSIG,
2 SIGCNT, LEAD, N, OUTIME, SUM, SUM2)

```

```

C          CHECK BACKLOG SIZE          I J

```

```

207 DO 209 I = 1,6
208 IF (NUM(1,2) - NUMMAX) 209, 209, 417
209 CONTINUE

```

```

C          CONTROL MODE - SWITCH      I K

```

```

210 GO TO (215, 235),MODEC
215 CALL CONTRO (SIGNAL, SIGCNT, INDSIG, MTAG, MDET, MZDNS, MZDEW)
220 IF (MODEP - 2) 235, 230, 225
225 IF (MODEP - 3) 235, 230, 235
230 CALL DEBUGB (CLOCK, INDSIG, MDET, SIGCNT)
235 CALL SCAN
240 GO TO 410

```

```

C
C
C          PROGRAM IV - SUMMARY AND DISPLAY PROGRAM
C
C          CLOCK INCREMENTING, ETC.          IV A THRU IV F
410 CLOCK = CLOCK + 1.0
411 GO TO (412, 415), MO
412 IF (CLOCK) 501, 413, 413
413 MO = 2
    GO TO 502
415 IF (CLOCK - OUTIME) 501, 416, 416
416 N = N + 1
    GO TO 420

C
C          BACKLOG LIMIT EXCEEDED          IV G
417 WRITE OUTPUT TAPE 6, 418, NUMMAX
4180FORMAT (18H BACKLOG LIMIT OF , 12, 10H EXCEEDED., 10X,
1 28HRUN IS THEREFORE TERMINATED./)
    N = NUSAM + 1
    GO TO 420

C
C          DISPLAY RESULTS FOR SAMPLE          IV G
420 WRITE OUTPUT TAPE 6, 520, N, CLOCK
    WRITE OUTPUT TAPE 6, 521
    WRITE OUTPUT TAPE 6, 522
    WRITE OUTPUT TAPE 6, 523, ((NUMIN(I,J), J=1,3), I=1,6)
    WRITE OUTPUT TAPE 6, 524, ((NUMOUT(I,J), J=1,3), I=1,6)
    WRITE OUTPUT TAPE 6, 525, (NUM(I,1), I=1,6)
    WRITE OUTPUT TAPE 6, 526, (NUM(I,2), I=1,6)
    WRITE OUTPUT TAPE 6, 527
    WRITE OUTPUT TAPE 6, 528, (DELAY(I,1), I=1,6)
    WRITE OUTPUT TAPE 6, 529, (DELAY(I,2), I=1,6)
    WRITE OUTPUT TAPE 6, 530, (DELAY(I,3), I=1,6)
    WRITE OUTPUT TAPE 6, 531
    WRITE OUTPUT TAPE 6, 532, (NDELAY(I,1), I=1,6)
    WRITE OUTPUT TAPE 6, 533, (NDELAY(I,2), I=1,6)
    WRITE OUTPUT TAPE 6, 534, (NDELAY(I,3), I=1,6)
429 DO 430 K = 1,2
    DO 430 J = 1,3
430 SEC(K,J) = 0.0
    DO 432 I = 1,4
    DO 432 J = 1,3
432 SEC(1,1) = SEC(1,1) + DELAY(1,J)
    DO 434 I = 5,6
    DO 434 J = 1,3
434 SEC(1,2) = SEC(1,2) + DELAY(1,J)
    SEC(1,3) = SEC(1,1) + SEC(1,2)
    NSEC = 0
    DO 438 I = 1,4
    DO 438 J = 1,3
438 NSEC = NSEC + NDELAY(1,J)
    SEC(2,1) = NSEC
    NSEC = 0
    DO 442 I = 5,6
    DO 442 J = 1,3
442 NSEC = NSEC + NDELAY(1,J)
    SEC(2,2) = NSEC
    SEC(2,3) = SEC(2,1) + SEC(2,2)
    NCARS = 0
    DO 446 I = 1,4
    DO 446 J = 1,3
446 NCARS = NCARS + NUMOUT(1,J)
    CARS(1) = NCARS

```



```

NCARS = 0
DO 448 I = 5,6
DO 448 J = 1,3
448 NCARS = NCARS + NUMOUT(I,J)
CARS(2) = NCARS
CARS(3) = CARS(1) + CARS(2)
DO 460 K = 1,2
DO 460 J = 1,3
B = CARS(J) - PCARS(J)
IF (B) 456, 456, 458
456 AVE(K,J) = 0.0
GO TO 460
458 AVE(K,J) = (SEC(K,J) - PSEC(K,J)) / B
460 CONTINUE
DO 464 K = 1,2
DO 464 J = 1,3
SUM(K,J) = SUM(K,J) + AVE(K,J)
464 SUM2(K,J) = SUM2(K,J) + AVE(K,J)**2
DO 468 K = 1,2
DO 468 J = 1,3
468 PSEC(K,J) = SEC(K,J)
DO 470 J = 1,3
470 PCARS(J) = CARS(J)
WRITE OUTPUT TAPE 6, 540
WRITE OUTPUT TAPE 6, 541, (AVE(1,J), J = 1,3)
WRITE OUTPUT TAPE 6, 542, (AVE(2,J), J = 1,3)

C
C MISCELLANEOUS IV H THRU IV M
473 IF (N - NUSAM) 474, 480, 480
474 IF (MODEP - 10) 478, 475, 478
475 MOUT = 2
GO TO 480
477 MOUT = 1
478 OUTIME = OUTIME + SAMPLE
GO TO 501

C
C DISPLAY RUN SUMMARY IV N
480 B = N
DO 486 K = 1,2
DO 486 J = 1,3
AVEAVE(K,J) = SUM(K,J) / B
STDDEV(K,J) = (SQRT(B * SUM2(K,J) - SUM(K,J)**2)) / B
IF (CARS(J)) 482, 482, 484
482 OAVE(K,J) = 0.0
GO TO 486
484 OAVE(K,J) = SEC(K,J) / CARS(J)
486 CONTINUE
WRITE OUTPUT TAPE 6, 550
WRITE OUTPUT TAPE 6, 551
WRITE OUTPUT TAPE 6, 541, (AVEAVE(1,J), J = 1,3)
WRITE OUTPUT TAPE 6, 554, (AVEAVE(2,J), J = 1,3)
WRITE OUTPUT TAPE 6, 552
WRITE OUTPUT TAPE 6, 541, (STDDEV(1,J), J = 1,3)
WRITE OUTPUT TAPE 6, 554, (STDDEV(2,J), J = 1,3)
WRITE OUTPUT TAPE 6, 553
WRITE OUTPUT TAPE 6, 541, (OAVE(1,J), J = 1,3)
WRITE OUTPUT TAPE 6, 554, (OAVE(2,J), J = 1,3)
490 N1 = 0
N2 = 0
NLT = 0
NRT = 0
WRITE OUTPUT TAPE 6, 560
DO 492 I = 1,2

```

```

      DO 492 J = 1,3
492  N1 = N1 + NUMOUT(1,J)
      DO 493 I = 3,4
      DO 493 J = 1,3
493  N2 = N2 + NUMOUT(1,J)
      DO 494 I = 1,4
      NRT = NRT + NUMOUT(1,3)
494  NLT = NLT + NUMOUT(1,1)
      V1 = N1
      V2 = N2
      VLT = NLT
      VRT = NRT
      IF (V1 + V2) 495, 495, 601
601  RATE = (V1 + V2) * (3600.0 / CLOCK)
      DIST = (V1 / (V1 + V2)) * 100.0
      PCRT = (VRT / (V1 + V2)) * 100.0
      PCLT = (VLT / (V1 + V2)) * 100.0
C HEADINGS PRINTED BY 490 +4, VALUES WILL NOT PRINT IF VOLUME IS ZERO
  WRITE OUTPUT TAPE 6, 561, RATE, DIST, PCRT, PCLT
495  N1 = 0
      N2 = 0
      NLT = 0
      NRT = 0
      DO 496 J = 1,3
496  N1 = N1 + NUMOUT(5,J)
      DO 497 J = 1,3
497  N2 = N2 + NUMOUT(6,J)
      DO 498 I = 5,6
      NRT = NRT + NUMOUT(1,3)
498  NLT = NLT + NUMOUT(1,1)
      V1 = N1
      V2 = N2
      VLT = NLT
      VRT = NRT
      IF (V1 + V2) 603, 603, 602
602  RATE = (V1 + V2) * (3600.0 / CLOCK)
      DIST = (V1 / (V1 + V2)) * 100.0
      PCRT = (VRT / (V1 + V2)) * 100.0
      PCLT = (VLT / (V1 + V2)) * 100.0
      WRITE OUTPUT TAPE 6, 562, RATE, DIST, PCRT, PCLT
603  IF (JCOUNT - 5) 660, 620, 620
620  K = JCOUNT - 1
      DO 640 I = 1,K
      IPLUS1 = I + 1
      DO 640 J = IPLUS1, JCOUNT
625  IF (FILE(I) - FILE(J)) 640, 640, 630
630  B = FILE(I)
      FILE(I) = FILE(J)
      FILE(J) = B
640  CONTINUE
650  FJCNT = JCOUNT
      J85 = 0.85 * FJCNT
      P85 = FILE(J85)
      WRITE OUTPUT TAPE 6, 564, P85
660  WRITE OUTPUT TAPE 6, 563
C
C          OUTPUT SWITCH = MOUT          IV P
499  GO TO (500, 477), MOUT
500  GO TO 10
501  GO TO 207
502  GO TO 50
C
C          FORMAT FOR PRINTING OF RESULTS

```

```

520 FORMAT (30X, 13HSAMPLE NUMBER, 14, 26X, 7HCLOCK =, F7.0)
5210FORMAT (15X, 13HNORTH OUTSIDE, 6X, 12HNORTH INSIDE, 5X,
1 13HSOUTH OUTSIDE, 6X, 12HSOUTH INSIDE, 10X, 4HEAST, 14X, 4HWEEST)
5220FORMAT (4X, 4HCARS, 7X, 2HLT, 4X, 2HST, 4X, 2HRT, 4X, 2HLT, 4X,
1 2HST, 4X, 2HRT, 4X, 2HLT, 4X, 2HST, 4X, 2HRT, 4X, 2HLT, 4X,
2 2HST, 4X, 2HRT, 4X, 2HLT, 4X, 2HST, 4X, 2HRT, 4X, 2HLT, 4X,
3 2HST, 4X, 2HRT)
523 FORMAT (11H GENERATED , 18I6)
524 FORMAT (11H RELEASED , 18I6)
525 FORMAT (11H IN LANES , 112, 5I18)
526 FORMAT (11H BACKLOGGED, 112, 5I18/)
5270FORMAT (16H CUM TOTAL DELAY, 5X, 13HNORTH OUTSIDE,
1 4X, 46HNORTH INSIDE SOUTH OUTSIDE SOUTH INSIDE, 9X,
2 4HEAST, 13X, 4HWEEST)
528 FORMAT (5X, 12HLEFT TURN , 6E17.8)
529 FORMAT (5X, 13HSTRAIGHT THRU, E16.8, 5E17.8)
530 FORMAT (5X, 12HRIGHT TURN , 6E17.8)
531 FORMAT (18H CUM STOPPED DELAY)
532 FORMAT (5X, 12HLEFT TURN , 6I17)
533 FORMAT (5X, 13HSTRAIGHT THRU, 116, 5I17)
534 FORMAT (5X, 12HRIGHT TURN , 6I17)
5400FORMAT (35H AVERAGE DELAY FOR SAMPLE - SEC/CAR, 11X,
1 11HMAIN STREET, 11X, 11HSIDE STREET, 11X, 12HBOTH STREETS)
541 FORMAT (5X, 11HTOTAL DELAY, 19X, 3F22.8)
542 FORMAT (5X, 13HSTOPPED DELAY, 17X, 3F22.8////)
C FORMAT FOR RUN SUMMARY
550 FORMAT (54X, 11HRUN SUMMARY)
5510FORMAT (32H MEAN OF SAMPLE DELAYS - SEC/CAR, 14X, 11HMAIN STREET,
1 11X, 11HSIDE STREET, 11X, 12HBOTH STREETS)
552 FORMAT (28H VARIABILITY OF SAMPLE MEANS)
553 FORMAT (30H OVERALL AVERAGE DELAY FOR RUN)
554 FORMAT (5X, 13HSTOPPED DELAY, 17X, 3F22.8)
5600FORMAT (17H ACTUAL VALUES OF, 6X, 15HVOLUME VEH./HR., 10X,
1 17HPCT. DISTRIBUTION, 9X, 16HPCT. RIGHT TURNS, 11X,
2 15HPCT. LEFT TURNS)
561 FORMAT(5X, 11HMAIN STREET, 8X, F8.0, 3F26.1)
562 FORMAT(5X, 11HSIDE STREET, 8X, F8.0, 3F26.1)
563 FORMAT (///)
564 FORMAT (49H 85TH PERCENTILE OF SS TOTAL DELAY AT STOP SIGN =, F7.2)
END
* LIST
* LABEL
CCOMP SUBPROGRAM TO COMPUTE PROBABILITIES OF VEHICLE ARRIVALS
SUBROUTINE COMP (VOLUME, VOLK, PROB)
DIMENSION VOLUME(6), VOLK(6), PROB(6,2)
DO 12 I = 1, 6
IF (VOLUME(I)) 3, 3, 6
3 PROB(I,1) = 0.0
PROB(I,2) = 0.0
GO TO 12
6 QA = (1.0 - VOLK(1)) ** (1.0/7.0)
PROB(I,1) = 1.0 - QA
IF (PROB(I,1) - 1.0) 8, 7, 8
7 PROB(I,2) = 1.0
GO TO 12
8 SIGMA = 0.0
DO 10 K = 1, 6
10 SIGMA = SIGMA + QA ** K
PROB(I,2) = (1.0 - VOLK(I)) / ((7200.0/VOLUME(I)) - 3.0 - SIGMA)
12 CONTINUE
RETURN
END
* LIST

```

```

*      LABEL
CCONTRO  PROGRAM II SEMI-TRAFFIC-ACTUATED SIGNAL CONTROLLER
        OSUBROUTINE CONTRO (SIGNAL, SIGCNT, INDSIG, MTAG, MDET, MZDNS,
1      MZDEW)
        COMMON CLOCK
        DIMENSION SIGNAL(6), SIGCNT(6), MTAG(6)
1      GO TO ( 5, 20, 50, 50, 35), INDSIG
C M.S. SIGNAL IS GREEN
5      IF (CLOCK - SIGCNT(1)) 90, 6, 6
6      GO TO ( 90, 7), MDET
7      INDSIG = 2
        MZDNS = 1
        DO 10 K = 1, 4
10     MTAG(K) = 1
        SIGCNT(2) = CLOCK + SIGNAL(2)
        GO TO 90
C M.S. SIGNAL IS AMBER
20     IF (CLOCK - SIGCNT(2)) 90, 21, 21
21     INDSIG = 3
        MZDEW = 2
        MTAG(5) = 2
        MTAG(6) = 2
        SIGCNT(3) = CLOCK + SIGNAL(3)
        SIGCNT(4) = CLOCK + SIGNAL(3) + SIGNAL(4)
        SIGCNT(5) = CLOCK + SIGNAL(5)
        GO TO 90
C S.S. SIGNAL IS AMBER
35     IF (CLOCK - SIGCNT(6)) 90, 36, 36
36     INDSIG = 1
        MZDNS = 2
        DO 40 K = 1, 4
40     MTAG(K) = 2
        SIGCNT(1) = CLOCK + SIGNAL(1)
        GO TO 90
C S.S. SIGNAL IS GREEN
50     IF (CLOCK - SIGCNT(5)) 52, 70, 70
52     IF (CLOCK - SIGCNT(3)) 62, 62, 54
54     IF (CLOCK - SIGCNT(4)) 56, 74, 74
56     GO TO (90, 58), MDET
58     SIGCNT(4) = CLOCK + SIGNAL(4)
        INDSIG = 4
62     MDET = 1
        GO TO 90
70     IF (CLOCK - SIGCNT(4)) 72, 74, 74
72     MDET = 2
74     INDSIG = 5
        MZDEW = 1
        MTAG(5) = 1
        MTAG(6) = 1
        SIGCNT(6) = CLOCK + SIGNAL(6)
90     RETURN
        END
*      LIST
*      LABEL
CSCAN  LANE SCAN PROGRAM III
        SUBROUTINE SCAN
        OCOMMON CLOCK, ARAY, BRAY, LEAD, NUM, PREV, MGEN, FRTURN, PROB,
1      NUMIN, XONS, XOEW, RN1, RN2, MODEP, MODEC, NUMOUT, DELAY,
2      NDELAY, BLOCK, MDET, MTAG, MZDNS, MZDEW, INDSIG, SIGNAL, XDET,
3      CLAG, TXLT, TXST, TXRT, TXEND, XEND, JCOUNT, FILE
C
        ODIMENSION ARAY(6,100,5), BRAY(6,100,2), LEAD(6,2), NUM(6,2),
1      PREV(6), MGEN(6,2), FRTURN(6,2), PROB(6,2), NUMIN(6,3),

```

```

2  NUMOUT(6,3), DELAY(6,3), NDELAY(6,3), BLOCK(2,3), MTAG(6),
3  SIGNAL(6), XDET(2), CLAG(2,2), TXEND(2,3), XEND(2,3), FILE(4000)

```

C

```

    DIMENSION LOC(6)

```

C

```

    FREQUENCY
OFREQUENCY      50(0,1,9), 100(9,2,1), 120(9,2,1), 110(4,4,2,2),
1  122(1,9,4), 124(1,5,1), 160(1,9,4), 180(1,5,1), 150(4,4,2,2),
2  182(5,1,9), 201(1,2,9), 204(9,2,0), 206(1,2,9), 161(4,4,2,2),
3  208(3,1,9), 209(1,5,1), 241(2,9,1), 244(4,1,9), 230(4,4,2,2),
4  247(9,1,4), 249(9,3,1), 253(2,1,5), 258(1,5,1), 270(4,4,2,2),
5  280(9,2,1), 281(1,5,1), 282(9,1,5), 283(9,1,5), 430(4,4,2,2),
6  285(1,5,1), 288(0,9,5), 290(5,1,9), 293(1,5,1), 294(2,1,3),
7  297(2,1,3), 500(2,1,3), 508(0,4,3), 600(1,5,1), 602(9,3,1)
OFREQUENCY      604(3,1,9), 606(3,1,9), 782(9,3,1), 802(3,1,9),
1  804(1,5,1), 805(3,1,8), 806(3,1,8), 807(3,1,8), 850(1,5,1),
2  890(9,1,2), 891(9,1,2), 894(0,1,9), 896(9,1,5), 920(9,1,5),
3  922(9,1,5), 990(9,1,2), 991(9,1,2), 993(5,1,0), 242(0,1,5),
4  165(5,1,9), 170(5,1,9), 164(1,9), 220(4,1)

```

C

C

```

    LANE SETUP ROUTINE

```

```

    III A1

```

```

10 I = 1
   GO TO 20
15 I = I + 1
20 GO TO (21, 21, 22, 22, 23, 24), I
21 IO = 3
   IOR = 6
   IOL = 5
   GO TO 30
22 IO = 1
   IOR = 5
   IOL = 6
   GO TO 30
23 IO = 6
   IOR = 1
   IOL = 3
   GO TO 30
24 IO = 5
   IOR = 3
   IOL = 1

```

```

C SETTINGS FOR M SWITCHES - 1=MS SIGNAL, 2=MS STOP, 3=SS SIGNAL, 4=SS STOP

```

```

30 IF (I = 4) 31, 31, 32
31 GO TO (33, 34), MODEC
32 GO TO (35, 36), MODEC
33 M = 1
   GO TO 39
34 M = 2
   GO TO 39
35 M = 3
   GO TO 39
36 M = 4
39 GO TO 50

```

C

C

```

    VEHICLE SETUP ROUTINE

```

```

    III A2

```

```

50 IF (NUM(I,1)) 52, 52, 55
52 XP = 2100.0
   VP = 44.0
   GO TO 940
55 LED = LEAD(I,1)
   L = LED
   GO TO 61
60 L = LNEXT(L)
61 TOA = ARAY(I,L,1)

```



```

      TURN = ARAY(I,L,2)
      X     = ARAY(I,L,3)
      V     = ARAY(I,L,4)
      DREQ  = ARAY(I,L,5)
65  GO TO (70, 70, 80, 80),M
70  IF (DREQ) 75, 80, 80
75  ARAY(I,L,5) = 0.0
      XP = X
      VP = V
      GO TO 890
80  ZS = 101.0
      ZD = 103.0
      ZT = 104.0

C
C           IS THIS THE LEAD CAR           III B
100 IF (LED - L) 110, 140, 110

C
C           SWITCH      M1                 III M1
110 GO TO (130, 130, 120, 130),M

C
C           SPACING BYPASS ROUTINE         III C1
120 IF (LXPOS(LED,2) - L) 130, 122, 130
122 IF (ARAY(I,LED,5)) 124, 130, 130
124 IF (TURN) 130, 140, 140

C
C           SPACING RESTRICTION ROUTINE    III C2
130 ZS = ZSPACE(X, V, XP, VP)

C
C           ACCEL. RESTRICTION ROUTINE     III D
140 ZA = ZACCEL( V )

C
C           SWITCH      M2                 III M2
150 GO TO (160, 180, 160, 170),M

C
C           SIGNAL STOPPING ROUTINE        III E1
160 IF (DREQ) 180, 180, 161
161 GO TO (162, 162, 163, 163),M
162 MZD = MZDNS
      GO TO 164
163 MZD = MZDEW
164 GO TO ( 165, 167),MZD
165 IF (X - 1800.0) 200, 200, 166
166 ZD = ZDECEL (DREQ, X, V)
      GO TO 200
167 ARAY(I,L,5) = 0.0
169 GO TO 165

C
C           STOP SIGN STOPPING ROUTINE     III E2
170 IF (X - 1800.0) 176, 176, 172
172 D = 6.0
      ZD = ZDECEL(D, X, V)
176 GO TO 200

C
C           TURNING RESTRICTION ROUTINE    III F
180 IF (TURN) 182, 200, 182
182 IF (X - 1835.0) 186, 186, 184
184 CALL ZTURN (ZT,X,V,MZT,VTURN)
186 GO TO 200

C
C           VEHICLE PROCESSING ROUTINE     III G
200 Z = MINIF( ZS, ZA, ZD, ZT)
201 IF (Z) 202, 203, 203
202 Z = 0.0

```

```

203 XNOW = X + Z
204 IF (Z - ZT) 205, 220, 205
205 VNOW = 2.0 * Z - V
206 IF (VNOW) 207, 209, 208
207 VNOW = 0.0
    GO TO 209
208 IF (VNOW - 4.5) 209, 215, 215
209 IF (TURN) 210, 212, 214
210 NDELAY(I,1) = NDELAY(I,1) + 1
    GO TO 215
212 NDELAY(I,2) = NDELAY(I,2) + 1
    GO TO 215
214 NDELAY(I,3) = NDELAY(I,3) + 1
215 XP = XNOW
    VP = VNOW
    ARAY(I,L,3) = XNOW
    ARAY(I,L,4) = VNOW
    GO TO 230
220 GO TO (205, 222), MZT
222 VNOW = VTURN
    GO TO 206

```

```

C
C                               SWITCH      M3                III M3
230 GO TO (240, 270, 240, 270), M

```

```

C
C                               -      TAGGING ROUTINE        III H

```

```

240 K = MTAG(I)
241 GO TO (242, 259, 258), K
242 IF (NUM(I,1)) 250, 250, 243
243 B = 2000.0 - XNOW
244 IF (B) 248, 246, 246
246 DREQ = (VNOW * VNOW) / (2.0 * B)
247 IF (DREQ - 12.0) 253, 253, 248
248 KL = LEAD(I,1)
    KN = NUM(I,1)
249 IF (LXPOS(KL,KN) - L) 259, 251, 259
250 KL = LEAD(I,1)
    KN = NUM(I,1)
251 LOC(I) = LNXENT(KL,KN)
    MTAG(I) = 3
    GO TO 259
253 IF (DREQ - 6.0) 254, 255, 255
254 DREQ = 6.0
255 ARAY(I,L,5) = DREQ
    MTAG(I) = 2
    GO TO 259
258 IF (LOC(I) - L) 259, 254, 259
259 GO TO 270

```

```

C
C                               SWITCH      M4                III M4
270 GO TO (280, 280, 920, 800), M

```

```

C
C                               MS  RELEASE CHECKING ROUTINE  III J1

```

```

280 IF (LED - L) 285, 281, 285
281 IF (TURN) 282, 283, 283
282 IF (2016.0 - XNOW) 300, 300, 890
283 IF (2041.0 - XNOW) 450, 450, 890
285 IF (TURN) 299, 288, 299
288 IF (INDSIG - 1) 299, 290, 299
290 IF (XNOW - 1800.0) 299, 299, 292
292 LDE = LEAD(I,1)
293 IF (ARAY(I,LDE,2)) 294, 299, 294
294 IF (LXPOS(LDE,2) - L) 297, 295, 297

```

```

295 MPASS = 1
    GO TO 500
297 IF (LXPOS(LDE,3) - L) 299, 298, 299
298 MPASS = 2
    GO TO 500
299 GO TO 890

```

```

C
C          MS LT DECISION ROUTINE          III K1

```

```

300 TA1 = 100.0
    TA2 = 100.0
    TA3 = 100.0
303 IF (NUM(I0+1,1)) 310, 310, 304
304 K = (LEAD(I0+1,1))
    IF (2012.0 - ARAY(I0+1,K,3)) 308, 308, 305
305 IF (ARAY(I0+1,K,4)) 310, 310, 306
306 IF (ARAY(I0+1,K,5)) 307, 307, 310
307 TA1 = (2012.0 - ARAY(I0+1,K,3)) / ARAY(I0+1,K,4)
    GO TO 310
308 IF (ARAY(I0+1,K,2)) 310, 330, 330
310 IF (NUM(I0,1)) 322, 322, 312
312 K = LEAD(I0,1)
    IF (2012.0 - ARAY(I0,K,3)) 316, 316, 313
313 IF (ARAY(I0,K,4)) 322, 322, 314
314 IF (ARAY(I0,K,5)) 315, 315, 322
315 TA2 = (2012.0 - ARAY(I0,K,3)) / ARAY(I0,K,4)
    GO TO 322
316 IF (ARAY(I0,K,2)) 330, 330, 318
318 IF (NUM(I0,1) - 2) 322, 320, 320
320 K = LXPOS(K, 2)
    IF (ARAY(I0,K,4)) 322, 322, 319
319 IF (ARAY(I0,K,5)) 321, 321, 322
321 TA3 = (2012.0 - ARAY(I0,K,3)) / ARAY(I0,K,4)
322 V2070 = SQRTF(VNOW * VNOW + 6.0 * (2070.0 - XNOW))
    TNEED = (V2070 - VNOW) / 3.0
324 IF (TNEED - 4.68333) 328, 328, 326
326 TNEED = 4.68333
328 TAVAIL = MINIF(TA1, TA2, TA3)
    IF (TNEED - TAVAIL) 341, 341, 330
330 IF (2016.0 - XNOW) 332, 340, 340
332 XNOW = 2016.0
    XP = XNOW
    ARAY(I,L,3) = XNOW
    VNOW = 0.0
    VP = VNOW
    ARAY(I,L,4) = VNOW
340 GO TO 890
341 GO TO 400

```

```

C
C          MS LT RELEASE ROUTINE          III L1

```

```

400 CALL TIME (I,TOA,TURN,XNOW,VNOW,TNEED)
    KL = LEAD(I,1)
    LEAD(I,1) = LNEXT(KL)

```

```

C
C          SWITCH      MS          III M5

```

```

430 GO TO (890, 900, 890, 900),M

```

```

C
C          MS ST + RT RELEASE ROUTINE    III N1

```

```

450 CALL TIME (I,TOA,TURN,XNOW,VNOW,TNEED)
    KL = LEAD(I,1)
    LEAD(I,1) = LNEXT(KL)
    GO TO 890

```

```

C
C          PASSING ROUTINE      (MS)          III P

```

```

500 IF (I - 2) 502, 506, 508
502 IADJ = 2
    MQ = 1
    GO TO 515
506 IADJ = 1
    MQ = 2
    GO TO 515
508 IF (I - 3) 599, 510, 512
510 IADJ = 4
    MQ = 1
    GO TO 515
512 IADJ = 3
    MQ = 2
515 IF (NUM(IADJ,1)) 599, 517, 520
517 GO TO (518, 565),MQ
518 ARAY(I,L,5) = -6.0
    GO TO 565
520 K = LEAD(IADJ,1)
    IF (VNOW - ARAY(IADJ,K,4)) 526, 526, 524
524 S = 22.0 + VNOW + (((VNOW - ARAY(IADJ,K,4))*2) / 12.0)
    GO TO 528
526 S = 22.0 + VNOW
528 IF (ARAY(IADJ,K,3) - (XNOW + S)) 529, 529, 530
529 MP = 1
    GO TO 537
530 MP = 2
532 IF (NUM(IADJ,1) - 2) 549, 535, 535
535 K = LXPOS(K,2)
537 B = (XNOW - 22.0) - ARAY(IADJ,K,3)
    IF (B) 599, 599, 542
542 IF (ARAY(IADJ,K,4)) 599, 599, 545
545 TAVAIL = B / ARAY(IADJ,K,4)
547 IF (TAVAIL - 3.0) 599, 549, 549
549 GO TO (550, 552),MQ
550 ARAY(I,L,5) = -7.0
552 KL = LEAD(IADJ,1)
    KF = KL - 1
    IF (KF) 553, 553, 554
553 KF = 100
554 LEAD(IADJ,1) = KF
    NUM(IADJ,1) = NUM(IADJ,1) + 1
555 GO TO (557, 560),MP
557 DO 558 K = 1,5
558 ARAY(IADJ,KF,K) = ARAY(I,L,K)
    GO TO 568
560 DO 562 K = 1,5
    ARAY(IADJ,KF,K) = ARAY(IADJ,KL,K)
562 ARAY(IADJ,KL,K) = ARAY(I,L,K)
    GO TO 568
565 KL = LEAD(IADJ,1)
    DO 566 K = 1,5
566 ARAY(IADJ,KL,K) = ARAY(I,L,K)
    NUM(IADJ,1) = 1
568 GO TO (575, 570),MPASS
570 K2 = LXPOS(LDE, 2)
    DO 572 K = 1, 5
572 ARAY(I,L,K) = ARAY(I,K2,K)
    GO TO 576
575 K2 = LXPOS(LDE, 2)
576 DO 577 K = 1, 5
577 ARAY(I,K2,K) = ARAY(I,LDE,K)
    NUM(I,1) = NUM(I,1) - 1
    LEAD(I,1) = LNEXT(LDE)

```

599 GO TO 890

C
C SS RELEASE CHECKING ROUTINE III J2

600 IF (TURN) 601, 606, 606
601 KL = LEAD(I,1)
602 IF (KL - L) 890, 604, 890
604 IF (2016.0 - XNOW) 620, 620, 890
606 IF (2034.0 - XNOW) 750, 750, 890

C
C SS LT DECISION ROUTINE III K2

620 IF (NUM(I0,1)) 670, 670, 622
622 K = LEAD(I0,1)
IF (2012.0 - ARAY(I0,K,3)) 626, 626, 639
626 IF (ARAY(I0,K,2)) 628, 654, 628
628 IF (NUM(I0,1) - 2) 670, 630, 630
630 K = LNEXT(K)
IF (2012.0 - ARAY(I0,K,3)) 634, 634, 639
634 IF (ARAY(I0,K,2)) 636, 654, 636
636 IF (NUM(I0,1) - 3) 670, 638, 638
638 K = LNEXT(K)
639 IF (ARAY(I0,K,4)) 670, 670, 640
640 IF (ARAY(I0,K,5)) 641, 641, 670
641 TAVAIL = (2012.0 - ARAY(I0,K,3)) / ARAY(I0,K,4)
645 V2057 = SQRTF(VNCW * VNOW + 6.0 * (2057.0 - XNOW))
TNEED = (V2057 - VNOW) / 3.0
648 IF (TNEED - 4.0) 652, 652, 650
650 TNEED = 4.0
652 IF (TNEED - TAVAIL) 670, 670, 654
654 IF (2016.0 - XNOW) 656, 669, 669
656 K = LEAD(I0,1)
IF (ARAY(I0,K,5)) 658, 660, 660
658 XNOW = 2016.0
659 XP = XNOW
ARAY(I,L,3) = XNOW
GO TO 666
660 ARAY(I,L,5) = -5.0
662 IF (2032.0 - XNOW) 664, 669, 669
664 XNOW = 2032.0
GO TO 659
666 VNOW = 0.0
VP = VNOW
ARAY(I,L,4) = VNOW
669 GO TO 890
670 GO TO 700

C
C SS LT RELEASE ROUTINE III L2

700 CALL TIME (I,TOA,TURN,XNOW,VNOW,TNEED)
KL = LEAD(I,1)
LEAD(I,1) = LNEXT(KL)
GO TO 890

C
C SS ST + RT RELEASE ROUTINE III N2

750 CALL TIME (I,TOA,TURN,XNOW,VNOW,TNEED)
780 KL = LEAD(I,1)
782 IF (KL - L) 784, 790, 784
784 DO 786 K = 1, 5
786 ARAY(I,L,K) = ARAY(I,KL,K)
790 LEAD(I,1) = LNEXT(KL)
GO TO 890

C
C STOP SIGN DECISION ROUTINE III Q

800 TA1 = 100.0
TA2 = 100.0


```

      TA3 = 100.0
      TA4 = 100.0
802 IF (1997.0 - XNOW) 804, 849, 849
804 IF (TURN) 805, 806, 807
805 IF (CLOCK - BLOCK(I-4,1)) 849, 849, 809
806 IF (CLOCK - BLOCK(I-4,2)) 849, 849, 809
807 IF (CLOCK - BLOCK(I-4,3)) 849, 849, 809
809 IF (NUM(IOL,1)) 820, 820, 810
810 K = LEAD(IOL,1)
      IF (2012.0 - ARAY(IOL,K,3)) 814, 812, 812
812 TA1 = (2012.0 - ARAY(IOL,K,3)) / ARAY(IOL,K,4)
      GO TO 820
814 IF (ARAY(IOL,K,2)) 849, 849, 816
816 IF (NUM(IOL,1) - 2) 820, 818, 818
818 K = LNEXT(K)
      GO TO 812
820 IF (NUM(IOL+1,1)) 830, 830, 822
822 K = LEAD(IOL+1,1)
      IF (2012.0 - ARAY(IOL+1,K,3)) 826, 824, 824
824 TA2 = (2012.0 - ARAY(IOL+1,K,3)) / ARAY(IOL+1,K,4)
      GO TO 830
826 IF (ARAY(IOL+1,K,2)) 828, 849, 849
828 IF (TURN) 849, 849, 832
830 IF (TURN) 834, 834, 832
832 TAVAIL = MINIF(TA1, TA2)
      IF (TAVAIL - CLAG(I-4,2)) 849, 848, 848
834 TAVAIL = MINIF(TA1, TA2)
      IF (TAVAIL - CLAG(I-4,1)) 849, 836, 836
836 IF (NUM(IOR,1)) 842, 842, 838
838 K = LEAD(IOR,1)
      IF (2012.0 - ARAY(IOR,K,3)) 849, 840, 840
840 TA3 = (2012.0 - ARAY(IOR,K,3)) / ARAY(IOR,K,4)
842 IF (NUM(IOR+1,1)) 847, 847, 844
844 K = LEAD(IOR+1,1)
      IF (2012.0 - ARAY(IOR+1,K,3)) 849, 846, 846
846 TA4 = (2012.0 - ARAY(IOR+1,K,3)) / ARAY(IOR+1,K,4)
847 TAVAIL = MINIF(TA3, TA4)
      IF (TAVAIL - CLAG(I-4,1)) 849, 848, 848
848 GO TO 850
849 GO TO 890

```

STOP SIGN RELEASE ROUTINE III R

```

850 IF (TURN) 852, 864, 874
852 WAIT = CLOCK - TOA - TXLT
      DELAY(I,1) = DELAY(I,1) + WAIT
      NUMOUT(I,1) = NUMOUT(I,1) + 1
854 B = CLOCK + 4.0
      IF (BLOCK(I-4,2) - B) 856, 857, 857
856 BLOCK(I-4,2) = B
857 IF (BLOCK(I-4,3) - B) 858, 860, 860
858 BLOCK(I-4,3) = B
860 B = CLOCK + 1.0
      IF (BLOCK(I-4,1) - B) 862, 880, 880
862 BLOCK(I-4,1) = B
      GO TO 880
864 WAIT = CLOCK - TOA - TXST
      DELAY(I,2) = DELAY(I,2) + WAIT
      NUMOUT(I,2) = NUMOUT(I,2) + 1
866 B = CLOCK + CLAG(I-4,1)
      IF (BLOCK(I-4,1) - B) 868, 880, 880
868 BLOCK(I-4,1) = B
      GO TO 880
874 WAIT = CLOCK - TOA - TXRT

```

```

      DELAY(I,3) = DELAY(I,3) + WAIT
      NUMOUT(I,3) = NUMOUT(I,3) + 1
      GO TO 860
880  NUM(I,1) = NUM(I,1) - 1
      KL = LEAD(I,1)
      LEAD(I,1) = LNEXT( KL )
      JCOUNT = JCOUNT + 1
      FILE(JCOUNT) = WAIT

C
C           IS THIS THE LAST CAR           III S
890  IF (MODEP - 5) 893, 892, 891
891  IF (MODEP - 6) 893, 892, 893
892  CALL DEBUGC (I, L, X, V, TOA, TURN, XNOW, VNOW, DREQ, Z, ZS, ZA,
      1  ZD, ZT, BLOCK, MZDNS, MZDEW, MTAG, MDET, TAVAIL, TNEED, LOC)
893  KN = NUM(I,1)
894  IF (KN) 940, 940, 895
895  KL = LEAD(I,1)
896  IF (L - LXPOS( KL,KN )) 60, 940, 60

C
C           BLOCKING OF SS ROUTINE           III T
900  B = CLOCK + TNEED - 1.0
      IF (BLOCK(IOR-4,2) - B) 902, 903, 903
902  BLOCK(IOR-4,2) = B
903  IF (BLOCK(IOR-4,1) - B) 904, 905, 905
904  BLOCK(IOR-4,1) = B
905  B = CLOCK + TNEED
      IF (BLOCK(IOL-4,2) - B) 907, 908, 908
907  BLOCK(IOL-4,2) = B
908  IF (BLOCK(IOL-4,1) - B) 909, 910, 910
909  BLOCK(IOL-4,1) = B
910  GO TO 890

C
C           DETECTOR ROUTINE (SS)           III U
920  IF (X -XDET(I-4)) 922, 926, 926
922  IF (XNOW -XDET(I-4)) 926, 924, 924
924  MDET = 2
926  GO TO 600

C
C           GENERATION ROUTINE           III W
940  CALL GEN (I, XP, VP)

C
C           IS THIS THE LAST LANE           III X
990  IF (MODEP - 3) 993, 992, 991
991  IF (MODEP - 5) 992, 992, 993
992  CALL DEBUGE (I, CLOCK, ARAY, LEAD, NUM, INDSIG)
993  IF (I - 6) 15, 999, 999
999  RETURN
      END
*      LIST
*      LABEL

CTIME  SUBPROGRAM TO COMPUTE VEHICLE DELAYS
      SUBROUTINE TIME (I,TOA,TURN,XNOW,VNOW,TNEED)
      OCOMMON  CLOCK, ARAY, BRAY, LEAD, NUM, PREV, MGEN, FRTURN, PROB,
      1  NUMIN, XONS, XOEW, RN1, RN2, MODEP, MODEC, NUMOUT, DELAY,
      2  NDELAY, BLOCK, MDET, MTAG, MZDNS, MZDEW, INDSIG, SIGNAL, XDET,
      3  CLAG, TXLT, TXST, TXRT, TXEND, XEND

C
      ODIMENSION  ARAY(6,100,5), BRAY(6,100,2), LEAD(6,2), NUM(6,2),
      1  PREV(6), MGEN(6,2), FRTURN(6,2), PROB(6,2), NUMIN(6,3),
      2  NUMOUT(6,3), DELAY(6,3), NDELAY(6,3), BLOCK(2,3), MTAG(6),
      3  SIGNAL(6), XDET(2), CLAG(2,2), TXEND(2,3), XEND(2,3)

C
      OFREQUENCY  1(1,5,1), 7(3,1,2), 10(1,5,1), 12(9,4,0), 22(1,5,1),

```

```

      1 24(9,4,0), 36(1,4,9)
C
      1 IF (TURN) 2, 4, 6
      2 J = 1
        GO TO 7
      4 J = 2
        GO TO 7
      6 J = 3
      7 IF (I - 4) 8, 8, 20
      8 K = 1
     10 IF (TURN) 12, 30, 30
     12 IF (TNEED - 4.68333) 30, 26, 26
     20 K = 2
     22 IF (TURN) 24, 30, 30
     24 IF (TNEED - 4.0) 30, 26, 26
     26 B = 14.6060606
        GO TO 34
    300B = (XEND(K,J) - XNOW)/44.0 + (44.0 - VNOW)/3.0 -
           1 (1936.0 - VNOW*VNOW)/264.0
     34 BT = CLOCK - TOA + B - TXEND(K,J)
     36 IF (BT) 40, 40, 38
     38 DELAY(I,J) = DELAY(I,J) + BT
     40 NUMOUT(I,J) = NUMOUT(I,J) + 1
        NUM(I,1) = NUM(I,1) - 1
        RETURN
      END
*      LIST
*      LABEL
CGEN      SUBPROGRAM TO GENERATE AND ENTER VEHICLES
          SUBROUTINE GEN (I, XP, VP)
          OCOMMON CLOCK, ARAY, BRAY, LEAD, NUM, PREV, MGEN, FRTURN, PROB,
           1 NUMIN, XONS, XOEW, RN1, RN2, MODEP
          ODIMENSION ARAY(6,100,5), BRAY(6,100,2), LEAD(6,2), NUM(6,2),
           1 PREV(6), MGEN(6,2), FRTURN(6,2), PROB(6,2), NUMIN(6,3)
          OFREQUENCY 1(5,1), 3(5,1), 8(2,1,3), 9(1,0,5), 11(1,0,5),
           1 13(0,5,5), 23(1,0,5), 24(1,0,5), 34(5,0,0), 40(0,5,5),
           2 50(0,2,1), 52(3,1,2), 60(1,2,9), 90(9,1,1), 91(9,1,1)
C
    100 IF (I - 4) 105, 105, 110
    105 MRN = 1
        GO TO 120
    110 MRN = 2
    120 K = MGEN(I,1)
        1 GO TO (2, 46), K
        2 K = MGEN(I,2)
        3 GO TO (4, 6), K
        4 T12 = 0.0
        GO TO 140
        6 T12 = 0.5
    140 GO TO (145, 150), MRN
    145 RN1 = RAND(W)
        GO TO 8
    150 RN1 = RANDS(W)
        8 IF (CLOCK - PREV(1) - 4.5) 9, 9, 11
        9 IF (RN1 - PROB(1,1)) 14, 13, 13
       11 IF (RN1 - PROB(1,2)) 14, 13, 13
       13 IF (T12) 6, 6, 44
       14 PREV(1) = CLOCK + T12
C
C      BACKLOGGING SUBROUTINE
    16 KL = LEAD(I,2)
       KN = NUM (I,2)
       K = LNXENT( KL, KN )

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      BRAY(I,K,1) = PREV(I)
18 GO TO (20, 21),MRN
20 RN2 = RAND(W)
   GO TO 23
21 RN2 = RANDS(W)
23 IF (RN2 - FRTURN(I,1)) 31, 24, 24
24 IF (1.0 - FRTURN(I,2) - RN2) 25, 25, 28
25 BRAY(I,K,2) = -5.0
   NUMIN(I,1) = NUMIN(I,1) + 1
   GO TO 33
28 BRAY(I,K,2) = 0.0
   NUMIN(I,2) = NUMIN(I,2) + 1
   GO TO 33
31 BRAY(I,K,2) = +5.0
   NUMIN(I,3) = NUMIN(I,3) + 1
33 NUM(I,2) = NUM(I,2) + 1
34 IF (NUM(I,2) - 100) 40, 95, 95
C      RETURN TO GENERATION ROUTINE
40 IF (T12) 41, 41, 43
41 MGEN(I,2) = 2
   GO TO 50
43 MGEN(I,1) = 2
44 MGEN(I,2) = 1
   GO TO 50
46 MGEN(I,1) = 1
C
C      ENTERING SUBROUTINE
50 IF (NUM(I,2)) 90, 90, 51
51 KL = LEAD(I,2)
   TOA = BRAY(I,KL,1)
52 IF (I - 4) 53, 53, 54
53 XO = XONS
   GO TO 55
54 XO = XOEW
55 ZE = ZENTER( XP, VP, XO, TOA, CLOCK )
60 IF (ZE) 90, 62, 62
62 KAL = LEAD(I,1)
   KAN = NUM (I,1)
   K= LNXENT( KAL, KAN )
   ARAY(I,K,1) = BRAY(I,KL,1)
   ARAY(I,K,2) = BRAY(I,KL,2)
   ARAY(I,K,3) = XO + ZE
   ARAY(I,K,4) = 44.0
   ARAY(I,K,5) = 0.0
75 LEAD(I,2) = LNEXT( KL )
   NUM (I,2) = NUM(I,2) - 1
   NUM (I,1) = NUM(I,1) + 1
C      RETURN TO GENERATION ROUTINE
90 IF (MODEP - 8) 93, 92, 91
91 IF (MODEP - 9) 93, 92, 93
92 CALL DEBUGD (I, CLOCK, ZE, RN1, RN2, PREV, MGEN, BRAY, LEAD, NUM)
93 RETURN
C      SPECIAL PRINT-OUT INDICATING FULL BACKLOG LIST
95 WRITE OUTPUT TAPE 6, 96, I, CLOCK, NUM(I,2)
96 FORMAT (34H0BACKLOG CAPACITY EXCEEDED IN LANE, I3, F15.2, I15)
   GO TO 40
END
*      LIST
*      LABEL
CLXPOS      SUBPROGRAM TO FIND INDEX OF VEHICLE IN ANY POSITION
      FUNCTION LXPOS (LEAD, LX)
      FREQUENCY 2(10,I,1)
1 LXPOS = LEAD + LX - 1

```

```

2 IF (LXPOS - 100) 4, 4, 3
3 LXPOS = LXPOS - 100
4 RETURN
  END
*   LIST
*   LABEL
CLNEXT      SUBPROGRAM TO FIND INDEX OF NEXT VEHICLE IN LINE
  FUNCTION LNEXT (LNOW)
    FREQUENCY 2(10,1,1)
  1 LNEXT = LNOW + 1
  2 IF (LNEXT - 100) 4, 4, 3
  3 LNEXT = LNEXT - 100
  4 RETURN
    END
*   LIST
*   LABEL
CLNXTENT    SUBPROGRAM TO FIND INDEX OF NEXT VEHICLE TO ENTER
  FUNCTION LNXENT (LEAD, NUM)
    FREQUENCY 2(10,1,1)
  1 LNXENT = LEAD + NUM
  2 IF (LNXENT - 100) 4, 4, 3
  3 LNXENT = LNXENT - 100
  4 RETURN
    END
*   LIST
*   LABEL
CZSPACE     SUBPROGRAM TO COMPUTE ZS
  FUNCTION ZSPACE (X, V, XP, VP)
    FREQUENCY 3(0,1,10), 1(10,1,10)
  1 IF (V = VP) 9, 9, 2
  2 R = 20.25 - 1.5 * V - 4.5 * VP + 3.0 * (XP - X - 22.0)
  3 IF (R) 4, 4, 6
  4 R2 = 0.0
  5 GO TO 7
  6 R2 = SQRTF (R)
  7 ZSPACE = 0.5 * (V + VP) - 4.5 + R2
  8 RETURN
  9 ZSPACE = (XP - X - 22.0 + V) / 3.0
 10 RETURN
    END
*   LIST
*   LABEL
CZACCEL     SUBPROGRAM TO COMPUTE ZA
  FUNCTION ZACCEL (V)
    FREQUENCY 2(5,1,10)
  1 B = V + 3.0
  2 IF (44.0 - B) 3, 4, 4
  3 B = 44.0
  4 ZACCEL = 0.5 * (V + B)
  5 RETURN
    END
*   LIST
*   LABEL
CZDECEL     SUBPROGRAM TO COMPUTE ZD
  FUNCTION ZDECEL (D, X, V)
    FREQUENCY 1(1,10,5), 5(0,1,10)
  1 IF (D = 6.0) 4, 4, 2
  2 ZDECEL = 0.5 * V - 0.25 * D + SQRTF ((D**2/16.0) - 0.25 * D * V +
    0.5 * D * (2000.0 - X))
  3 RETURN
  4 R = 2.25 - 1.5 * V + 3.0 * (2000.0 - X)
  5 IF (R) 6, 6, 8
  6 R2 = 0.0

```



```

      GO TO 9
      8 R2 = SQRTF (R)
      9 ZDECEL = 0.5 * V - 1.5 + R2
      RETURN
      END
*      LIST
*      LABEL
CZTURN      SUBPROGRAM TO COMPUTE ZT
      SUBROUTINE ZTURN (ZT,X,V,MZT,VTURN)
      FREQUENCY 3(2,1,6), 6(0,1,9), 11(6,1,2), 22(9,1,5)
      1 MZT = 1
      2 B = 2016.0 - X
      3 IF (B) 40, 40, 5
      5 R = 58.5 - 1.5*V + 3.0*B
      6 IF (R) 7, 7, 9
      7 R2 = 0.0
      GO TO 10
      9 R2 = SQRTF (R)
      10 ZT = 0.5 * V - 1.5 + R2
      11 IF (ZT - B) 50, 50, 20
C      VEHICLE PASSES THE TURN POINT (X=2016.)
      20 VMXTP = SQRTF(V*V + 6.0*B)
      22 IF (VMXTP - 15.0) 40, 40, 24
C      COMPUTE REVISED ZT AND SPECIAL V
      24 BT = 1.0 - (B + B)/(V + 15.0)
      ZT = B + 15.0*BT + 1.5*BT*BT
      28 VTURN = 15.0 + 3.0*BT
      30 MZT = 2
      GO TO 50
      40 ZT = 104.5
      50 RETURN
      END
*      LIST
*      LABEL
CZENTER      SUBPROGRAM TO COMPUTE ZE
      FUNCTION ZENTER (XP, VP, XO, TOA, CLOCK)
      ZE1 = XP - XO - 66.0 - (((44.0 - VP)**2) / 12.0 )
      ZE2 = (CLOCK - TOA) * 44.0
      ZENTER = MIN1F (ZE1, ZE2)
      RETURN
      END
*      LIST
*      LABEL
CDEBUGA      SUBPROGRAM TO CHECK OUT INITIALIZATION
      OSUBROUTINE DEBUGA (MZDNS, MZDEW, MTAG, MGEN, CLAG, PROB,
      1 TXEND, TXLT, TXST, TXRT, BLOCK, PREV, INDSIG, SIGCNT,
      2 LEAD, N, OUTIME, SUM, SUM2)
      DIMENSION MTAG(6), MGEN(6,2), CLAG(2,2), PROB(6,2), BLOCK(2,3),
      1 PREV(6), SIGCNT(6), LEAD(6,2), SUM(2,3), SUM2(2,3), TXEND(2,3)
      COMMON CLOCK
      WRITE OUTPUT TAPE 6, 2, CLOCK, MZDNS, MZDEW, MTAG, MGEN, CLAG
      2 FORMAT (16H0DEBUGA, CLOCK =, F6.1, 2013, 4F9.4)
      WRITE OUTPUT TAPE 6, 4, TXEND, TXLT, TXST, TXRT, BLOCK(2,3), PREV(6)
      4 FORMAT (9F10.5, 2F10.1)
      WRITE OUTPUT TAPE 6, 6, ((PROB(I,J), J=1,2), I=1,6)
      6 FORMAT (8H PROB = , 12F9.5)
      OWRITE OUTPUT TAPE 6, 8, INDSIG, SIGCNT(1), LEAD(6,2), N, OUTIME,
      1 SUM(2,3), SUM2(2,3)
      8 FORMAT (1X, 16, F8.2, 218, 3F20.8)
      RETURN
      END
*      LIST
*      LABEL

```

```

CDEBUGB      SUBPROGRAM TO CHECK OUT TRAFFIC SIGNAL CONTROLLER
      SUBROUTINE DEBUGB (CLOCK, INDSIG, MDET, SIGCNT)
      DIMENSION SIGCNT(6)
      WRITE OUTPUT TAPE 6, 2, CLOCK, INDSIG, MDET, SIGCNT
2  FORMAT (16H0DEBUGB, CLOCK =, F8.1, 2I8, 6F12.1)
      RETURN
      END

```

```

*      LIST
*      LABEL

```

```

COEBUGC      SUBPROGRAM TO CHECK OUT VEHICLE PROCESSING COMPUTATIONS
      OSUBROUTINE DEBUGC (I, L, X, V, TOA, TURN, XNOW, VNOW, DREQ, Z,
1  ZS, ZA, ZD, ZT, BLOCK, MZDNS, MZDEW, MTAG, MDET, TAVAIL,
2  TNEED, LOC)
      DIMENSION BLOCK(2,3), MTAG(6), LOC(6)
      WRITE OUTPUT TAPE 6, 2, I, L, X, V, TOA, TURN, XNOW, VNOW, DREQ
2  FORMAT (9H0CAR DATA, 2I6, 7F14.6)
      WRITE OUTPUT TAPE 6, 4, Z, ZS, ZA, ZD, ZT
4  FORMAT (4H Z =, 5F20.8)
      WRITE OUTPUT TAPE 6, 6, BLOCK
6  FORMAT (8H BLOCK =, 6F18.1)
      OWRITE OUTPUT TAPE 6, 8, MZDNS, MZDEW, MTAG(I), MDET, TAVAIL,
1  TNEED, LOC(I)
8  FORMAT (7H MISC =, 4I10, 2F20.6, I13)
      RETURN
      END

```

```

*      LIST
*      LABEL

```

```

CDEBUGD      SUBPROGRAM TO CHECK OUT GENERATION OF VEHICLES
      OSUBROUTINE DEBUGD (I, CLOCK, ZE, RN1, RN2, PREV, MGEN, BRAY,
1  LEAD, NUM)
      DIMENSION PREV(6), MGEN(6,2), BRAY(6,100,2), LEAD(6,2), NUM(6,2)
      OWRITE OUTPUT TAPE 6, 2, I, CLOCK, ZE, RN1, RN2, PREV(I),
1  MGEN(I,1), MGEN(I,2)
2  FORMAT (15H0DEBUGD, LANE =, I2, F8.1, 4F16.6, 2I10)
      IF (NUM(I,2)) 12, 12, 4
4  L = LEAD(I,2)
      NPOS = 1
6  WRITE OUTPUT TAPE 6, 7, I, NPOS, (BRAY(I,L,K), K = 1,2)
7  FORMAT (8H BACKLOG, 2I10, 2F25.8)
      IF (NUM(I,2) - NPOS) 12, 12, 8
8  NPOS = NPOS + 1
      L = LNEXT(L)
      GO TO 6
12 RETURN
      END

```

```

*      LIST
*      LABEL

```

```

CDEBUGE      SUBPROGRAM TO DISPAY VEHICLE DATA EACH TIME INCREMENT
      SUBROUTINE DEBUGE (I, CLOCK, ARAY, LEAD, NUM, INDSIG)
      DIMENSION ARAY(6,100,5), LEAD(6,2), NUM(6,2)
      IF (I - 1) 50, 50, 10
5  WRITE OUTPUT TAPE 6, 6, CLOCK, INDSIG
60FORMAT (119H -----
1  -----,
2  /8H CLOCK =, F8.0, 3X, 28H LANE POS, TOA TURN,
3  3X, 4HXNOW, 11X, 4HVNOW, 10X, 4HDREQ, 12X, 16H TRAFFIC SIGNAL =, I2)
10 IF (NUM(I,1)) 50, 50, 15
15 WRITE OUTPUT TAPE 6, 16
16 FORMAT (/)
20 L = LEAD(I,1)
      NPOS = 1
25 WRITE OUTPUT TAPE 6, 26, I, NPOS, (ARAY(I,L,K), K=1,5)
26 FORMAT (18X, 2I5, F10.1, F9.1, F16.5, 2F14.5)

```

```

      IF (NUM(I,1) - NPOS) 50, 50, 30
30  NPOS = NPOS + 1
      L = LNEXT (L)
      GO TO 25
50  RETURN
      END
*      LABEL
*      FAP
*RAND      SUBPROGRAM TO GENERATE RANDOM NUMBERS FOR MAIN STREET
      COUNT 15
      ENTRY SET
      ENTRY RAND
SET  CLA      RAND+9
      XCA
      CLA*    1,4
      ARS     18
      STO     RAND+9
      XCA
      TRA     2,4
RAND LDQ      RAND+9
      MPY     RAND+8
      STQ     RAND+9
      CLA     RAND+7
      LLS     27
      FAD     RAND+7
      TRA     2,4
      OCT     170000000200
      DEC     305175781250
      DEC     1
      END
*      LABEL
*      FAP
*RANDS     SUBPROGRAM TO GENERATE RANDOM NUMBERS FOR SIDE STREET
      COUNT 15
      ENTRY SETS
      ENTRY RANDS
SETS  CLA     RANDS+9
      XCA
      CLA*    1,4
      ARS     18
      STO     RANDS+9
      XCA
      TRA     2,4
RANDS LDQ     RANDS+9
      MPY     RANDS+8
      STQ     RANDS+9
      CLA     RANDS+7
      LLS     27
      FAD     RANDS+7
      TRA     2,4
      OCT     170000000200
      DEC     305175781250
      DEC     1
      END

```