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A REAL-TIME ADVISORY SIGN CONTROL SYSTEM FOR URBAN HIGHWAYS

by

Stephen R. Kleinman

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date

Richard Wiener
Chairman of Examining Committee

19 May 1971
date

Executive Officer

Prof. Morris Ettenberg

Prof. Stanley Katz

Prof. Ralph Mekel

Prof. Richard Wiener, Chairman
Supervisory Committee

The City University of New York

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Abstract

A REAL-TIME ADVISORY SIGN CONTROL SYSTEM FOR URBAN HIGHWAYS

A real-time computer controlled advisory speed sign system is proposed in order to improve the level of comfort and safety on an urban expressway at high traffic volumes. By transmitting advance warnings of impending slowdowns the system attempts to prevent sudden sharp decelerations caused by the amplifying effect of car-following. The control system output consists of command settings for the advisory signs located along the highway at intervals of one-tenth mile. Roadbed detectors continually monitor and transmit speed and density data to the on-line computer. The processing of this information in accordance with a control algorithm results in command settings for the advisory speed signs.

For practical reasons the sign settings are restricted to the usual 5 mi/hr increments and a particular sign is set only if a significant response is necessitated thus insuring the highest possible compliance. The effect of partial compliance is investigated by varying the percentage of drivers that heed the advisory sign settings.

The sign control algorithm is fashioned to minimize the total average acceleration noise for all vehicles. Based on a calculus of variations solution to a simplified highway situation a desired average deceleration is determined for vehicles on each one-tenth mile section of highway upstream of the disturbance. The desired deceleration is expressed in terms of the measured section speeds and densities. Sign settings are chosen so that the predicted average vehicle deceleration on each section equals the desired deceleration. The predicted average deceleration is derived from an assumed sign-following law as a function of a car's speed when entering the section and the speed setting of the advisory sign located at the next section boundary.

An elaborate computer simulation which incorporates the detectors, signs, sign control algorithm, and the vehicles as they respond to other cars and advisory signs is developed. Flow disturbances are programmed in order to test the effectiveness of the sign control algorithm. The significant reduction in acceleration noise, even for partial compliance, indicates that meaningful improvements in safety and comfort can be achieved by advisory sign control.

CHAPTER 1

INTRODUCTION

In recent years the highways in and around metropolitan areas have become increasingly subject to congestion. In the vicinity of urban areas it is neither feasible nor desirable to eliminate congestion by construction of additional highways. The cost of rights-of-way and the social impact of displacing large numbers of people are prohibitive. Yet the penalty in terms of increased travel times, frazzled nerves, and higher accident rates that are characteristic of congested traffic mandates a solution.

To this end considerable sums of money have been spent to sponsor theoretical and experimental studies of the various aspects of traffic flow. This research has resulted in a better understanding of the dynamics of traffic flow and in many cases has led to implementation of surveillance and control systems that have improved the quality of flow.

As of the beginning of 1970, seventeen of the States and Washington, D.C., have implemented some form of freeway surveillance and control system[1]. Nine of the ten most populous states are in this category.

The basic goals of these systems are (1) to prevent congestion, (2) to communicate alternative route and speed information to motorists, (3) to provide rapid detection of accidents, and (4) to provide service to stranded motorists.

Aside from accidents and disabled vehicles, the most severe disruptions to expressway flow occur because the demand is greater than the capacity. Thus, quite appropriately, attempts to prevent congestion in tunnels and on expressways have concentrated on limiting the rate at which vehicles enter a section of roadway so as to keep the flow rate downstream from an entrance less than the section's capacity.

Initial efforts to control traffic utilizing both a theoretical and experimental approach were made by Edie and Foote[2,3,4] of the Port of New York Authority. They attempted to increase the flow in the Lincoln Tunnel by restricting the vehicle input rate, on a two minute basis, to be less than the capacity of the tunnel bottleneck. The tunnel controls have increased in sophistication over the years, progressing from manual to digital computer control[5]. Their system has achieved an increase in flow of between five and ten percent and has dramatically reduced automotive exhaust emissions and stoppages inside the tunnel.

Entrance ramp control, in one of its several forms[6], is currently the most effective method of preventing congestion on urban expressways. In its simplest form it consists of closing selected entrance ramps during peak hours. The ramp metering method utilizes a traffic signal light at the entrance ramp to control the ingress of vehicles. The input rate is either determined a priori based on historical data or computed in real-time from traffic measurements. A more sophisticated version of ramp metering incorporates gap acceptance merging[7,8,9] which minimizes disturbances in the vicinity of entrance ramps by releasing vehicles only when sufficiently large gaps in the traffic stream are available. Pacer merging control systems consist of a sequence of lights that display a moving green signal to assist vehicles in merging into available gaps.

The major freeway surveillance and control projects have been implemented on the following highways:

(1) Eisenhower Expressway[10, 11, 12] formerly the Congress Street Expressway (Chicago, Illinois)

(2) Gulf Freeway[6, 13] (Houston, Texas)

(3) John C. Lodge Freeway[14, 15] (Detroit, Michigan)

These three control projects have each been successful in improving the level of service of the highway.

Currently the only dynamic traffic-responsive method being employed to regulate the flow on heavily traveled expressways is entrance ramp metering. However entrance ramp metering is limited in that it exerts no control over vehicles already on the roadway. Under dense traffic conditions it is all too well known that the unpredictable response of an inattentive driver can initiate a shock wave that causes upstream traffic to sharply decelerate or come to a prolonged standstill. Such an occurrence, which cannot be substantially mitigated by ramp control, produces severe strain and discomfort among drivers and increases the probability of an accident.

The potential instability of dense highway traffic is due in part to the driver reaction time. A system that transmits advance warning of impending decelerations would be a stabilizing influence and would substantially reduce rear-end accidents. The effect of advance warning on accident rate has been demonstrated by a project on Interstate Highway No. 5 in Portland, Oregon. There a traffic actuated "PREPARE TO STOP" sign is used on the approach to a drawbridge to warn motorists (who are traveling at 70 mi/hr) of when a long queue of stopped vehicles is ahead. Galvanic skin reflex studies conducted by the Bureau of Public Roads[16] have shown that driver tension, and therefore discomfort, decreases as predictability of interferences increases. Michaels and Solomon tested a vehicle mounted signal system[17] that provided advance information on the magnitude of an acceleration or deceleration. They found that car-following behavior was significantly affected with this system. A driver's headway exhibited less variability.

In this research a particular system capable of dampening flow disturbances by transmitting to drivers advance warning of impending slowdowns is proposed and investigated. The project has been motivated by the belief that a properly designed advance warning system will improve the driver's level of comfort and reduce the number of highway accidents.

The type of advance warning system that has been investigated in this research is a real-time computer controlled advisory speed sign system. The control system output consists of command settings for the advisory signs located along the highway at intervals of one-tenth mile. Roadbed detectors continually monitor and transmit speed and density data to an on-line computer. The processing of this information in accordance with a control algorithm results in command settings for the advisory speed signs. For practical reasons the sign settings are restricted to 5 mi/hr increments and the rate at which signs are changed is such that a driver is not presented with a rapidly varying sequence of sign settings. In addition, a particular sign is set only if a significant response is necessitated thus ensuring the highest possible compliance. Compliance will be further improved because any driver who slows down in response to a sign forces the following drivers to decelerate.

Since it has been shown[18] that a quantitative measure of driver comfort and safety is the acceleration noise,

$$\sigma^2 = \frac{1}{T}\int_0^T [a(t)]^2\, dt$$

the sign control algorithm is fashioned to minimize the total average acceleration noise for all vehicles. Based on a calculus of variations solution to a simplified highway situation, a desired average deceleration is determined for vehicles on each one-tenth mile section of highway upstream of the slowdown. The desired deceleration is expressed in terms of the measured section speeds and densities. Sign settings are chosen so that the predicted average vehicle deceleration on each section equals the desired deceleration. The predicted average deceleration is derived from an assumed sign-following law as a function of a car's speed when entering the section and also the speed setting of the advisory sign located at the next section boundary.

An elaborate computer simulation which incorporates the detectors, signs, the sign control algorithm, and the vehicles as they respond to other cars and advisory signs has been developed and is presented in Chapter 3. Flow disturbances have been programmed, and the simulation run both with and without sign control in order to test the effectiveness of the sign control algorithm in reducing driver acceleration noise.

The advisory speed sign concept for expressways bears an analogy to the traffic signal funnel system[19,24-27]. The signal funnel consists of a sequence of changeable speed signs in advance of a signalized intersection or crossing. When the traffic signal turns red the upstream signs advise motorists to decrease their speed, thus delaying their arrival at the intersection until the light turns green. The purpose of the signal funnel is to prevent delays due to poor starting performance of a long queue at the signal light. Subsidiary benefits are smoother velocity profiles and hence greater motorist comfort.

The concept of a remotely controlled speed sign on highways is not innovative. Several facilities have such signs that are used to change the posted speed limit when weather conditions warrant. However, a system of advisory speed signs being dynamically regulated by a computer in response to current local traffic perturbations has not been seriously proposed. Recent literature[20,21], however, indicates that thinking is progressing in the direction of on-freeway real-time responsive traffic control systems.

The surveillance and control system on the John C. Lodge Freeway[15] included a limited study of the effects of changeable speed signs during peak periods. The results were inconclusive due to the following shortcomings of the study: (1) The motorists did not understand the advance warning nature of the signs and probably interpreted the speeds as regulatory, (2) the signs were not dynamically controlled; they were used in an attempt to reduce the flow upstream from fixed geometric bottlenecks, and (3) the signs were controlled by an operator on the basis of television surveillance rather than by computer processing of detector data. In addition, the freeway demand was not restricted by ramp control during peak periods.

It is not expected that advisory sign control will be effective when demand exceeds capacity. Also, light traffic poses no problems and does not warrant sign control. Advisory sign control is intended for conditions of dense traffic with the demand restricted to being below the capacity flow rate. Under such conditions congestion is often precipitated by a minor perturbation within a local pocket of high flow such as a compact platoon of several vehicles. It is expected that in a practical system ramp control and advisory sign control will be used together with the former maintaining the environment in which the latter can be effective.

In Chapters 2, 3, and 4 details of the sign control system are presented. In Chapters 2 and 3 the simulation program and the models used for vehicle dynamics are described. Chapter 4 presents a description and justification of the sign control algorithm. The numerical results comparing the system performance with sign control to the performance without sign control are included in Chapter 5.

CHAPTER 2

SIMULATION PROGRAM

2.1 Justification for Simulation

Positive proof of the effectiveness of the proposed control system can be obtained only by building a prototype on an existing highway and comparing before and after performance indices. However the high cost of building such a system mandates that a preliminary determination be made of the possible improvements afforded by the system. To make this determination a digital computer simulation program has been developed which incorporates the roadbed detectors, the advisory speed signs, the sign control algorithm, and the several models that govern the dynamics of vehicles as they respond to other cars and to the advisory signs. For a particular case the simulation is run both with and without advisory sign control and the performance indices are compared to determine the degree of improvement.

Such a simulation of a complex system involving the human element has the disadvantage of being both an approximation and an oversimplification of the actual dynamics. However it has the potential of being far more realistic than those analytic models that describe a driver's response by a single second order differential equation. Although an experiment on an actual highway is more realistic the simulation offers several significant advantages. For example, a physical modification, such as the spacing of the advisory signs, can be effected by a programming change in a simulated system whereas the same change in an actual system would be expensive, time consuming, and disruptive. The sensitivity of the performance index to any parameter of the control system can be easily obtained since the inputs to the simulation are readily reproduced. A simulated highway also allows the effects of increased volume to be estimated before the actual demand exists.

2.2 The Simulation Program

Simulation Approach   The simulation program is written in Fortran for the IBM 360/50 computer; it occupies about 112 K bytes of storage. Fortran was selected instead of one of the general purpose simulation languages such as GPSS and CSMP because of its greater flexibility and the faster execution time possible by using the Fortran-H compiler. The ratio of simulated time (vehicle-minutes) to CPU time is approximately 100.

On an actual highway every aspect of a vehicle's response to the motion of the car ahead or to an advisory sign varies among different drivers and varies in time for a particular driver. This simulation ignores the time variation and considers only two of the more critical parameters as random variables. One of these parameters is the desired headway factor for the i-th driver, $HDRV_i$, which also determines his sensitivity of response to the car ahead. The other is the compliance factor for the i-th driver, $COMPLY_i$, which specifies whether or not a driver heeds the advisory sign settings.

Since drivers have certain characteristics specified as samples from a probability density function it is advisable to repeat the simulation with different sample populations. It can then be ascertained to what extent different sample populations affect the improvements afforded by the control system and an expected value for the improvement can be estimated. Provision has been made to automatically repeat a simulation run using a different driver sample. The parameter NENS specifies the number of times a simulation should be repeated under identical conditions except for different driver populations. The expected values of the headway factor and the compliance factor are held constant for these runs.

The Simulated System A single-lane, straight, level roadway is simulated on which no passing is allowed. Although it is not realistic to consider that expressways will have only one lane in urban areas, it is likely that a control strategy formulated for a single-lane roadway may be applied to a multi-lane roadway by the introduction of appropriate averages over the several lanes. A justification of control on the basis of a lane composite is that in heavy traffic the flow on all lanes of a particular section of roadway exhibits a certain uniformity. Thus it is assumed that the simulated lane of traffic represents one lane of a multi-lane expressway on which passing opportunities are rare due to dense traffic conditions. The high density assumption implies that every vehicle is coupled to the preceding vehicle; each vehicle responds, after a reaction time, to a significant acceleration of the car ahead. The models of vehicle dynamics are appropriate to this situation.

The length of the roadway may be an integral number of miles up to a maximum of 10 miles in the current version of the program. The roadway is considered to be a sequence of 0.1 mile segments referred to as sections.

A pair of vehicle detectors located at each section boundary are simulated. These detectors produce outputs that allow calculation of the speed of the vehicle most recently passing each detector and the vehicle count on each 528 foot section of roadway. In practice the detectors would be of the induction loop design which are readily available, economical, and easily installed.

Computer controlled advisory speed signs are also simulated. These signs are similarly located at the section boundaries spaced by 0.1 mile. Each sign is either on or off as the current traffic conditions warrant. A sign that is on displays an advisory speed which is limited to one of the standard 5 mi/hr increments.

Since the length of roadway being simulated is intended to be a segment of a much longer highway it is necessary to avoid the end effects associated with vehicles exiting from the simulated roadway. When vehicle k exits from the roadway vehicle k+1 is deprived of its "leader" and unless appropriate measures are taken a disturbance can propagate back upstream from the terminal point. To alleviate this problem a runoff section equal in length to 20 percent of the unextended roadway is provided.

Input Parameters Several different types of input constants allow flexibility in the simulation. Certain constants are parameters in the models for car-following. By changing these parameters the effect, for example, of reaction time on stability can be observed. Other input constants describe physical items of a simulation run such as the length of roadway, the number of vehicles generated, and whether or not the advisory signs are to be used. Certain constants determine the speed and headways of vehicles as they enter the highway. There is provision for generating drivers with uniform car-following characteristics or with sensitivity factor chosen from a probability density function so as to yield a specified input flow. Constants specifying the desired input flow and certain characteristics of the density function are inputs to the simulation. In addition certain parameters specify the desired dynamics of the first car. It is the programmed maneuvers of the first car that initiate all car-following responses. The options available for the motion of the first car are described in a later section. Another constant specifies the percent of drivers that obey the advisory speed signs. Certain constants select printout during the course of the simulation that is useful for debugging, tracing the microscopic motion of the vehicles, or tracing the logic of the sign control algorithm.

Simulation Output Printout may be obtained during the course of the simulation for purposes of debugging or of studying the simulation on a microscopic level.

An option permits printing the speed of all cars on the roadway at one second intervals. This output is printed at intervals of 5 seconds of simulation time between prescribed limits.

For the first twenty cars there is the option of printing position, distance from the car ahead, speed, acceleration, and current mode of operation. The time interval between printing of these variables is specified as an input constant. This form of detailed printout proved useful in the initial phase of testing and refining the car-following models. It has further use in plotting spacing versus speed for a particular maneuver.

An option is included that allows tracing of the logic of the sign control algorithm. At every sign setting interval a graphic representation of the highway is printed. The number of cars on each section and the detector velocity indication at each section boundary is clearly shown. Then intermediate variables in the computation of each sign setting are printed. This is followed by the computed sign setting or the appropriate explanation of why the sign is not to be turned on. After this is printed for each sign the results of the rounding algorithm follow. The sign setting rounded to one of the 5 mi/hr increments is printed or the reason why the sign is turned off is indicated.

Every 30 seconds a table is printed containing the number of vehicles on each section, the velocity indication at each detector site, and the setting of each sign. These data are of the six previous sampling instants spaced by 5 seconds. This table presents a clear picture of the sign profile at a particular time and its evolution over successive 5 second intervals.

At the conclusion of each run additional results are printed. These outputs are described below.

The output of a particular run is identified by printing the values used for certain of the input parameters or options that may be changed between runs. This output indicates the length of highway and the number of vehicles simulated, the type of maneuver undergone by the first vehicle, the entering flow rate, whether entering vehicles are generated with uniform or random headway factors, and whether or not sign control is being used.

For each vehicle the output lists its travel time, stopped time, desired headway factor, speed and spacing both upon entering and leaving the highway, and its acceleration noise for the trip.

A table of COMPLY_i is printed indicating for each driver whether or not he responds to the advisory sign settings or ignores them. The percent of drivers that comply is also printed.

The duty cycle for each advisory speed sign is also given. For the i-th sign this quantity is the ratio of the number of 5 second intervals during which the i-th sign is on to the number of 5 second intervals at the beginning of which the i-th section is non-empty. The sum of these numerators divided by the sum of these denominators is an indicator of the overall duty cycle of the signs.

Cumulative statistics are printed giving, for all cars, the total travel time, total acceleration noise (not including that of the pre-programmed lead vehicle), and the total stopped time. Average statistics give the average travel time, average speed upon leaving the highway, average spacing upon entering and leaving the highway, and average acceleration noise (not including the lead vehicle).

When several runs are made for the purpose of obtaining results for different driver sample populations the ensemble statistics are printed at the end of the set of runs.

Storage of Variables The basic time increment used in the simulation is 0.2 seconds. In this interval of time a vehicle travels approximately one car length at 60 mi/hr. This time increment allows reaction time to be easily simulated to an accuracy of 0.2 seconds.

Since the car-following and sign-following models include time delays, it is necessary to retain certain values computed at previous time increments. Specifically, the acceleration of the k-th vehicle at time t is a function of the position and speed of it and of vehicle (k-1) during the previous 2.0 seconds. Thus at any time t, 11 storage locations are needed for $x_k(t)$, $x_k(t-0.2)$, . . . , $x_k(t-2.0)$ and 11 locations are needed for $v_k(t)$, $v_k(t-0.2)$, . . . , $v_k(t-2.0)$. Sufficient storage is reserved for 350 vehicles in the current version of the program.

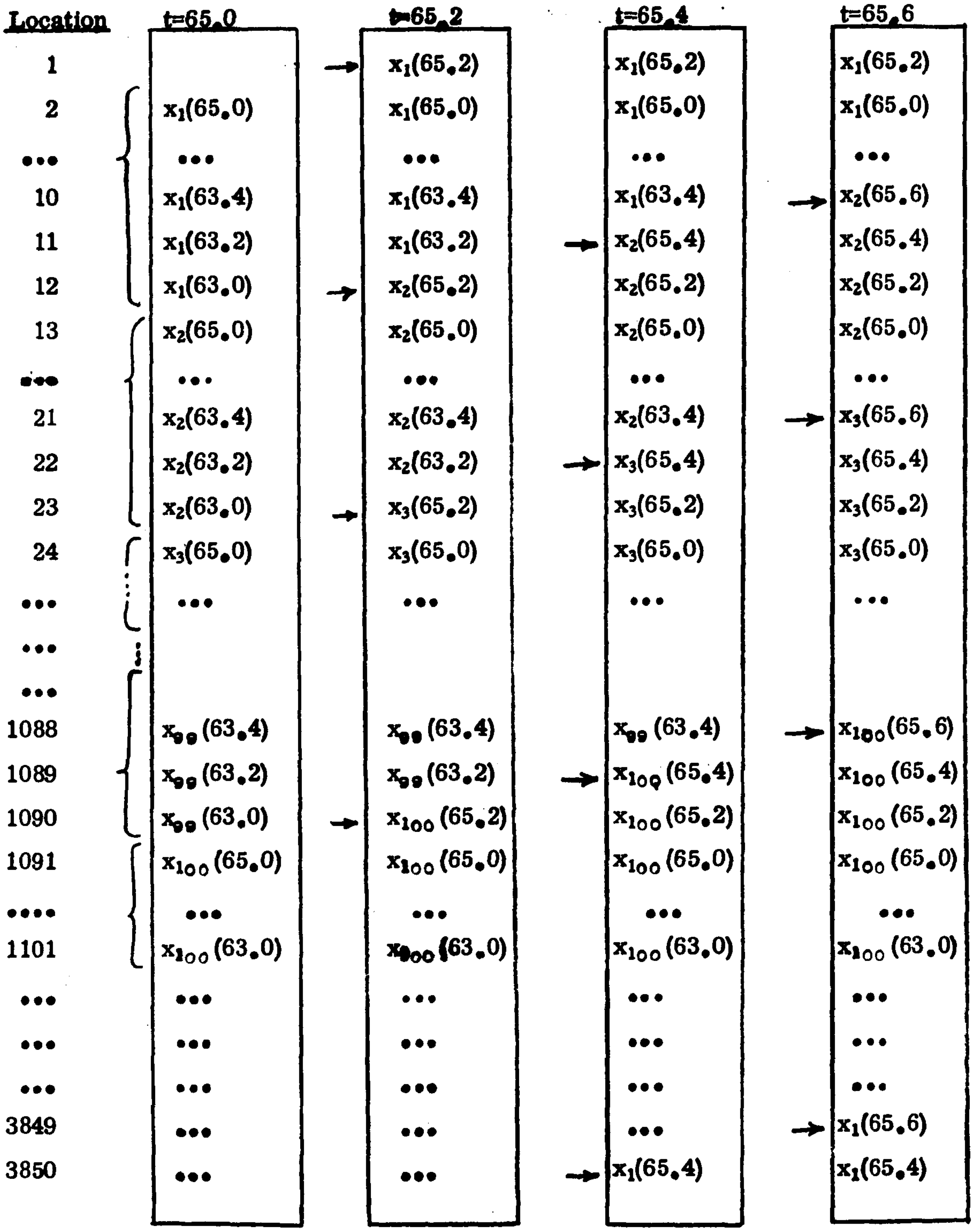
The usual approach for storing these variables is to employ double-subscript arrays. Then X(I,J) might represent the position of the I-th vehicle at time $t = 0.2\ (J-1)$ where t is the current simulation time and J is in the range $1 \leq J \leq 11$.

The approach described above is inefficient for two reasons. Firstly, at every update time ten move operations are necessary for each vehicle on the highway. Secondly, the indexing procedure for double-subscript arrays takes far more execution time than that for single-subscript arrays. The disadvantages are overcome by the following storage method.

The particular scheme used for storing the position and speed information is chosen to minimize the number of times that data is moved from one location to another. Figure 2-1 indicates how the values of position for 100 vehicles are stored. The rows correspond to storage locations and the column headings indicate the values of simulation time for which the contents of storage are shown. In row 2, column 3, the notation $x_1(65.0)$ indicates that at $t = 65.4$ sec, location 2 contains the value of position for car 1 at $t = 65.0$.

When t is incremented from $t=65.0$ to $t=65.2$ the new values for position are computed for all 100 cars. That is $x_i(65.2)$ are computed for $1<i<100$. As shown in column 2, the new value $x_i(65.2)$ is stored adjacent to the previous value $x_i(65.0)$. The quantity $x_i(65.2)$ replaces in storage the oldest value of position stored for the (i-1)-th vehicle, $x_{i-1}(63.0)$, which is no longer needed. The arrows in Fig.2-1 indicate where the most recent values are stored. At $t=65.4$ it is noted that the new value $x_1(65.4)$ is stored at the bottom of the array since the top of the array has been filled. A single variable keeps track of the current position of car 1 (or the car furthest downstream if car 1 has already left the highway). The current positions of successive cars are spaced by 11 locations.

An identical storage arrangement is used for the speeds of the vehicles being simulated. This storage scheme obviates the need to shift values in storage or use double subscript notation. The one-dimensional arrays that store position and speed are designated by XCAR and VCAR



Location	t=65.0	t=65.2	t=65.4	t=65.6
1		→ $x_1(65.2)$	$x_1(65.2)$	$x_1(65.2)$
2	$x_1(65.0)$	$x_1(65.0)$	$x_1(65.0)$	$x_1(65.0)$
•••	•••	•••	•••	•••
10	$x_1(63.4)$	$x_1(63.4)$	$x_1(63.4)$	→ $x_2(65.6)$
11	$x_1(63.2)$	$x_1(63.2)$	→ $x_2(65.4)$	$x_2(65.4)$
12	$x_1(63.0)$	→ $x_2(65.2)$	$x_2(65.2)$	$x_2(65.2)$
13	$x_2(65.0)$	$x_2(65.0)$	$x_2(65.0)$	$x_2(65.0)$
•••	•••	•••	•••	•••
21	$x_2(63.4)$	$x_2(63.4)$	$x_2(63.4)$	→ $x_3(65.6)$
22	$x_2(63.2)$	$x_2(63.2)$	→ $x_3(65.4)$	$x_3(65.4)$
23	$x_2(63.0)$	→ $x_3(65.2)$	$x_3(65.2)$	$x_3(65.2)$
24	$x_3(65.0)$	$x_3(65.0)$	$x_3(65.0)$	$x_3(65.0)$
•••	•••	•••	•••	•••
•••				
•••				
1088	$x_{99}(63.4)$	$x_{99}(63.4)$	$x_{99}(63.4)$	→ $x_{100}(65.6)$
1089	$x_{99}(63.2)$	$x_{99}(63.2)$	→ $x_{100}(65.4)$	$x_{100}(65.4)$
1090	$x_{99}(63.0)$	→ $x_{100}(65.2)$	$x_{100}(65.2)$	$x_{100}(65.2)$
1091	$x_{100}(65.0)$	$x_{100}(65.0)$	$x_{100}(65.0)$	$x_{100}(65.0)$
••••	•••	•••	•••	•••
1101	$x_{100}(63.0)$	$x_{100}(63.0)$	$x_{100}(63.0)$	$x_{100}(63.0)$
•••	•••	•••	•••	•••
•••	•••	•••	•••	•••
•••	•••	•••	•••	•••
3849	•••	•••	•••	→ $x_1(65.6)$
3850	•••	•••	→ $x_1(65.4)$	$x_1(65.4)$

Fig. 2-1 Storage Layout

respectively in the Fortran program.

The current acceleration of the i-th vehicle is stored as ANØW(I). The array IBRNCH(I) stores the mode of each car at the previous simulation time which is used to determine the point of entry into the subroutine that computes each car's motion. That is IBRNCH(I), in part, remembers the previous state of the I-th vehicle. The array IDMØDE(I) stores another component of each vehicle's state, indicating the type of braking behavior the car was engaged in at the previous simulation time. The number of the highway section currently occupied by the I-th vehicle is stored in CECT(I).

Detector derived data are stored in the arrays ND(I,J) and VD(I,J) with ND holding the number of vehicles on each section and VD holding detector speed indications. As the simulation time progresses the index J increases from J = 2 to J = 7 and then repeats this cycle being incremented at 5 second intervals. If at a particular time, say t = 84 sec., the second subscript has the value J = 3 then ND(I,3) is the number of vehicles currently on section I. ND(I,2) equals the number of vehicles that were on section I at the end of the previous 5 second interval, that is, at t = 80 sec. The quantities ND(I,1), ND(I,7), ND(I,6), ND(I,5), ND(I,4) respectively represent the number of vehicles on section I at times 75, 70, 65, 60, and 55 seconds. In the same manner VD(I,3) represents the detected speed from the vehicle most recently having passed detector I. And VD(I,6) represents the speed detected at the I-th detector just prior to t = 65 sec.

The speed setting of the I-th advisory sign is stored in VSIGN(I, J) and the array LSIGN(I) indicates, for each sign, whether it is currently on or off. The second index J in VSIGN(I, J) is utilized in the same manner as with ND and VD. In this way values of ND, VD, and VSIGN at the six previous 5 second intervals are retained.

Generation of Vehicles The cars enter the roadway at a constant speed, V, which is the same for all vehicles and is an input parameter to the program. The vehicles continue at constant speed until all cars have entered the roadway, at which time the lead vehicle commences its maneuver. This method of entering the cars onto the highway assures that the initial conditions will be the same for a run without sign control as for a run with sign control, as explained further in Section 3.2.

The time of entrance of a vehicle is such that the desired following distance for the current speed exists between the vehicle and the vehicle ahead. The desired following distance for the i-th driver is a function of $HDRV_i$, the headway factor assigned to the i-th driver. By specifying the mean value of the headway factor, in addition to the entering speed, the average rate at which vehicles enter the roadway is determined, as is shown in Section 3.2. This rate at which vehicles are generated represents the demand for service on the roadway and is referred to by the letter D. The demand, D, is an input parameter that is varied between 1600 and 2300 vehicles per hour. After the lead vehicle begins its maneuver, actual flow rates achieved on the simulated highway are between 1400 and 1700 vehicles per hour.

It is to be noted that the demand rate D differs from the usual definition of demand in that the vehicles in this simulation have been generated under perturbation-free conditions. On an actual highway, flow rates achieved under conditions of interacting vehicles are considerably lower as is found to be the case in this simulation.

Motion of First Vehicle The motion of the first car to enter the highway is pre-programmed according to several input parameters. The acceleration of the first vehicle is determined by the input constants VI3, NREP; TF3(1),..., TF3(5); AF3(1),..., AF3(4). The car's initial speed is VI3 and its acceleration is zero until t = TF3(1). At this time the car initiates a maneuver described as follows:

$$a_1(t) = \begin{cases} \mathrm{AF3}(1) & \text{for } \mathrm{TF3}(1) < t < \mathrm{TF3}(2) \\ \mathrm{AF3}(2) & \text{for } \mathrm{TF3}(2) < t < \mathrm{TF3}(3) \\ \mathrm{AF3}(3) & \text{for } \mathrm{TF3}(3) < t < \mathrm{TF3}(4) \\ \mathrm{AF3}(4) & \text{for } \mathrm{TF3}(4) < t < \mathrm{TF3}(5) \end{cases}$$

After t = TF3(5) this basic maneuver is repeated until it is executed NREP times. Thereafter the car continues at constant velocity until it leaves the highway. The subroutine F3 controls the motion of the first car. It provides values for the current acceleration, the new velocity, and the new position of the first vehicle.

As shown above the motion of the first car is periodic with period P = TF3(5) - TF3(1) seconds. The usual specification for the constants yields a constant deceleration followed by an interval of constant speed; then a constant acceleration back to the original speed followed by an interval of constant speed.

The first vehicle commences its maneuver shortly after all vehicles enter the highway and usually continues the periodic motion until the vehicle reaches the end of the highway extension (runoff section) where it is terminated.

Dynamics of Following Vehicles Vehicles respond to the motion of other cars and to the advisory speed signs according to the models given in subroutine G1. These models are described in detail in Section 3.1.

Advisory Sign Settings Subroutine SETSGN contains the logic for computing the speed settings of the advisory signs. Every 5 seconds sign settings are determined by analyzing the detector information in the arrays ND and VD. The sign settings are rounded to the standard 5 mi/hr increments. The details of the sign setting algorithm are presented in Chapter 4.

CHAPTER 3

MODELS OF VEHICLE DYNAMICS

3.1 Models of Vehicle Dynamics

Introduction There is a vast literature to draw upon in selecting mathematical models to describe how a vehicle responds to its environment, especially to the motion of other vehicles. These models, often termed car-following laws, are limited to highway traffic without passing, a situation that is approximated on multi-lane expressways with dense traffic.

Models of Single-lane Traffic -- Historical Background

Reuschel[28] (1950) and Pipes[29] (1953) were the first to study the motion of a line of cars under the assumption that vehicle spacing is linearly proportional to speed. The stimulus-response interpretation is that a vehicle's acceleration is proportional to its current relative velocity with respect to the car ahead.

Chandler, Herman, and Montroll[30] (1958) and Kometani and Sasaki[31,32] (1958, 1959) were the first to allow for possible instability in car-following by introducing a reaction time into a linear car-following model. These researchers and others[33] analyzed the transient response of the following car and the propagation of a sinusoidal disturbance down a line of vehicles. Estimates for the parameters of these car-following laws were obtained from actual traffic data by statistical methods.

Lee[34] (1966) later generalized the previous linear models by expressing a vehicle's acceleration as a superposition integral involving a memory function multiplied by the relative velocity at previous times.

The first non-linear model for car-following was postulated by Gazis, Herman, and Potts[35] (1959) to provide a better curve-fit to experimental steady-state flow data. Additional non-linear models were proposed by several researchers[36-39] in the following years and some limited investigations of the dynamics of traffic under non-linear models have appeared in the literature.[40-42]

<u>Limitations of Basic Car-following Models</u> Essentially all of the above models are of the form

$$\ddot{x}_k(t) = \lambda_{m,n} \frac{\dot{x}_k^m(t)}{[x_{k-1}(t)-x_k(t)]^n} [\dot{x}_{k-1}(t-\tau) - \dot{x}_k(t-\tau)]$$

except for Lee's model given by

$$\ddot{x}_k(t) = \int_0^t M(t-\lambda) [\dot{x}_{k-1}(\lambda) - \dot{x}_k(\lambda)] \, d\lambda$$

The linear model, with n=m=0, is adequate in describing small fluctuations from a steady-state speed but is unrealistic when large changes in velocity and spacing occur. The non-linear models offer an extended range of applicability and, in addition, predict an increase in the average spacing between vehicles when the speed undergoes a periodic perturbation. However, the advantages of the above models due to their simplicity and mathematical tractability are counterbalanced by their limitations.

These models are limited in that τ and λ are fixed quantities. It has been found[43] that λ is different for acceleration and deceleration maneuvers. The value of reaction time should also be different for acceleration and deceleration because of the safety consideration involved in a vehicle's response to a slowdown. Ideally the reaction time should be divided into components of perception time and time to effect the control response. Each of these component delays vary among different situations and different drivers and even depend on the severity of prior disturbances.

Another limitation is the failure of the above models to constrain vehicle accelerations to be within the range of vehicle performance.

These models are also limited to describing a vehicle's response as a velocity-sensitive mode whereas in reality the varied highway situations demand qualitatively different responses. Realistic modeling requires emphasis on understanding driver behavior to the extent that situations can be distinguished in which drivers react to different stimuli. It has been recognized that vehicles on a roadway are not always in the car-following mode where they respond to relative velocity. Michaels[44] (1963) analyzed the information used by the driver in three distinct modes: overtaking, steady-state following, and responding to an acceleration of the car ahead.

Formulation of the Simulation Models Most of the drawbacks of the simple car-following models can be overcome in a computer simulation because the constraint of mathematical tractability can be relaxed. Reaction time and sensitivity can be easily varied and can differ among drivers, thus introducing a realistic random aspect to traffic flow. Different modes of response characterized by different mathematical models can be easily implemented.

In this simulation a vehicle is considered, at a given time, to be in one of three principal modes: the car-following mode, the distance-detection mode, or the sign-following mode. In the car-following mode a vehicle is responding to the motion of the car ahead; in the distance-detection mode a vehicle is attempting to modify the spacing to the car ahead; and in the sign-following mode a vehicle is responding to the speed setting of an advisory sign.

The car-following models are non-linear but reduce to linear models for small perturbations from a steady-state. Deceleration and acceleration responses are computed by different models. The sign-following model is patterned after a linear car-following model with the constants appropriately modified. Variation among drivers is achieved by specifying a parameter appearing in the car-following model and in the distance-detection model as a random variable. Another random variable determines for each driver, whether or not he heeds the advisory sign settings.

The models governing a vehicle's dynamics, as specified by the logic of subroutine G1, are described in further detail in the following sections.

The Car-following Mode In general the i-th vehicle is undergoing car following if the (i-1)-th vehicle is accelerating (or decelerating) at a significant rate or if the i-th vehicle is still responding significantly to a prior maneuver of the car ahead.

In order for the i-th vehicle to transfer from the car-following (CF) mode to the distance-detection (DD) mode it is required that: (a) the (i-1)-th car have $|a_{i-1}| < 1.0$ for the previous 1.0 second and (b) the i-th vehicle have an acceleration within the range of that used in the DD mode and (c) that the rate of change of visual angle to the car ahead be sufficiently small.

To compute ACF, the acceleration due to car-following, it is first determined whether the response will be an acceleration or a deceleration since the model is different for each of these cases. In determining ACF for the i-th vehicle the expression $\Delta v(t-\tau) = v_{i-1}(t-\tau) - v_i(t-\tau)$ is evaluated for $\tau = \tau_a$ and $\tau = \tau_d$. These different values of τ represent the time lag associated with acceleration and deceleration. The values used are $\tau_a = 1.4$ sec. and $\tau_d = 1.0$ sec.

If $\Delta v(t-\tau_d)$ is negative then a deceleration is indicated. If both $\Delta v(t-\tau_d)$ and $\Delta v(t-\tau_a)$ are positive then an acceleration is indicated. If $\Delta v(t-\tau_d) > 0$ and $\Delta v(t-\tau_a) < 0$ then ACF is taken to be zero.

Car-following Deceleration Model For a deceleration the model for ACF is

$$\mathrm{ACF} = \mathrm{FACTOR} \times \Delta v(t-\tau_d)/\mathrm{HDRV}_i \qquad (3\text{-}1)$$

subject to modifications discussed below. The constant HDRV_i, termed the headway factor, is generated for each vehicle as an independent sample from a specified probability density function. The term FACTOR accounts for the difference between the driver's desired spacing to the rear bumper of the car ahead, SD, and the actual spacing, SA. These spacings are given by

$$SD \equiv HDRV_i \times v_{i-1}(t)$$

$$SA \equiv x_{i-1}(t) - x_i(t) - 20$$

Using this notation, FACTOR is expressed as

$$FACTOR = \begin{cases} 1.0 & \text{for } v_{i-1}(t) < 20 \\ \dfrac{20}{v_{i-1}(t)} + \left[1 - \dfrac{20}{v_{i-1}(t)}\right]\left[\dfrac{SD}{SA}\right] & \text{for } v_{i-1}(t) \geq 20 \end{cases}$$

The quantity FACTOR biases the deceleration according to whether the inter-vehicle spacing is larger or smaller than desired. FACTOR varies from 1.0 to $\frac{SD}{SA}$ as $v_{i-1}(t)$ increases from zero toward infinity. Also,when SD = SA it is noted that FACTOR = 1.0.

The deceleration of vehicle i is modified in certain cases if the acceleration of the car ahead is negative. If SA/SD is less than 1.6, the value of ACF given by Eq.(3-1) is modified by addition of the quantity

$$FCTR \times a_{i-1}(t) = \sqrt{\frac{1.6 - SA/SD}{9.6}}\, a_{i-1}(t)$$

FCTR varies from 0.338 when SA/SD = 0.5 to 0.25 when SA = SD to zero when SA/SD = 1.6. This term accounts for an anticipatory reaction due to car (i-2) since $a_{i-1}(t)$ is proportional to $v_{i-2}(t-\tau) - v_{i-1}(t-\tau)$. The term FCTR is plotted in Fig. 3-1.

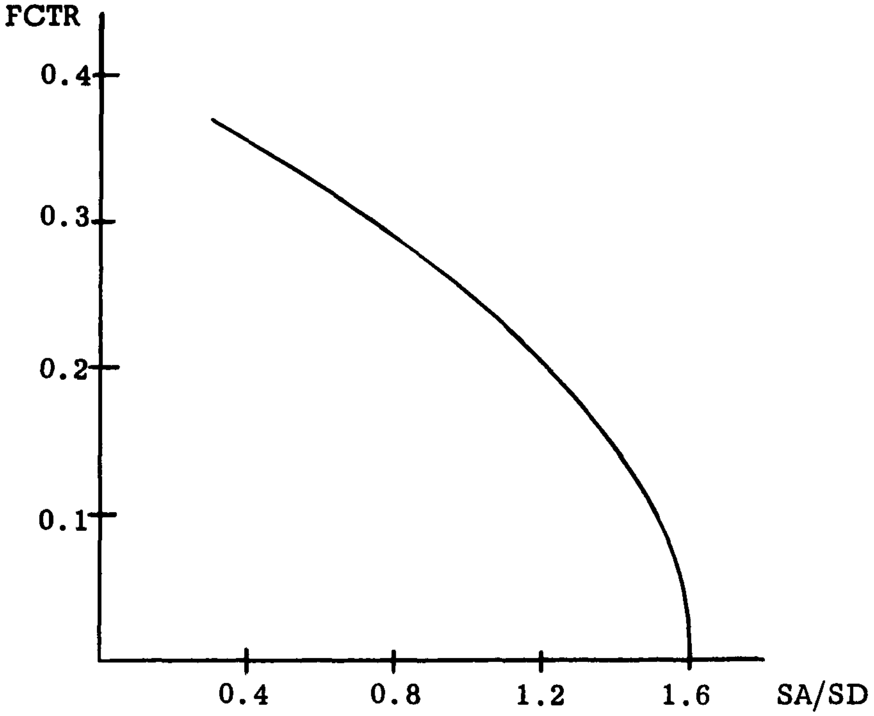


Fig. 3-1 Anticipatory factor used in deceleration model

The magnitude of decelerations are limited to be less than 10 ft/sec^2 unless an unsafe spacing condition exists or unless the vehicle is still responding to a prior unsafe spacing situation. The minimum safe spacing is given by

$$\text{SSAFE} = \frac{1}{2a_m}\{v_{i-1}^2(t) - v_i^2(t) + [a_m - a_i(t)][2v_i(t) + a_i(t)\tau]\tau\}$$

Then SSAFE equals the minimum inter-vehicle separation needed to avoid a collision if vehicle (i-1) suddenly decelerates to a standstill at the rate of $a_m = -24$ ft/sec^2. Vehicle i is assumed to decelerate at $a_m = -24$ ft/sec^2 after a minimum reaction time of $\tau = 0.45$ sec. The small reaction time is appropriate since the driver's foot is already on the brake.

If the car ahead is accelerating and if $v_i(t)$ is less than $v_{i-1}(t)$, even though v_i was greater than v_{i-1} at $t-\tau_d$, then the magnitude of the previously computed deceleration is decreased by multiplying ACF by the quantity

$$\text{FT} = \begin{cases} 1 - \dfrac{a_{i-1}(t)}{4} & \text{for} \quad 0 < a_{i-1}(t) < 4.0 \\ 0 & \text{for} \quad a_{i-1}(t) \geq 4.0 \end{cases}$$

Car-following Acceleration Model For an acceleration the model for ACF is

$$\text{ACF} = \begin{cases} \Delta v(t-\tau_a)/\text{HDRV}_i \times \left[1 - \dfrac{0.25}{\text{HDRV}_i} \times \dfrac{\Delta v(t-\tau_a)}{\text{AMAX}}\right] & \text{for } \Delta v(t-\tau_a) < 2 \times \text{AMAX} \times \text{HDRV}_i \\ \text{AMAX} & \text{for } \Delta v(t-\tau_a) > 2 \times \text{AMAX} \times \text{HDRV}_i \end{cases}$$

where AMAX is the maximum acceleration of which vehicle i is capable and is given by

$$\text{AMAX} = 12.4 - 0.0913\, v_i(t) \quad \text{ft/sec}^2$$

The value of ACF may be increased, to a maximum of 2.0 ft/sec^2, if the spacing to the car ahead is larger than normal. If SA/SD is greater than 1.2, the quantity FA is computed as

$$\text{FA} = \begin{cases} 10(\text{SA/SD} - 1.2) & \text{for} \quad 1.2 < \text{SA/SD} < 1.4 \\ 2.0 & \text{for} \quad \text{SA/SD} \geq 1.4 \end{cases}$$

If FA is greater than ACF then ACF is increased to FA.

If SA/SD is less than 1.6 and the car ahead is decelerating and if $v_i(t)$ is greater than $v_{i-1}(t)$, even though v_i was less than v_{i-1} at $t - \tau_a$, then the previously computed acceleration is decreased (to a minimum of 0) by multiplying ACF by the quantity

$$\text{FS} = \begin{cases} 1 + \dfrac{a_{i-1}(t)}{4} & \text{for} \quad -4 < a_{i-1}(t) < 0 \\ 0 & \text{for} \quad a_{i-1}(t) \leq -4 \end{cases}$$

<u>The Distance-detection Mode</u> In the distance-detection, DD, mode a vehicle responds to the current spacing between his vehicle and the car ahead. If this spacing is reasonably close to the desired spacing then the vehicle continues at constant speed. Otherwise the vehicle initiates a maneuver to increase or decrease the spacing.

In general a vehicle is in the DD mode if the absolute magnitude of the acceleration of the car ahead has been less than 1.0 ft/sec^2 during the previous second. A vehicle transfers from the DD mode to the CF mode when the above condition is violated and the acceleration due to car-following is outside the range of that possible in the DD sub-mode that the vehicle was in.

The DD mode is divided into sub-modes 1,2,3,4, and 5. The i-th vehicle is in mode 1 if its actual spacing, DA, and desired spacing, DD, to the car ahead at the current time satisfy

$$0.85 + 1/[v_{i-1}(t) + 10] < DA/DD < 1.2$$

where

$$DA = SA + 20 = x_{i-1}(t) - x_i(t)$$

$$DD = SD + 20 = HDRV_i \times v_{i-1}(t) + 20$$

In this mode the vehicle's acceleration is zero.

A vehicle transfers to mode 2 if it begins following too close to the car ahead. In mode 2 the vehicle decelerates according to

$$a_i(t) = \begin{cases} 0.8(-.03114\, v_i(t) - 0.390) & \text{for } v_i(t) > 27.63 \\ -1.0 & \text{for } v_i(t) \le 27.63 \end{cases} \qquad (3\text{-}2)$$

This value of $a_i(t)$ approximately equals eighty percent of the deceleration obtained by removing the foot from the accelerator without applying the brake. In mode 2 the vehicle decreases its speed so that the spacing to the car ahead increases until the condition

$$DD - DA \le \frac{1}{4}[v_i(t) - v_{i-1}(t)]^2 \qquad (3\text{-}3)$$

is satisfied. At this time the vehicle transfers to mode 3. In mode 3 the i-th vehicle accelerates at 2.0 ft/sec^2, while the inter-vehicle spacing is still increasing, until $v_i(t) \approx v_{i-1}(t)$. At this time, due to the condition of Eq.(3-3), the spacing is such that DA $\approx$ DD and the vehicle transfers to mode 1.

A vehicle is in mode 4 if it is too far from the car ahead. In this mode a vehicle begins to close the gap by accelerating at 2.0 ft/sec. with the restriction that its speed be not more than 12.0 ft/sec. greater than that of the vehicle ahead. At the appropriate time the vehicle transfers to mode 5. In mode 5 the vehicle decelerates by eighty percent of full engine braking, according to Eq.(3-2), until $v_i(t) \approx v_{i-1}(t)$. The point of switching from mode 4 to mode 5 is chosen such that DA $\approx$ DD when $v_i \approx v_{i-1}$. The vehicle next transfers to mode 1.

<u>The Headway Factor</u> The headway factor $HDRV_i$ appears in the models of both the car-following and the distance-detection modes. The correspondence between the dynamic car-following law and the steady-state speed-spacing relationship is now shown.

For small perturbations from a steady-state speed the car-following laws for both decelerations and accelerations reduce to the linear form

$$ACF = a_i(t) = \Delta v(t-\tau)/HDRV_i = [v_{i-1}(t-\tau) - v_i(t-\tau)]/HDRV_i \qquad (3\text{-}4)$$

Assume that vehicle i-1 is initially at constant speed and undergoes a small change in speed to a new steady-state value. Vehicle i responds according to Eq.(3-4) and eventually attains the same steady-state speed as vehicle i-1. The change in separation between these vehicles for this transition is found by integrating Eq.(3-4) to obtain

$$\Delta S = HDRV_i \times \Delta v$$

where S is the separation between front bumpers of vehicle i-1 and vehicle i. This result is consistent with the steady-state speed-spacing law given by

$$DD = HDRV_i \times v_{i-1} + 20$$

where DD is the desired steady-state separation.

Thus, for small perturbations, the car-following law that determines a vehicle's response also assures that the final spacing is correct for the new steady-state velocity. For larger perturbations the car-following laws become non-linear and result in a larger change in spacing than is desired. In these cases, after completing the car-following response, the vehicle transfers to the distance-detection mode to adjust its steady-state spacing.

The fact that HDRV may be a random variable allows for variation in dynamic response and steady-state following among drivers. The average value of HDRV determines the rate at which vehicles are generated as explained in Sections 2.2 and 3.2.

Sign Following After a vehicle's acceleration has been computed in either the car-following or the distance-detection mode, control is transferred to the sign-following logic. If advisory sign control is being used the vehicle's acceleration due to a sign, ASIGN, is then determined. The mathematical model for the response to a sign setting is presented in Chapter 4.

To determine the effect of varying the levels of driver compliance on the performance improvement due to sign control, the random variable COMPLY is incorporated into the simulation. For each vehicle a sample of the random variable is generated, having the value zero or one, which determines whether a driver follows or ignores the sign settings. The expected value of COMPLY is PCMPLY which is the fraction of drivers that respond to the signs. PCMPLY is an input parameter to the program.

Overall Acceleration In accord with the philosophy that the signs are used to warn of impending slowdowns rather than to attempt to speed up traffic, the overall acceleration at a specific time is given by

$$a_i(t) = \min\ [\text{ASIGN},\ A]$$

where A represents the acceleration in either the CF mode or DD mode as is appropriate.

3.2 Generation of Headway Factors

The primary goal of the simulation is to compare the vehicles' performance under advisory sign control to that without control. Therefore a computer run with control must start with the same initial configuration of vehicles as its counterpart without sign control.

This requirement implies that all vehicles must be on the highway before the start of the lead vehicle's maneuver. Otherwise the results with and without sign control would not be directly comparable since when a disturbance propagates back to the highway entrance some vehicles may be delayed in entering the roadway. The delay with sign control is different from the delay without sign control because of the different manner in which flow disturbances propagate.

Thus it is assumed that all vehicles enter the highway at the same speed V and proceed at constant speed until all cars are on the roadway. A vehicle's spacing, or time gap, upon entering the highway is equal to the driver's desired spacing for the entering speed V. The headway factor H, which determines the desired spacing and the sensitivity to car-following maneuvers, is the random variable that differentiates among drivers.

By specifying the entering speed and the mean value of the headway factor, the average rate at which vehicles enter the roadway is determined, as explained below. The discussion in this section relates the rate, D, at which vehicles enter the highway, called the demand, to HBAR, the average value of the headway factor.

It is emphasized that D represents the rate at which vehicles are generated at the entrance under perturbation-free conditions. After the lead vehicle begins its maneuver the following vehicles can no longer maintain their desired spacings and the resulting flow rates are in the range of 1400 to 1700 vehicles per hour, considerably below D.

Under the assumed conditions for entering vehicles the spacing (front bumper to front bumper) between the (i-1)-th and the i-th vehicle is given by $d_i = HDRV_i \times V + 20$. In this expression $HDRV_i$ is a sample of a random variable H with probability density function f(h). The particular form of this density function and the manner in which its shape depends on D is discussed in detail below.

The time headway at the entrance between vehicle i-1 and vehicle i is $t_i = d_i/V = HDRV_i + 20/V$. Since V is the same for all entering cars the average time headway at the entrance is $\overline{T} = HBAR + 20/V$ where HBAR is the expected value of the headway factor. The average flow at this point is $D = 1/\overline{T} = 1/(HBAR + 20/V)$. To yield a specified value of D requires that the entering headways satisfy $HBAR = 1/D - 20/V$ where D is in units of sec^{-1} (i.e. vehicles per second). It is noted that since the size of the gap between cars is $H \times V$ the time headway of the gap is $T_g = H$ and thus T_g and H have the same distribution.

The density function chosen for H is shown in Fig.3-2. The values of HMIN and HMODE are fixed given quantities. HMIN is the smallest headway factor allowed or the minimum time gap between the rear bumper of the car ahead and the front bumper of the following car. HMODE is the most likely value of the headway factor. The values HMIN = 0.3 and HMODE = 1.0 are taken to be reasonable. The maximum headway factor is a variable which is determined once D is specified.

This approach is justifiable for the following reasons. At any value of flow or speed there will always be a percentage of drivers who follow with a minimum time gap, taken here to be 0.3 sec. Suppose that for a fixed speed V the headway factor density has mode = HMODE and max h = $HMAX_2$ (see Fig.3-2) which determines D_2. To have a larger demand D_1 for the same entering speed requires a larger average density (smaller HBAR). The flow with smaller HBAR will be characterized by the elimination of the large gaps. From other researchers' work[45] it is known that the mean headway of close following vehicles remains essentially constant as flow changes. By keeping the mode fixed the mean time gap of those vehicles with $h <$ HMODE will remain constant as D changes.

This is shown by considering the conditional headway distribution $F_H(y)$ defined by

$$F_Y(y) = \Pr[H \leq y / H < \text{HMODE}] \qquad (3\text{-}5)$$

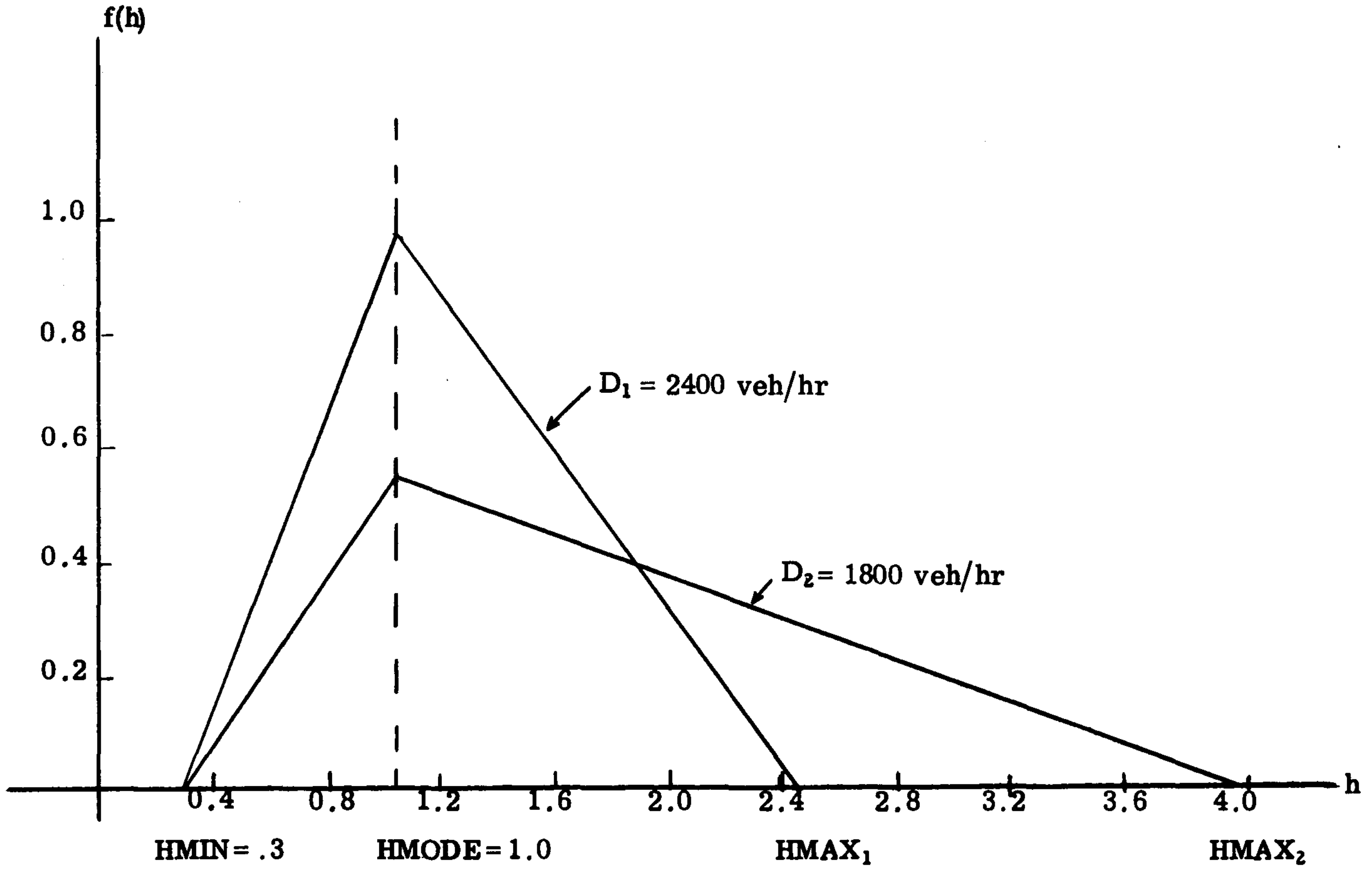


Fig. 3-2 Headway factor density function

The $E\{Y\}$ is given by

$$E\{Y\} = \text{HMIN} + \frac{2}{3}\left[\text{HMODE} - \text{HMIN}\right] \qquad (3\text{-}6)$$

which is independent of HMAX and D . Substituting the assumed values HMIN = 0.3 and HMODE = 1.0 in Eq.(3-6) gives

$$E\{Y\} = 0.767 \text{ sec.}$$

as the expected headway factor or time gap for those vehicles with headways less than the modal headway. For these vehicles the expected time headway (front bumper to front bumper) is

$$E\{Y + \frac{20}{V}\} = 0.767 + \frac{20}{V} \text{ sec.}$$

The headway factor distribution function is shown in Fig.3-3. From the density function, the mean value of the headway factor or time gap is computed as

$$\text{HBAR} = \frac{1}{3}\left[\text{HMIN} + \text{HMODE} + \text{HMAX}\right] \qquad (3\text{-}7)$$

Thus HMAX is determined by the assumed values for HMIN and HMODE and the desired value of HBAR to yield a specified D . From Eq.(3-7)

$$\text{HMAX} = 3\ \text{HBAR} - \text{HMIN} - \text{HMODE}$$

where

$$\text{HBAR} = \frac{1}{D} - \frac{20}{V}$$

As an example, suppose the entering velocity is 50 mi/hr = 73.3 ft/sec. and the desired average flow input is D = 1800 vehicles/hr = 0.5 vehicles/sec. Then $\text{HBAR} = \frac{1}{0.5} - \frac{20}{73.3} = 2.0 - 0.273 = 1.73$ sec.

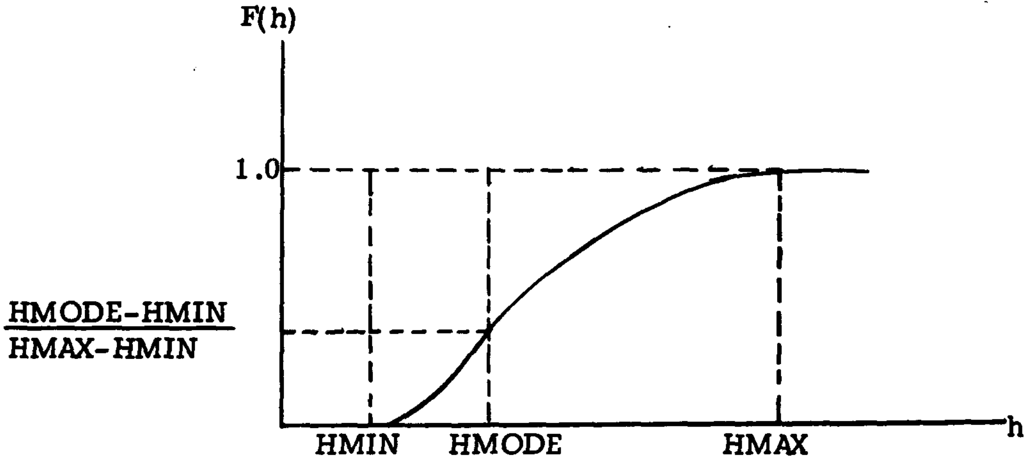


Fig.3-3 Headway factor distribution function

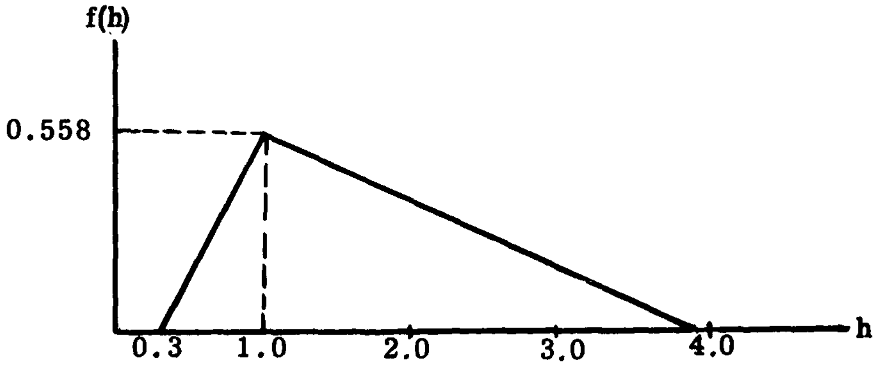


Fig.3-4 Headway factor density function for D = 1800 veh/hr, V = 50 mi/hr

and HMAX = 3(1.73) - 0.3 - 1.0 = 3.89 sec. The average time headway is $\bar{T} = 1/D = 2.0$ sec. The density function for H is shown in Fig. 3-4. The distribution function $F_H(h)$ is found by integration to be

$$F_H(h) = \begin{cases} \dfrac{(h - HMIN)^2}{(HMAX - HMIN)(HMODE - HMIN)} & \text{for } HMIN \leq h \leq HMODE \\ \\ 1 - \dfrac{(HMAX - h)^2}{(HMAX - HMIN)(HMAX - HMODE)} & \text{for } HMODE \leq h \leq HMAX \end{cases} \tag{3-8}$$

Evaluating $F_H(h)$ at h = HMODE gives

$$F(HMODE) = \frac{HMODE - HMIN}{HMAX - HMIN} \tag{3-9}$$

From the above results $F_H(HMODE = 1)$ can be plotted versus HMAX. This is the probability that a headway factor (or gap) is less than the mode (assumed to be 1) versus the maximum headway factor. Using HMIN = 0.3 and HMODE = 1 Eq.(3-9) gives

$$F(HMODE = 1) = \frac{0.7}{HMAX - 0.3}$$

which is plotted in Fig. 3-5. Substituting for HMAX in terms of D as given by

$$HMAX = 3\ HBAR - HMIN - HMODE = \frac{3}{D} - \frac{60}{V} - 1.3$$

yields

$$F(HMODE = 1) = \frac{0.7}{\frac{3}{D} - \frac{60}{V} - 1.6}$$

For V = 50 mi/hr = 73.3 ft/sec. this becomes

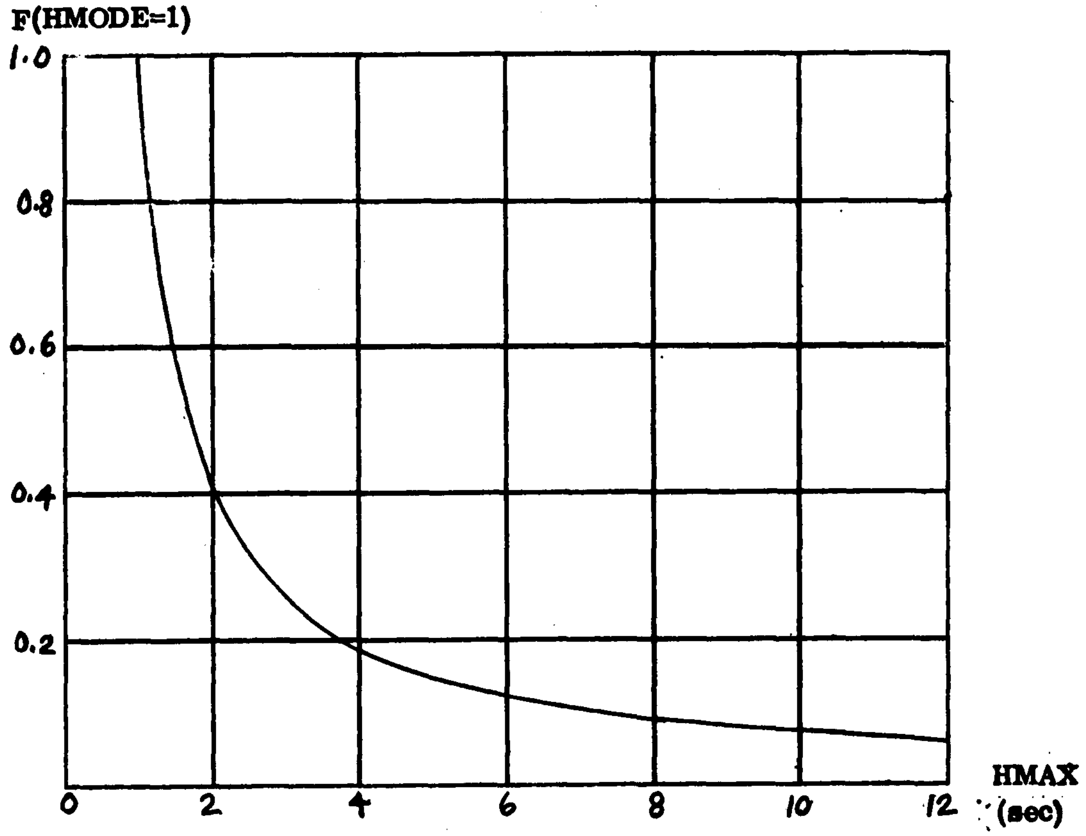


Fig.3-5 : **Probability that Headway Factor is Less than 1 vs. HMAX**

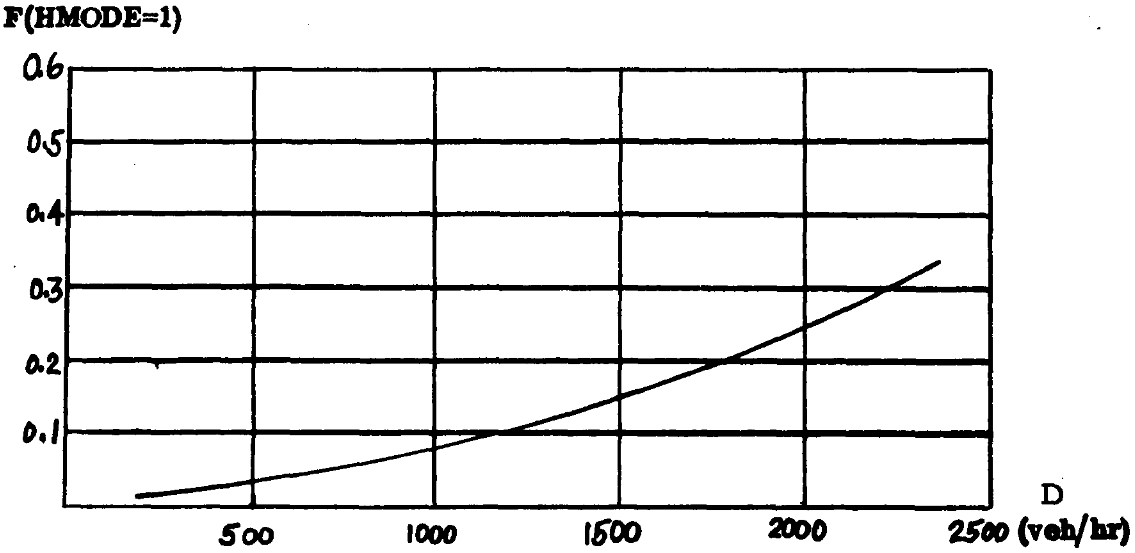


Fig.3-6: **Probability that Headway Factor is Less than 1 vs.** D
for V = 50 mi/hr

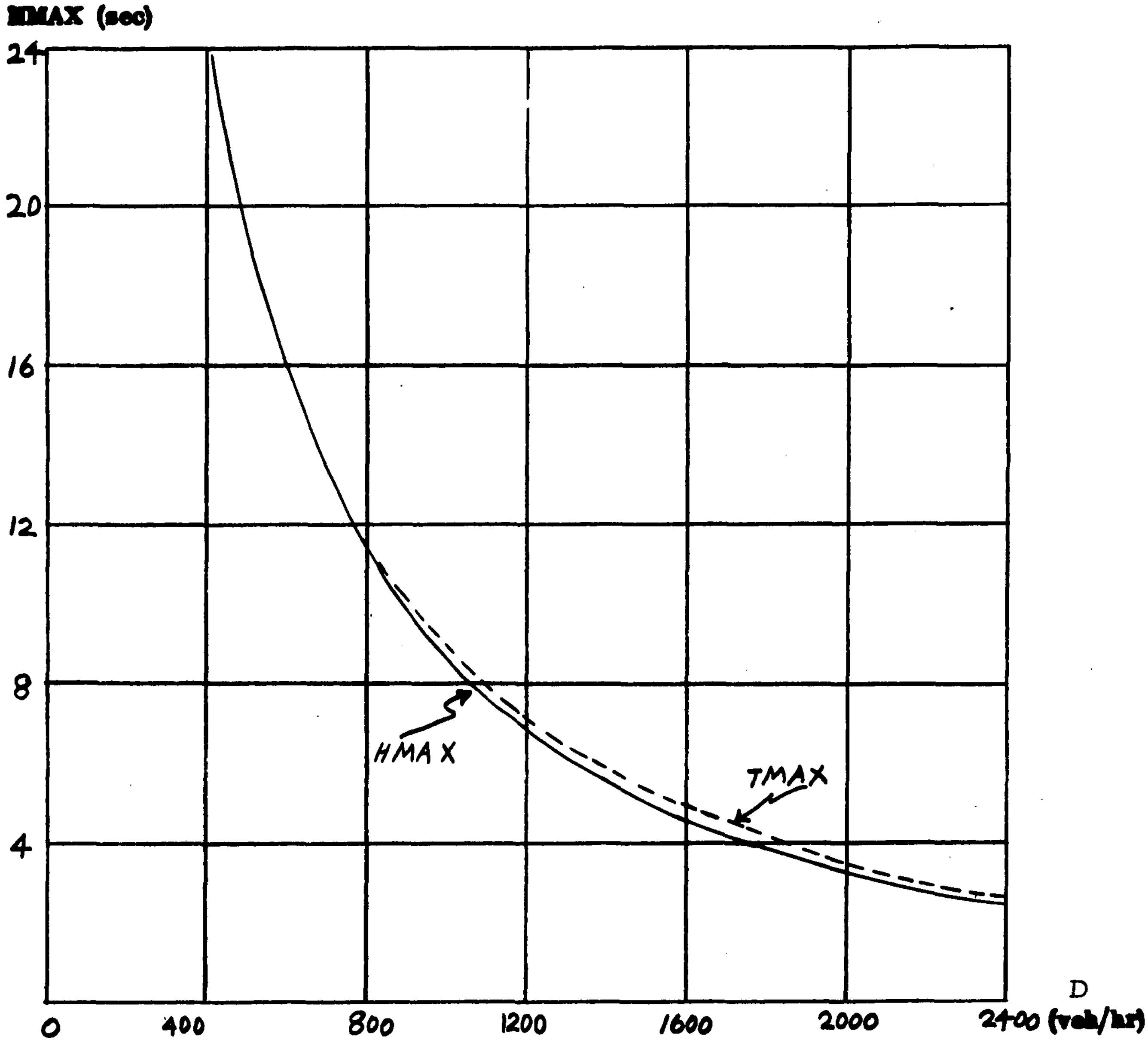


Fig. 3-7 **Maximum Headway Factor vs. D and Maximum Time Headway vs. D for V = 50 mi/hr**

$$F(\text{HMODE} = 1) = \frac{0.7}{\frac{3}{D} - 2.42}$$

which is plotted in Fig. 3-6.

Figure 3-7 is a plot of the maximum headway factor (or gap) as a function of the demand rate for V = 50 mi/hr.

$$\text{HMAX} = 3\ \text{HBAR} - \text{HMIN} - \text{HMODE}$$
$$= 3\left(\frac{1}{D} - \frac{20}{V}\right) - 1.3 = \frac{3}{D} - 2.12$$

Also shown on Fig. 3-7 is TMAX, the maximum headway (seconds) versus D(for V=50 mi/hr), as given by

$$\text{TMAX} = \text{HMAX} + \frac{20}{V} = \text{HMAX} + 0.273$$

Data from Michigan freeways[46] agree well with our assumed density function. The Michigan studies found that approximately 2/3 of the vehicles are spaced at less than the mean headway for a wide range of average flow. From our density function

$$\Pr[T_g < \bar{t}\,] = \Pr[H < \text{HBAR}] = F(\text{HBAR})$$

$$= 1 - \frac{(\text{HMAX} - \text{HBAR})^2}{(\text{HMAX} - \text{HMIN})(\text{HMAX} - \text{HMODE})}$$

Substituting HMIN = 0.3, HMODE = 1.0 gives

$$\text{HBAR} = \frac{1}{D} - \frac{20}{V} = \frac{1}{D} - 0.273 \qquad (\text{for } V = 50 \text{ mi/hr})$$

$$\text{HMAX} = 3\ \text{HBAR} - \text{HMIN} - \text{HMODE} = \frac{3}{D} - \frac{60}{V} - 1.3 = \frac{3}{D} - 2.12$$

$$F(HBAR) = 1 - \frac{(\frac{2}{D} - 1.85)^2}{(\frac{3}{D} - 2.42)(\frac{3}{D} - 3.12)}$$

This is plotted in Fig.3-8. It is seen that F(HBAR) is essentially constant at 0.55 over a wide range of demand rate. The fact that F(HBAR) is constant agrees with the Michigan studies and the actual value of 0.55 is not far from their range of 0.64 - 0.69.

The headway distributions for different 1 minute flow rates obtained in the Michigan study are shown in Fig.3-9. The variation in the shape of the density function for different flow rates is similar to that of our proposed density function. It is noted that the Michigan study gives the headway density function whereas we give the headway factor (or gap) density function. A direct comparison is not possible since it is not known at what speed the measured flow levels were attained.

It is seen that the modal headway varies between 1.2 and 1.7 sec for lanes 2 and 3 for flows between 1000 and 2000 vehicles/hour. We have assumed HMODE = 1 and thus t_{mode} = HMODE + 20/V. Tabulating t_{mode} for a reasonable range of V gives

V(ft/sec)	t_{mode}
90	1.22
70	1.29
50	1.40
30	1.67

which shows a range of t_{mode} similar to the Michigan study.

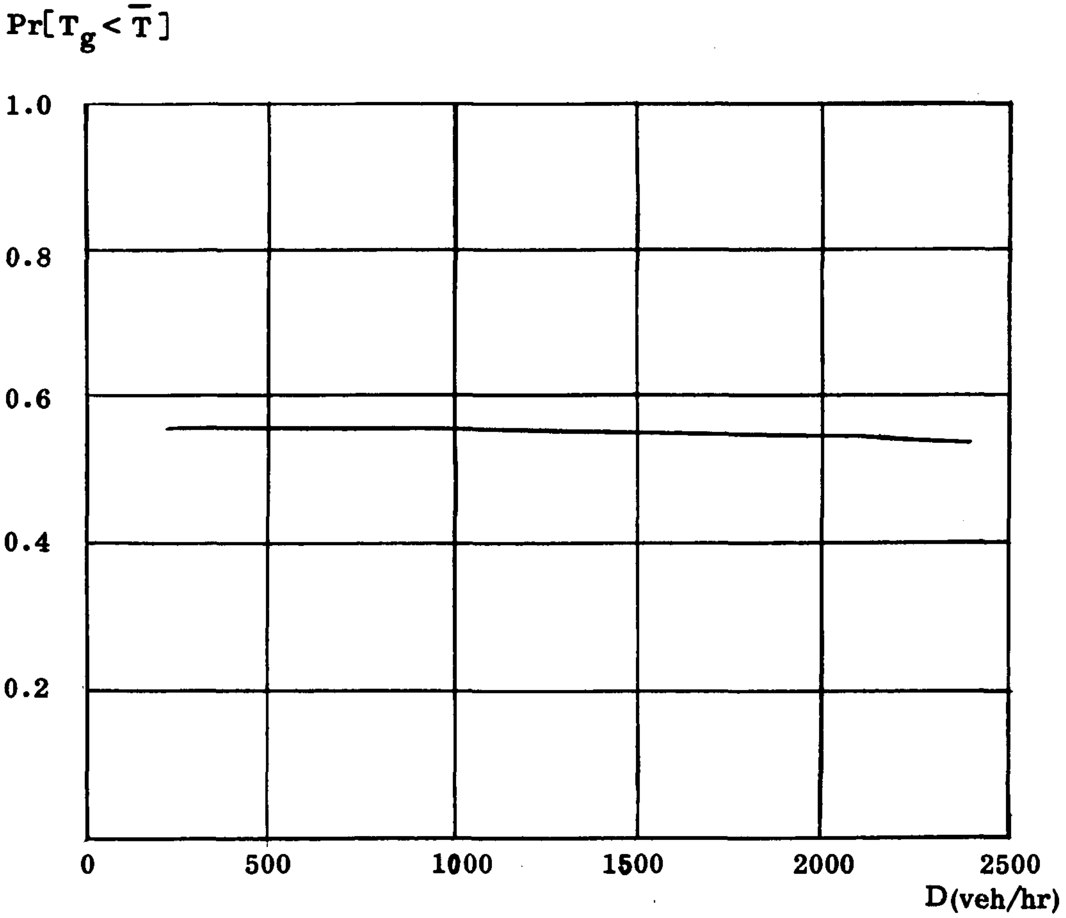


Fig.3-8 Probability that Headway is Less than Mean Headway vs. D for V = 50 mi/hr

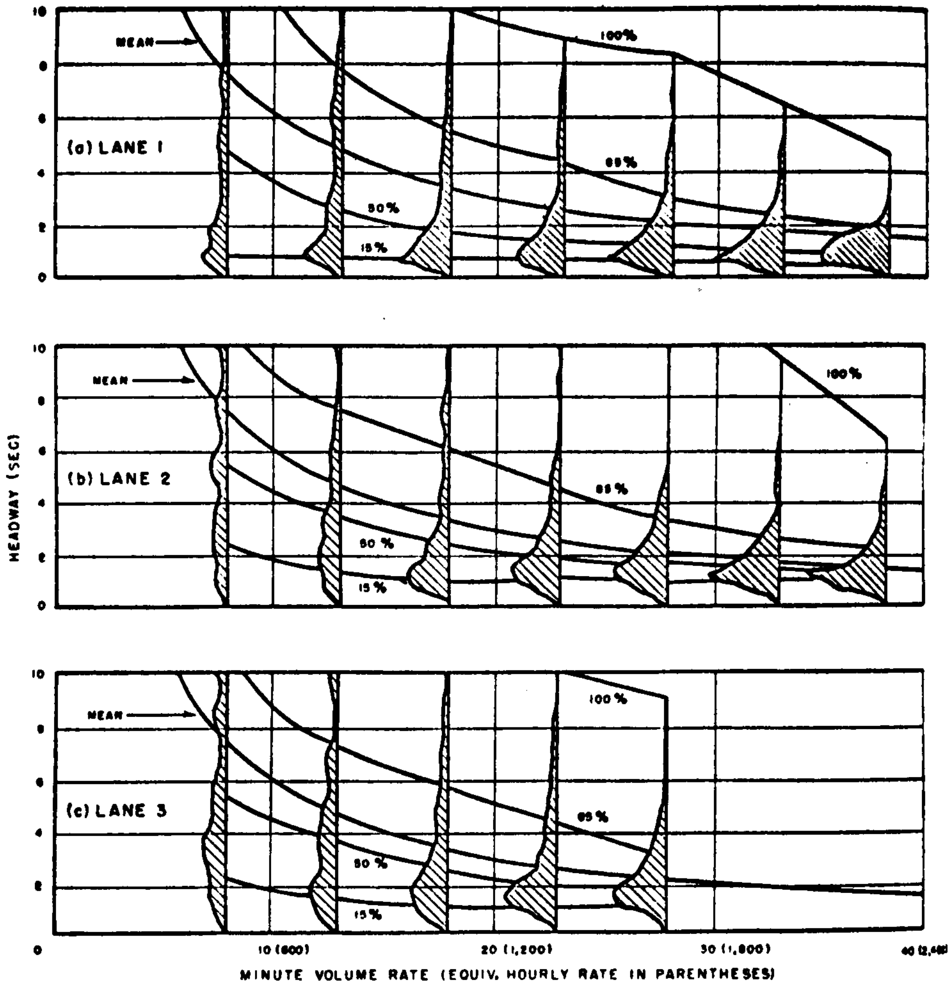


Fig. 3-9 **Headway Density Function vs. D**

Our density function also agrees with the Michigan study in that (1) the mode is always less than the median headway and (2) the median is less than the mean headway.

Thus, having made a good case for our proposed density function the procedure for generating entering headways is given below.

1. Choose appropriate values for entering velocity V and entering flow rate D.
2. Then compute $\text{HBAR} = \frac{1}{D} - \frac{20}{V}$ and $\text{HMAX} = 3 \times \text{HBAR} - \text{HMIN} - \text{HMODE} = 3 \times \text{HBAR} - 1.3$. The density function for headway factor, $f(h)$, and $F(h)$, are thus completely determined.
3. Generate a pseudo-random number R in the interval (0,1).
4. Calculate $h = F^{-1}(R)$. Then $h = F^{-1}(R)$ is a sample from $f(h)$. [See Fig. 3-10].
5. Calculate $d = hV + 20$ as the distance headway for this vehicle at the entrance. Repeat steps 3, 4, 5 to generate successive vehicles.

It is noted that this density function is proposed to represent the headway factor (or gap) density on a typical lane of a multi-lane expressway under non-congested conditions.

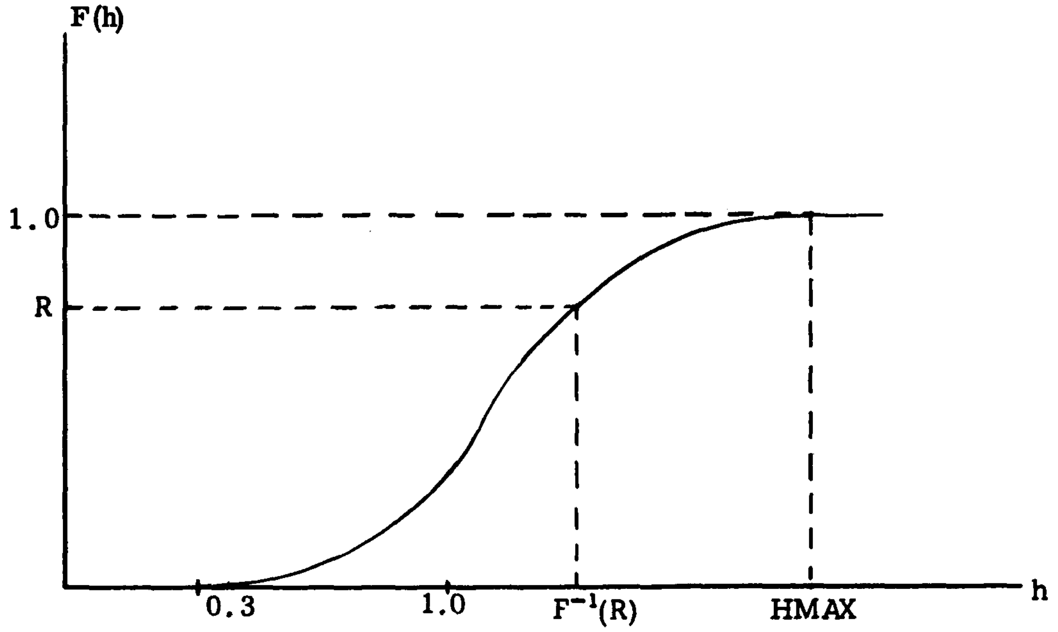


Fig. 3-10 Generating samples from f(h)

CHAPTER 4

DERIVATION AND APPLICATION OF THE SIGN CONTROL ALGORITHM

4.1 Acceleration Noise as an Index of Performance

A quantitative measure of smoothness, comfort, and safety for a driver over an entire trip has been proposed by researchers[18,22,30,33,47-49] in the traffic flow field. This measure is termed acceleration noise and is given by

$$\sigma^2 = \frac{1}{T}\int_0^T [a(t) - \bar{a}]^2 \, dt \qquad (4\text{-}1)$$

where $\bar{a}$ is the time average of a(t) over the interval (0,T).

From Eq.(4-1) it is seen that σ^2 is minimized when $a(t) = \text{constant} = \bar{a}$. This optimum cannot be practically attained since a driver is forced by the behavior of other drivers to decelerate and accelerate during his trip. Although it is the role of sign control to lessen these perturbations, they cannot be completely eliminated. Conceptually, the only way to completely avoid the effect of the car ahead is to allow sufficient intervehicle spacing so that any foreseeable deceleration disturbance would be cancelled by a succeeding acceleration before the gap is closed. Such a system is impractical and permits only very small values of flow.

The acceleration noise may also be expressed as

$$\sigma^2 = \frac{1}{T}\int_0^T [a(t)]^2 \, dt - [\bar{a}]^2 \qquad (4\text{-}2)$$

Over a reasonably long trip the average acceleration given by

$$\bar{a} = \frac{1}{T}\int_{0}^{T} a(t)\, dt = \frac{v(T)-v(0)}{T}$$

will be small and the second term in Eq.(4-2) can be neglected giving

$$\sigma^2 = \frac{1}{T}\int_{0}^{T} [a(t)]^2\, dt \qquad (4-3)$$

For other reasons it is desirable to omit $\bar{a}$ in the formulation of acceleration noise. It is unreasonable to consider two trips equally smooth if one has $a(t) \equiv 0$ and the other has $a(t) =$ constant, yet both of these cases give $\sigma^2 = 0$ using Eq.(4-1). Henceforth the term acceleration noise will refer to that given by Eq.(4-3).

It is noted that the quantity T refers to the total duration of the trip and not only to the duration of non-zero acceleration. Thus σ^2 is more appropriately termed "average" acceleration noise. The average attribute allows the direct comparison of values of σ^2 for trips of different duration as is illustrated below. For the three acceleration waveforms depicted in Fig.4-1, if all trips have the same duration 2T, then the values of σ^2 are

$$\sigma_A^2 = \tfrac{1}{2}A^2$$
$$\sigma_B^2 = A^2$$
$$\sigma_C^2 = 2A^2$$

However if case A represents a trip of duration T then

$$\sigma_A^2 = A^2$$

and the shorter trip has the same value of σ^2 as case B.

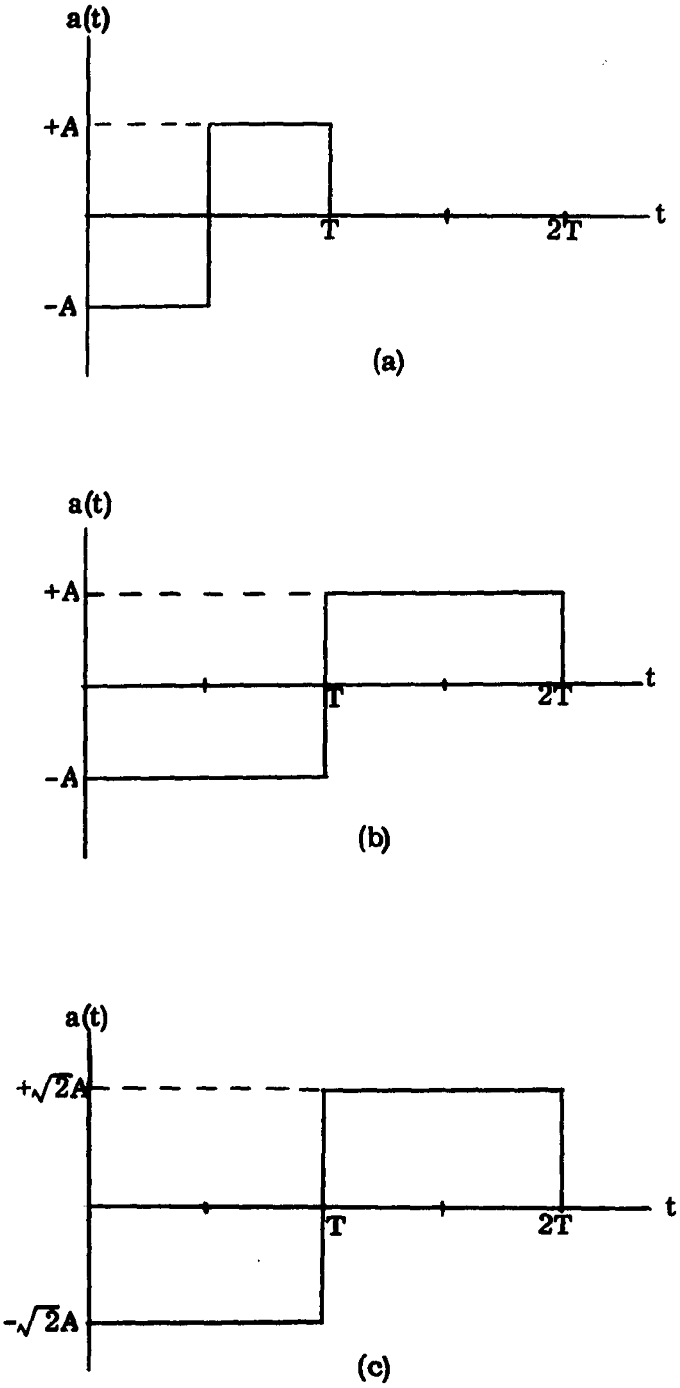


Fig. 4-1 Acceleration waveforms

In general a driver's trip, whether or not under sign control, can be separated into segments of time during which the vehicle is either accelerating or decelerating. The successive intervals of time alternate between acceleration and deceleration. It is assumed that the velocity changes over these successive intervals are independent in the sense that the deceleration undergone by a vehicle during one interval will not substantially affect its acceleration or deceleration in a succeeding interval. The intervals may be assumed to be separated by time periods of constant speed. Under these conditions it is meaningful to ask how the acceleration noise over each of the intervals contributes to the total. If T_i represents the end of the i-th interval then

$$\sigma^2 = \frac{1}{T_n - T_o}\left[\int_{T_o}^{T_1} a^2(t)\,dt + \int_{T_1}^{T_2} a^2(t)\,dt + \ldots + \int_{T_{n-1}}^{T_n} a^2(t)\,dt\right]$$

$$= \frac{1}{T_n - T_o}\left[(T_1 - T_o)\sigma_1^2 + (T_2 - T_1)\sigma_2^2 + \ldots + (T_n - T_{n-1})\sigma_n^2\right]$$

$$= \frac{1}{T}\sum_{i=1}^{n} (T_i - T_{i-1})\sigma_i^2 \qquad (4\text{-}4)$$

where σ_i^2 is the acceleration noise over the i-th interval.

From this analysis it is concluded that in order to minimize the acceleration noise over the entire trip it is sufficient to minimize the quantities

$$(T_i - T_{i-1})\sigma_i^2 = \int_{T_{i-1}}^{T_i} a^2(t)dt$$

over the i-th interval for each vehicle. This requires the assumption stated above that σ_i^2 and σ_j^2 can be minimized independently. This fact is utilized in the sign control algorithm.

4.2 Calculation of Optimum Deceleration for a Simple Highway Situation

The simple highway situation is considered in which all vehicles are initially traveling at the same constant speed, V_o, although at different spacings. The leading vehicle then decelerates to a new steady-state speed V_f. In this case it is assumed that the following vehicles eventually reach an equilibrium speed of V_f at a smaller spacing appropriate to the new speed. The optimum manner in which these vehicles should make the transition from V_o to V_f so that the integral $\int [a(t)]^2 dt$ is minimized for each vehicle is now considered.

Attention is directed to a particular following vehicle and the problem is formally stated as follows. Given two vehicles having initial speeds $v_1(0) = V_f$ and $v_2(0) = V_o > V_f$ and initial spacing $x_1(0) - x_2(0) = S_o > 0$ and given that $v_1(t) = V_f$ = constant. Find the acceleration of the following vehicle, $a_2(t)$, such that $I = \int_o^T [a_2(t)]^2 dt$ is minimized subject to the final conditions $v_2(T) = V_f$ and $x_1(T) - x_2(T) = S_f < S_o$. It is noted that the upper limit is given as T rather than infinity since it is expected that the optimum $a_2(t)$ is a function of the upper limit. Also, the following vehicle may be any of the vehicles upstream of the leading vehicle, not necessarily vehicle 2 in the line.

To simplify the calculation the following normalized and equivalent problem is solved. Given a vehicle initially having $x(0) = 0$ and $v(0) = V_o$. Find the acceleration a(t) to minimize $I = \int_o^T [a(t)]^2 dt$ and satisfy $x(T) = D$, v(T) = 0. This problem is of the form

> Minimize $I = \int_0^T f(t, x, \dot{x}, \ddot{x})dt$ with respect to x(t) subject to given values of x and $\dot{x}$ at the upper and lower limits.

According to the calculus of variations[50] the twice-differentiable function x(t) which extremizes I satisfies the differential equation

$$\frac{\partial f}{\partial x} - \frac{d}{dt}\left(\frac{\partial f}{\partial \dot{x}}\right) + \frac{d^2}{dt^2}\left(\frac{\partial f}{\partial \ddot{x}}\right) = 0$$

In the posed problem $f(t, x, \dot{x}, \ddot{x}) = [\ddot{x}(t)]^2$ and the above differential equation becomes

$$\frac{d^2}{dt^2}[2x(t)] = 0$$

which has the solution

$$\ddot{x}(t) = A + Bt \tag{4-5}$$

The final solution is found by solving for A and B in terms of the upper limit T, then evaluating I as a function of T, and then finding the value of T and hence the function a(t) that extremizes I.

Integration of Eq.(4-5) and imposition of the initial values of x and v yields

$$v(t) = At + \tfrac{1}{2}Bt^2 + V_0 \tag{4-6a}$$

$$x(t) = \tfrac{1}{2}At^2 + 1/6\,Bt^3 + V_0t \tag{4-6b}$$

Substituting the required values of x and v at the upper limit gives the two equations

$$AT + \tfrac{1}{2}BT^2 + V_0 = 0$$

$$\tfrac{1}{2}AT^2 + 1/6BT^3 + V_0T = D$$

These two linear simultaneous equations in A and B yield the solutions

$$A = -\frac{2}{T^2}\left[2\,V_oT - 3\,D\right] \tag{4-7a}$$

$$B = \frac{6}{T^3}\left[V_oT - 2\,D\right] \tag{4-7b}$$

The integral to be extremized is

$$I = \int_o^T (A + B\,t)^2\, dt \tag{4-8}$$

When the values of A and B given by Eqs.(4-7) are substituted into Eq.(4-8) and the integral is evaluated the result is

$$I = 4\left\{\frac{V_o^2}{T} - \frac{3\,D\,V_o}{T^2} + \frac{3\,D^2}{T^3}\right\} \tag{4-9}$$

$$\frac{dI}{dT} = -\frac{4\,V_o^2}{T^4}\left[T - \frac{3\,D}{V_o}\right]^2$$

Thus $dI/dT = 0$ at $T = 3D/V_o$ and at $T = \infty$. Also dI/dT is non-positive for all $T \geq 0$. Thus since $I \to +\infty$ for $T \to 0^+$ and $I \to 0^+$ for $T \to +\infty$ the shape of I(T) is deduced as shown in Fig.4-2. The unconstrained minimum of I occurs at $T = +\infty$ where $I = 0$. However the expression for v(t) given by Eq.(4-6a) becomes upon substitution of A and B from Eqs.(4-7)

$$v(t) = \frac{3}{T^3}(V_oT - 2\,D)(t - T)\,(t - t_o)$$

where

$$t_o = \frac{V_oT^2}{3[V_oT - 2D]}$$

For $T > 3D/V_o$ it is found that t_o is in the range $\frac{1}{3}T < t_o < T$ giving a parabolic speed profile as shown in Fig.4-3. Since a negative speed is inadmissible

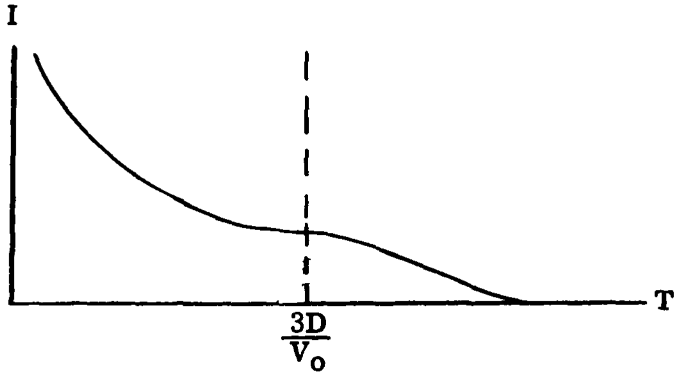


Fig. 4-2 The integral I(T)

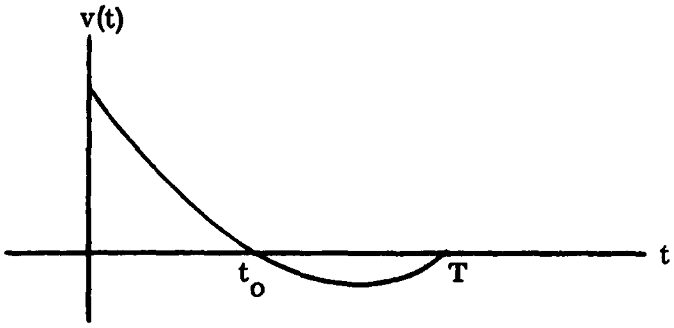


Fig. 4-3 Speed profile for $\frac{1}{3} T < t_o < T$

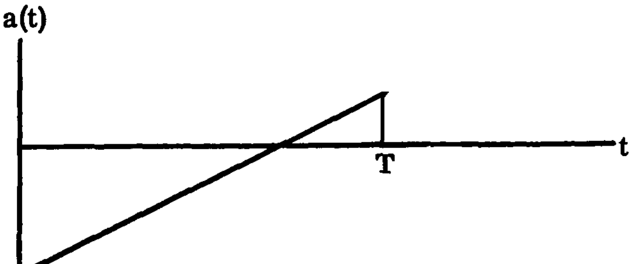


Fig. 4-4 Acceleration waveform for $T > 3D/V_o$

the unconstrained solution cannot be accepted. For an acceleration of the form $A+Bt$ the final time must be limited to $T \leq 3D/V_O$. This may also be seen by examining the expression for the acceleration at the final time

$$a(T) = A + BT = \frac{2}{T^2}(V_O T - 3D)$$

For $T > 3D/V_O$ it is seen that $a(T) > 0$ implying an acceleration waveform as shown in Fig.4-4. Since $v(T) = 0$ the $a(t)$ of Fig.4-4 would require that $v(t) < 0$ for some $t < T$.

Since $I(T)$ is monotonic decreasing, as previously shown, the optimum acceleration waveform is obtained by choosing $T = 3D/V_O$. This yields the motion given by

$$\begin{aligned} a(t) &= \frac{2}{9}\frac{V_O^3}{D^2}\left[t - \frac{3D}{V_O}\right] \\ v(t) &= \frac{1}{9}\frac{V_O^3}{D^2}\left[t - \frac{3D}{V_O}\right]^2 \qquad (4\text{-}10) \\ x(t) &= \frac{1}{27}\frac{V_O^3}{D^2}\left[t - \frac{3D}{V_O}\right]^3 + D \end{aligned}$$

for $0 \leq t \leq 3D/V_O$ as shown in Fig.4-5. Upon substitution of $T = 3D/V_O$ into Eq.(4-9) the integral I becomes

$$I = \frac{4}{9}\frac{V_O^3}{D}$$

It is noted that the minimizing function for the motion constrained by $v(t) \geq 0$ for $(0,T)$ has not been obtained. Rather the minimizing function for the unconstrained problem has been found and the result has been modified to

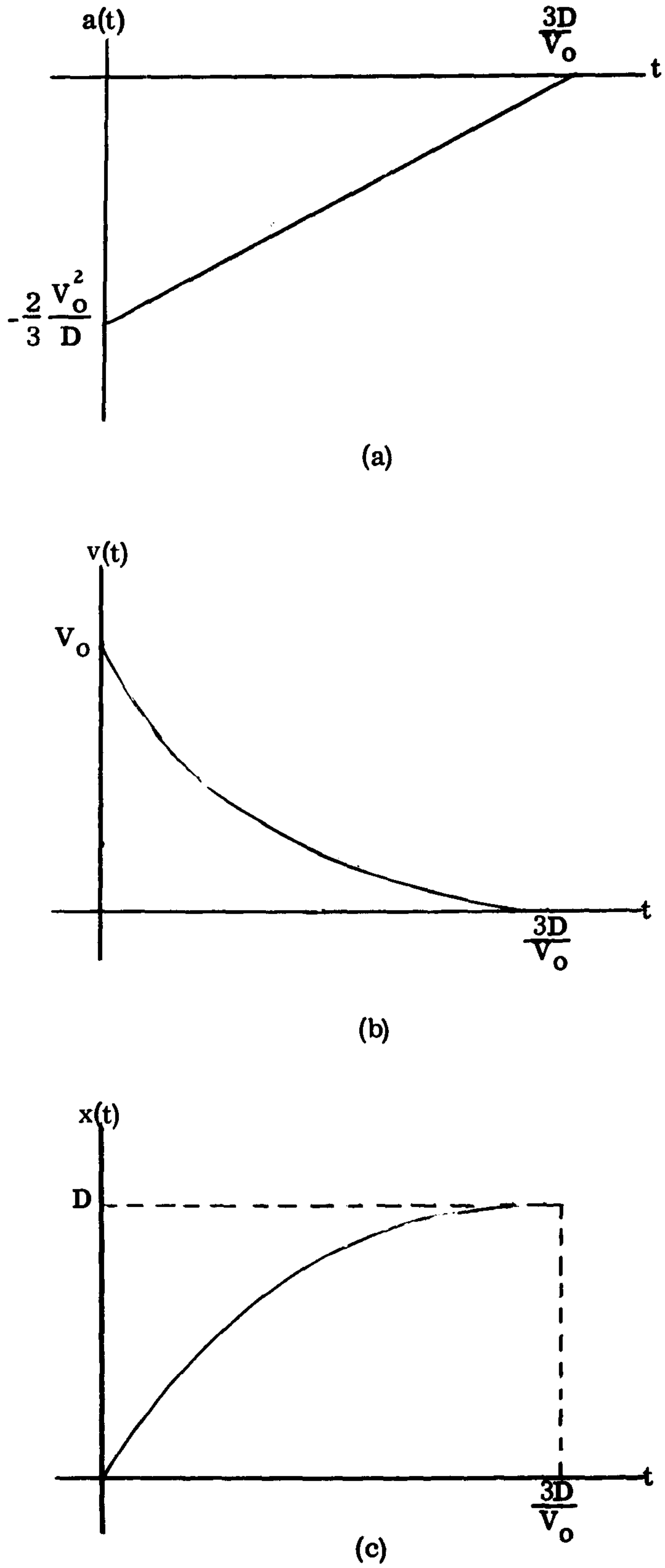


Fig. 4-5 Optimal motion: (a) acceleration, (b) velocity, (c) position

assure $v(t) \geq 0$ for $(0,T)$. The inclusion of such a constraint in the problem would make it impossible to find the solution by other than numerically based methods. However the result does yield a smaller value of I than any other function that is restricted to the interval $(0, 3D/V_o)$. Furthermore, as will be explained, there are reasons for believing that the solution obtained is also the solution to the constrained problem.

When the acceleration is assumed to be constant in $(0, T)$ then the solution satisfying the initial and final conditions on spacing and speed is $a(t) = -V_o^2/2D$ for $0 \leq t \leq 2D/V_o$. For the constant acceleration case it is found that $I = V_o^3/2D$. When the acceleration is assumed piecewise constant over two equal intervals of time then the solution that minimizes I and has $v(t) \geq 0$ for all t can be shown to yield $I = \frac{25}{54} V_o^3/D$. In addition an exponential acceleration, with time-constant D/V_o requiring infinite time, yields $I = V_o^3/2D$. These solutions are sketched in Fig.4-6 and summarized in Table 4-1. For comparison the ramp acceleration and the piecewise constant acceleration are shown on the same graph.

The fact that the piecewise constant acceleration curve closely follows the ramp acceleration curve supports the contention that the ramp acceleration is the minimizing function. It is expected that if a piecewise constant acceleration having three intervals were assumed, the resulting waveform that minimizes the integral I would more closely follow the ramp.

For the first problem posed of a vehicle decelerating from V_o to V_f while its spacing to a downstream car changes from S_o to S_f, the solution

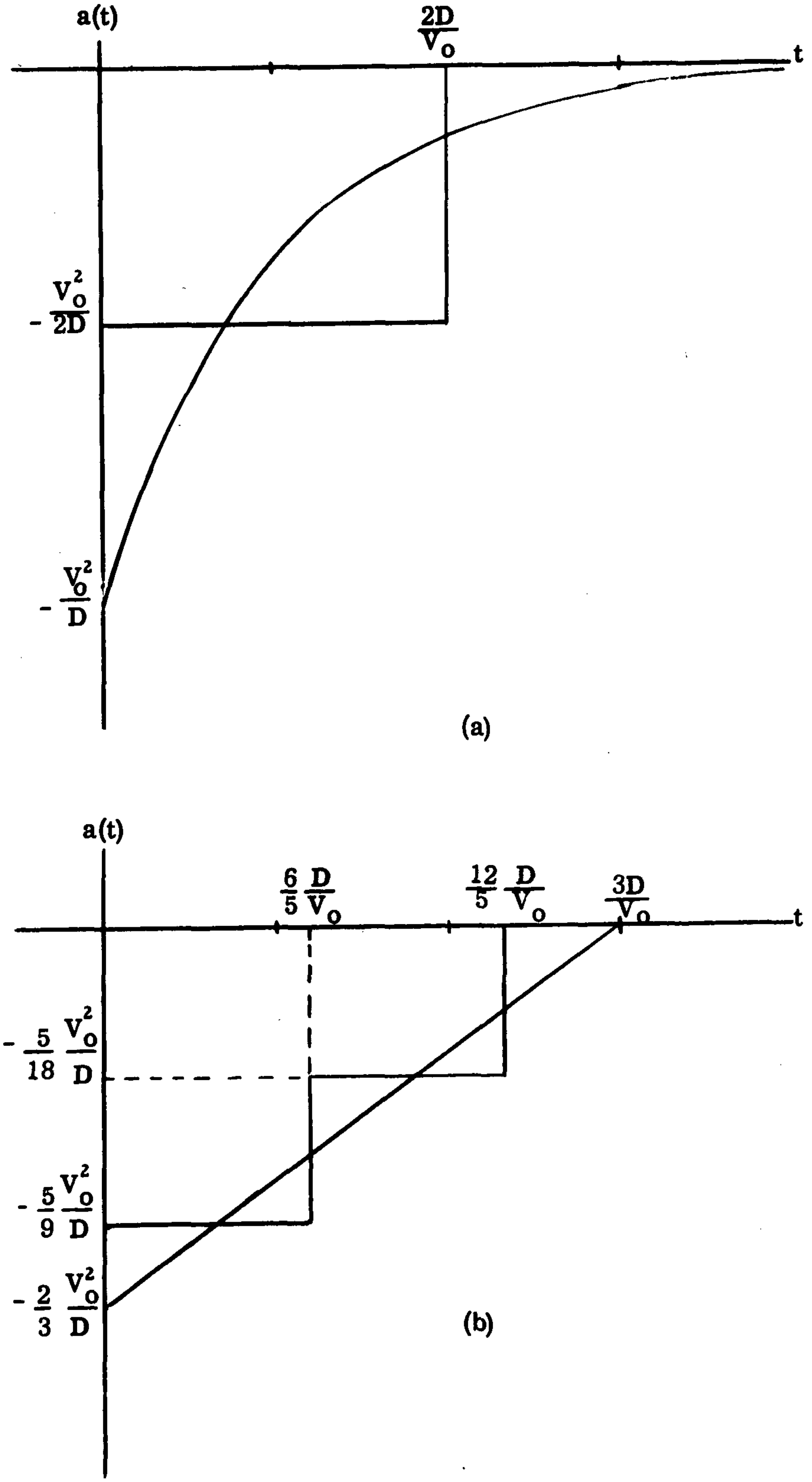


Fig. 4-6 Acceleration waveforms for optimal and sub-optimal solutions

Table 4.1 - Value of the Integral I for Optimal and Sub-optimal Waveforms

Acceleration Waveform	Time Duration	I	I/I_{ramp}
exponential	∞	$\frac{1}{2} V_o^3/D$	1.125
constant	$2D/V_o$	$\frac{1}{2} V_o^3/D$	1.125
piecewise constant	$\frac{12}{5} D/V_o$	$\frac{25}{54} V_o^3/D$	1.042
ramp	$3D/V_o$	$\frac{4}{9} V_o^3/D$	1.0

analogous to Eqs.(4-10) is found to be

$$a(t) = -\frac{2}{9}\frac{(\Delta V)^3}{(\Delta S)^2}\left[t - \frac{3\Delta S}{\Delta V}\right]$$

$$v(t) = -\frac{1}{9}\frac{(\Delta V)^3}{(\Delta S)^2}\left[t - \frac{3\Delta S}{\Delta V}\right]^2 + V_f$$

$$x(t) = -\frac{1}{27}\frac{(\Delta V)^3}{(\Delta S)^2}\left[t - \frac{3\Delta S}{\Delta V}\right]^3 + V_f t - \Delta S$$

for $0 \leq t \leq 3\Delta S/\Delta V$ and where $\Delta V = V_f - V_o$ and $\Delta S = S_f - S_o$. For this motion the integral I is

$$I = \frac{4}{9}\frac{(\Delta V)^3}{\Delta S}$$

For the constant deceleration case the problem is posed as follows. Given two vehicles (not necessarily consecutive) having initial speeds $v_1(0) = V_f$ and $v_2(0) = V_o$ and initial spacing $x_1(0) - x_2(0) = S_o > 0$ and given that $v_1(t) = V_f$ = constant. Find the constant acceleration, A, of the second vehicle in the interval (0, T) that satisfies $v_2(T) = V_f$ and $x_1(T) - x_2(T) = S_f$.

To achieve the desired speed change, $V_f - V_o$, it is required that $A = (V_f - V_o)/T$. Since $a_2(t) = A$ = constant, the speed $v_2(t)$ is a ramp function as shown in Fig.4-7. The negative of the shaded area equals the change in spacing. Thus $S_f - S_o = \frac{1}{2}T(V_f - V_o)$ and hence

$$T = 2(S_f - S_o)/(V_f - V_o).$$

Substituting this value of T in the expression for A gives the result

$$A = \tfrac{1}{2}(\Delta V)^2/(\Delta S) \qquad \text{for } 0 \leq t \leq T$$

$$T = 2(\Delta S)/(\Delta V)$$

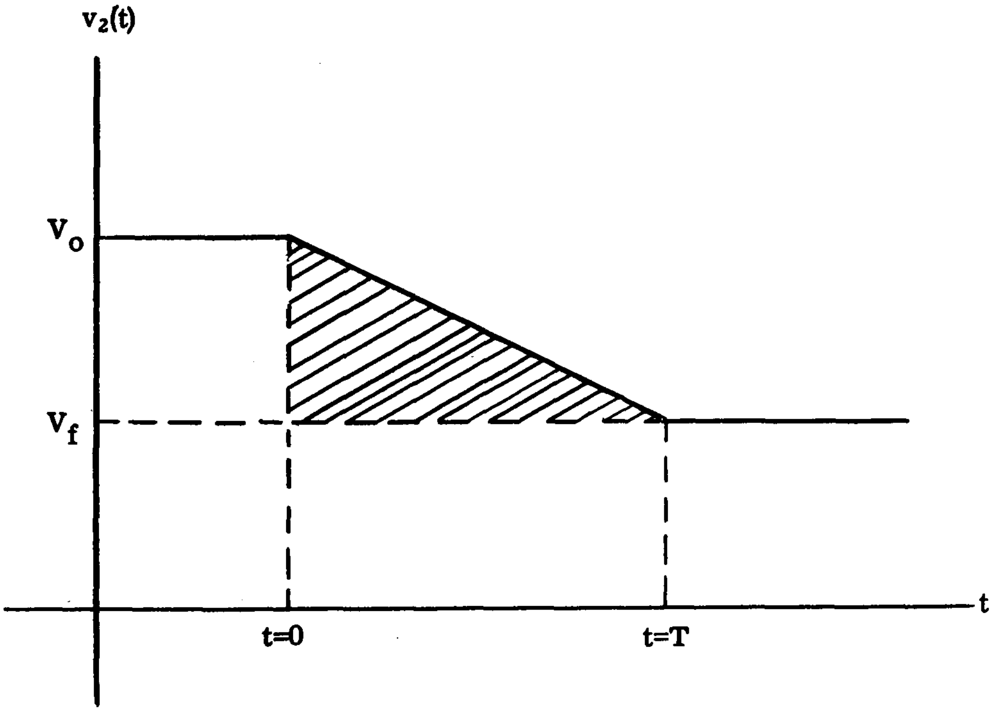


Fig. 4-7 **Speed of following vehicle for constant deceleration case**

where $\Delta V = V_f - V_o$ and $\Delta S = S_f - S_o$. The integral I for this case becomes

$$I = \tfrac{1}{2}(\Delta V)^3/(\Delta S)$$

It is noted that for the ramp acceleration there are an infinite number of solutions that satisfy the initial and final conditions while for the constant acceleration the solution is unique.

As shown in Table 4-1 the waveforms considered yield values of I not substantially different from the minimum value obtained for the ramp function. For this reason and for reasons of mathematical tractability the constant acceleration waveform is chosen for the sign control application. The same methods to be used could also be employed with the ramp function with the only difference being a substantial increase in program complexity.

4.3 The Sign Control Algorithm as Applied to a Simple Highway Situation

Assumptions It is assumed that the simple highway situation exists in which a line of vehicles are initially all traveling at speed V_o although at different spacings. The sequence of detectors spanned by these vehicles all register the speed V_o. It is assumed that the lead vehicle then decelerates to V_f and some time later passes a detector where the decrease in speed is registered.

At the next analysis time the settings for the advisory signs are computed on the basis of existing traffic conditions. These settings are valid for only 5 seconds after which time conditions are re-evaluated to determine new sign settings.

The basis for determing the sign settings is the temporary assumption that all vehicles upstream of the lead vehicle will eventually be forced to decelerate to V_f. The desired deceleration for these vehicles has previously been determined to be a constant given by $A_d = \frac{1}{2}(\Delta V)^2/(\Delta S)$ over an interval of time $T = 2(\Delta S)/(\Delta V)$. The approach used is to determine the sign settings such that the average deceleration due to the sign equals the desired deceleration for vehicles traversing an entire section under sign control.

Therefore to determine the advisory speed setting for the i-th sign, attention is focused on an imaginary vehicle located at the (i-1)-th detector that is 0.1 mile upstream of the i-th sign. It is this vehicle that responds to the initial setting of the i-th sign during the first 5 secs. of its journey on the i-th section.

The desired deceleration of the imaginary vehicle, A_d, will be expressed in terms of the measured section speeds and densities. This car's predicted average deceleration, A_a, will be derived from an assumed sign-following law as a function of its speed when entering the section and the speed setting of the advisory sign located at the next section boundary. Equating A_d to A_a will yield the solution for the advisory sign setting in terms of the detector outputs.

Computation of Desired Deceleration A section of highway is depicted in Fig.4-8. The vertical delineators indicate the detector locations, spaced by 0.1 mile. The k-th detector stores VD_k, the velocity of the vehicle most recently passing the detector, and ND_k, the number of vehicles currently on the k-th section of roadway. The advisory signs are also spaced by 0.1 mile and the speed setting is represented as V_{s_i} for the i-th sign.

In accordance with the simple highway situation previously described it is assumed that at a particular sampling time $VD_j = V_f$ and all other upstream detectors register $VD_k = V_o$, where $V_f < V_o$.

To determine the speed setting for the i-th sign it is necessary that the desired deceleration of an imaginary vehicle located 0.1 mile upstream of sign i be expressed in terms of the detector outputs. The desired deceleration for this vehicle is

$$A_d = \tfrac{1}{2}(\Delta V)^2/(\Delta S) \qquad (4\text{-}11)$$

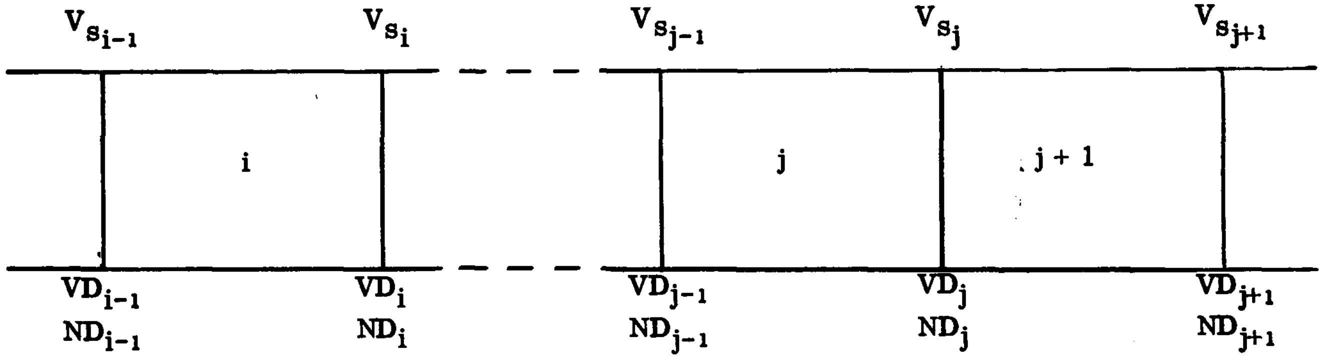


Fig.4-8 Representation of highway and location of detectors

for an interval of time $T = 2(\Delta S)/(\Delta V)$ where $\Delta V = V_f - V_o$ is the difference between the final speed after a slowdown and the initial speed and $\Delta S = S_f - S_o$ is the difference between final and initial spacings from the vehicle initiating the slowdown.

In this example the initial speed is $V_o = VD_{i-1}$ and the final speed is $V_f = VD_j$ so that

$$\Delta V = V_f - V_o = VD_j - VD_{i-1} \tag{4-12}$$

It is assumed that the vehicle that initiated the slowdown has just passed detector j. Thus the initial spacing equals the distance between detector i-1 and detector j, that is

$$S_o = 528\,(j - i + 1) \quad \text{feet} \tag{4-13}$$

The final spacing between the imaginary vehicle currently at detector i-1 and the vehicle assumed to be initiating the slowdown is determined from the number of vehicles between them and by the final speed. At the conclusion of the slowdown it is desired that each vehicle be at the spacing appropriate to its new speed. For the i-th vehicle this desired spacing is

$$\begin{aligned} DD_i &= HDRV_i \times V_f + 20 \\ &= HDRV_i \times VD_j + 20 \quad \text{feet} \end{aligned}$$

where $HDRV_i$ is the headway factor generated for the i-th vehicle.

The ND_k vehicles in section k initially occupy 528 feet. After the slowdown they will occupy less space. For these vehicles the sum of their desired final spacings to the front bumper of the car ahead is expressed as

$$S_f(k) = \sum_{i=1}^{ND_k} (HDRV_i \times VD_j + 20) = 20\,ND_k + VD_j \sum_{i=1}^{ND_k} HDRV_i \qquad (4\text{-}14)$$

where the sum is over the ND_k vehicles on the section. Since these vehicles initially occupied a 528 foot section

$$528 = \sum_{i=1}^{ND_k} (HDRV_i \times v_i + 20) = 20\,ND_k + \sum_{i=1}^{ND_k} HDRV_i \times v_i \qquad (4\text{-}15)$$

where v_i is the initial speed of the i-th vehicle. The v_i are approximated by the estimated average section speed, V_k, determined from the detectors at the section boundaries to be

$$V_k = (VD_{k-1} + VD_k)/2 \qquad (4\text{-}16)$$

Replacing v_i in Eq.(4-15) by V_k from Eq.(4-16) gives

$$528 = 20\ ND_k + V_k \sum_{i=1}^{ND_k} HDRV_i \qquad (4\text{-}17)$$

From Eq.(4-17)

$$\sum_{i=1}^{ND_k} HDRV_i = \frac{528 - 20\,ND_k}{V_k} \qquad (4\text{-}18)$$

Substituting from Eq.(4-18) into Eq.(4-14) gives

$$S_f(k) = 20\,ND_k + \frac{VD_j}{V_k}(528 - 20\,ND_k) \qquad (4\text{-}19)$$

or, using Eq.(4-16),

$$S_f(k) = 20\,ND_k + \frac{2\,VD_j}{VD_{k-1} + VD_k}(528 - 20\ ND_k) \qquad (4\text{-}20)$$

Thus the desired cumulative final spacing for the vehicles initially on sections i through j is

$$S_f = \sum_{k=i}^{j} S_f(k) \tag{4-21}$$

Substitution of the derived quantities into Eq.(4-21) gives, from Eq.(4-11),

$$A_d = \frac{1}{2} \frac{(VD_j - VD_{i-1})^2}{\sum_{k=i}^{j} \left[20\, ND_k + \frac{2\, VD_j}{VD_{k-1} + VD_k} (528 - 20\, ND_k) \right] - 528(j-i+1)} \tag{4-22}$$

This is the desired acceleration for a vehicle traversing the i-th section in response to a slowdown detected at the j-th detector.

Predicted Average Deceleration from Sign-following Model The average deceleration of a vehicle over a section of highway in response to a sign is determined from the sign-following model employed to represent the dynamic response. Knowledge of car-following theory leads to a realistic sign-following model in the form of a stimulus-response equation. The sign-following model chosen is given by

$$\dot{v}(t) = \beta[V_s - v(t - \tau_s)] \tag{4-23}$$

The response is the acceleration at the current time and the stimulus is the difference between V_s, the speed indication of the sign that the driver sees at time $t-\tau_s$ and $v(t-\tau_s)$, the vehicle's speed at $t-\tau_s$.

To facilitate further analysis of the model in order to obtain a sign setting algorithm the model is modified to become

$$\dot{v}(t) = \begin{cases} \beta[V_s - v(t-\tau_s)] & \text{for } t \geq \tau_s \\ 0 & \text{for } t < \tau_s \end{cases} \tag{4-24}$$

This modification has little effect on the dynamics of the response since in most cases the quantity $\dot{v}(t)$ is small for $0 \leq t \leq \tau_s$ because near the end of the previous section of highway the vehicle's speed will be nearly equal to the setting of the previous sign.

Values of β and τ_s are chosen to be equal to the corresponding parameters in the analogous car-following law for a very conservative driver. From data in Table I of Helly's paper[23] a reasonable choice is $\beta = 0.2\ \text{sec}^{-1}$, $\tau_s = 2.0$ sec.

The average deceleration of a vehicle traversing section i under control of the i-th sign may be found from Eq.(4-24) if the initial condition on the vehicle's speed, $v(0)$, and the speed setting of the sign, V_s, are known.

However for a given initial speed it is desired to find the value of V_s that yields a specified average acceleration. By an iterative procedure the value of V_s can be found that yields the specified average acceleration. Although this procedure may be readily implemented on a digital computer, a more direct solution for V_s would save substantial computation time. To this end an approximate solution is developed.

Let $v(0) = V_o$ and introduce the normalization

$$r(t) = \frac{v(t) - V_o}{V_s - V_o} \qquad (4\text{-}25)$$

into Eq.(4-24) yields the differential equation

$$\dot{r}(t) = \beta[1 - r(t-\tau)] \qquad (4\text{-}26)$$

where τ stands for τ_s and

$$r(0) = 0$$

$$r(\infty) = 1$$

The solution of Eq.(4-26) is of the form

$$r(t) = f(\beta, \tau, t)$$

independent of V_o and V_s with $f(\beta, \tau, 0) = 0$ and $f(\beta, \tau, \infty) = 1$. Thus, from Eq.(4-25),

$$v(t) = (V_s - V_o)\, f(\beta, \tau, t) + V_o \tag{4-27}$$

as is verified by the solution of Eq.(4-24) found by Laplace transform techniques to be

$$v(t) = \begin{cases} V_o & \text{for } 0 \le t \le \tau_s \\ V_o + (V_o - V_s) \displaystyle\sum_{k=1}^{[t/\tau_s]} (-\beta)^k \frac{1}{k!}(t - k\tau_s)^k & \text{for } \quad t > \tau_s \end{cases} \tag{4-28}$$

where $[t/\tau_s]$ is the largest integer in t/τ_s.

The average acceleration of a vehicle on a 528 foot section of highway is given by

$$A_a = \frac{v(T) - V_o}{T} \tag{4-29}$$

where $v(0) = V_o$ and T is the section travel time given by the solution of

$$x(T) = \int_o^T v(t)\, dt = 528$$

From Eq.(4-27)

$$v(T) - V_o = (V_s - V_o)\, f(\beta, \tau, T) \tag{4-30}$$

Typically the average speed on a section under sign control is in the range $40 < \overline{v} < 55$ mi/hr. In this range it is found that $f(\beta, \tau, T)$ varies by approximately 10 percent about a mean value. For an average speed of 55 mi/hr $T = 6.54$ sec. and $f(\beta, \tau, T) = 0.78$ while for an average speed of 40 mi/hr $T = 9.0$ sec. and $f(\beta, \tau, T) = 0.935$.

For the purpose of developing an approximation for average acceleration it is reasonable to approximate Eq.(4-30) by

$$v(T) - V_o \approx C(V_s - V_o) \tag{4-31}$$

From Eq.(4-27) an expression for the average velocity on a section is

$$\overline{v} = \frac{1}{T}\int_o^T v(t)\,dt = V_o + \left[\frac{1}{T}\int_o^T f(\beta, \tau, t)dt\right](V_s - V_o)$$

The value of $\frac{1}{T}\int_o^T f(\beta, \tau, t)dt$ varies by about 20 percent about a mean value for the typical range of T. Nevertheless a value of K is chosen that best approximates the average value of f over the typical range of T to give

$$\overline{v} \approx V_o + K(V_s - V_o)$$

Thus, the travel time on a 528 foot section is approximated by

$$T = \frac{528}{\overline{v}} \approx \frac{528}{V_o + K(V_s - V_o)} \tag{4-32}$$

Substituting the results of Eq.(4-31) and Eq.(4-32) into Eq.(4-29) gives

$$A_a \approx C_1(V_s - V_o)^2 + C_2 V_o(V_s - V_o) \tag{4-33}$$

as a reasonable form for the approximating function. Since $A_a = A_d$ in a sign control application both A_a and V_o are known. Once C_1 and C_2 are determined the quadratic equation (4-33) may easily be solved for V_s.

To determine C_1 and C_2 several hundred pairs of V_o and V_s were chosen in the range $88 \geq V_s + 40 \geq V_o \geq V_s + 4 \geq 34$. For each pair (V_o^i, V_s^i) the exact solution for average acceleration, A_T^i, was computed by the method previously outlined. The values of C_1 and C_2 were determined that minimize the squared error

$$\epsilon^2 = \sum_{i=1}^{N} (A_T^i - A_a^i)^2$$

where A_a^i is the approximation given by Eq.(4-33) for the i-th pair (V_o^i, V_s^i). The resulting approximation is

$$A_a \approx 0.000452\,(V_o - V_s)^2 + 0.001581\,V_o(V_s - V_o) \qquad (4\text{-}34)$$

with an average absolute error of 5.23 percent.

By trying other approximating functions it is found that the choice

$$A_a = -0.00087(V_o^2 - V_s^2) \qquad (4\text{-}35)$$

gives a slightly larger squared error than Eq.(4-34) and a slightly smaller average absolute error of 4.95 percent. Since Eq.(4-35) is algebraically simpler than Eq.(4-34), it is chosen for the sign control application.

When applying Eq.(4-35) to the setting of the i-th sign, $V_o = VD_{i-1}$ and $V_s = V_{s_i}$ yielding

$$A_a = -0.00087\,(VD_{i-1}^2 - V_{s_i}^2) \qquad (4\text{-}36)$$

for the predicted average acceleration of a vehicle traversing section i under control of the i-th sign.

Solution for Sign Setting Expressions for the desired average acceleration, A_d, and the predicted average deceleration, A_a, have been obtained. The value of the setting for the i-th sign, V_{s_i}, is found by equating A_d from Eq.(4-22) to A_a from Eq.(4-36) with $V_s = V_{s_i}$. The solution for V_{s_i} is

$$V_{s_i} = \left\{ VD_{i-1}^2 + \frac{575(VD_j - VD_{i-1})^2}{\sum_{k=i}^{j} \left[20\, ND_k + \frac{2VD_j(528-20ND_k)}{VD_{k-1} + VD_k} \right] - 528(j-i+1)} \right\}^{\frac{1}{2}} \qquad (4\text{-}37)$$

where VD_j is the speed indication of the downstream detector that is temporarily assumed to equal the final velocity of the upstream vehicles after the slowdown.

Rounding of Sign Settings For practical reasons the sign-settings are rounded to the standard 5 mi/hr increments. In addition, a sign is not turned on if only a minor response to the calculated setting is anticipated.

After computing the exact sign settings via Eq.(4-37) each sign is examined and those that are off are skipped. If the i-th sign is on, it is then ascertained whether a significant response is expected to the sign setting. If $VD_{i-1} - V_{s_i} \leq 2.5$ mi/hr the i-th sign is turned off. If $VD_{i-1} - V_{s_i} > 2.5$ mi/hr the sign setting, V_{s_i}, is rounded to the nearest 5 mi/hr. If, for the rounded sign setting, the quantity $VD_{i-1} - V_{s_i} \leq 2.5$ mi/hr the sign is turned off. If $VD_{i-1} - V_{s_i} > 2.5$ mi/hr, for the rounded value, then the rounded value is retained as the current sign setting.

Example of Sign Settings for a Simple Highway Situation An example from a simulation run with 80 vehicles is presented. All vehicles enter the roadway at a speed of 50 mi/hr and continue at this constant speed until t = 120 sec. At this time the first vehicle decelerates to 35 mi/hr at a rate of -3.0 ft/sec^2.

At t = 125 sec. the slowdown is detected and one sign is set; at t = 130 sec. two signs are set; and at t = 135 sec. five signs are set. The situation at t = 135 sec. is examined in more detail.

The detector information available at t = 135 sec. is shown tabulated below. The value of VD(I) is rounded to the nearest integer.

I	ND (I) (vehicles)	VD (I) (mi/hr)
11	4	50
12	5	50
13	5	50
14	5	50
15	3	48
16	4	46
17	4	35
18	6	34
19	2	--

From several computer runs it is found that the acceleration noise is minimum when the constant 575.0 in Eq.(4-37) is replaced by a constant between 600.0 and 625.0. For the example under consideration this constant is taken to be 625.0. Consequently the appropriate equation for determining the setting of the i-th sign due to a slowdown detected at VD_j is

$$V_{s_i} = \left\{ VD_{i-1}^2 + \frac{625.0(VD_j - VD_{i-1})^2}{\sum_{k=i}^{j} \left[20ND_k + \frac{2VD_j(528-20ND_k)}{VD_{k-1}+VD_k} \right] - 528(j-i+1)} \right\}^{\frac{1}{2}} \qquad (4\text{-}38)$$

The data from several simulations indicate that it is preferable not to set the sign that is located directly at the point where the slowdown is detected. It is found that the setting of this sign often retards vehicles in recovering from a slowdown after the vehicle causing the slowdown increases its speed. Therefore in this example sign 18 is skipped.

In determining the exact setting (before rounding) for sign 17 the appropriate values to substitute into Eq.(4-38) are

$j = 18$

$i = 17$

$VD_{16} =$ 66.9 ft/sec (46 mi/hr)

$VD_{17} =$ 50.9 ft/sec (35 mi/hr)

$VD_{18} =$ 50.4 ft/sec (34 mi/hr)

$ND_{17} = 4$

$ND_{18} = 6$

Substituting these values into Eq.(4-38) gives $V_{s_{17}} = 44.0$ ft/sec for the setting of sign 17.

To determine the exact setting for sign 14, for example, the values $j = 18$ and $i = 14$ should be used in Eq.(4-38). The value $j = 18$ should be used in finding V_{s_i} for all values of i less than j.

In the manner described above the exact settings of the other upstream signs are determined as shown tabulated below. The results of the rounding algorithm are also tabulated.

Sign Number	Speed Setting (ft/sec)	Speed Setting (mi/hr)	Rounded Setting (mi/hr)
17	44.0	30.0	30
16	60.0	40.9	40
15	66.1	45.1	45
14	68.3	46.5	45
13	69.4	47.3	45
12	70.2	47.9	OFF

It is noted that sign 12 is turned off because $VD_{11} - V_{s_{12}} = 50.0 - 47.9 = 2.1$ mi/hr is less than 2.5 mi/hr. That is, the sign is not turned on because the vehicle 528 ft upstream of the sign is traveling at a speed only slightly greater than the computed sign setting.

4.4 Application of Sign Control to a General Highway Situation

Introduction In the simplified highway situation previously described, the speed indications of the detectors are monotone decreasing in the downstream direction. This is intended to represent only an isolated component of the traffic pattern on an actual highway.

Sampling of the detector speed outputs at a random time generally yields a speed profile exhibiting peaks and valleys. A typical case is shown in Fig. 4-9.

General Procedure for Sign Setting The heuristic procedure for determining the sign settings is described for a typical case for which VD(I) are as shown in Fig. 4-9. The detector speed outputs VD(I) are scanned, starting at VD(7), to locate the first "local minimum" (LM). A local minimum occurs at detector K if both

$$VD(K-1) > VD(K)$$

$$VD(K+1) \geq VD(K)$$

at satisfied. The three local minima are identified by arrows on Fig. 4-9.

The first LM in Fig. 4-9 is VD(10). Sign 10 is not set since it is located at the local minimum. Sign settings for signs 9 and 8 are determined from Eq.(4-38) using $j = 10$ and the appropriate values for VD and ND. That is, V_{S_9} and V_{S_8} are computed on the basis of the LM of VD(10). Sign 9 is set to 65.9 ft/sec and sign 8 is set to 68.7 ft/sec.

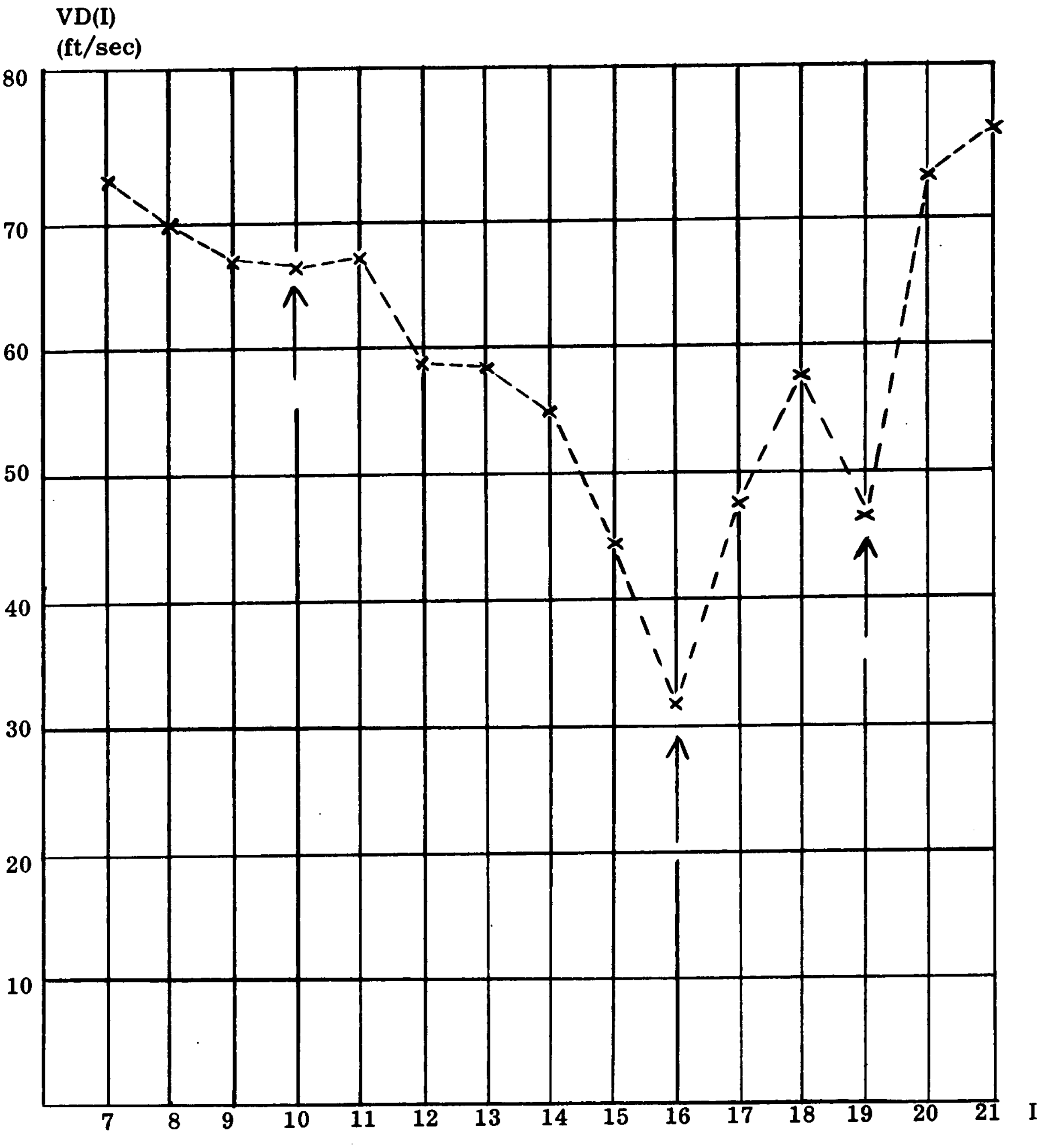


Fig. 4-9 Detector Speed Outputs for a Typical Case

The scan is continued and the second LM is found to be VD(16). Sign 16 is not set due to this local minimum because the LM occurs at the location of this sign. Signs 15 back through 8 are now considered on the basis of a slowdown assumed to originate from the second LM of VD(16). Thus, using the value $j = 16$ in Eq.(4-38), the computed settings (ft/sec) for signs 15 back through 10 are

$$V_{s_{15}} = 38.5$$

$$V_{s_{14}} = 48.2$$

$$V_{s_{13}} = 51.9$$

$$V_{s_{12}} = 59.6$$

$$V_{s_{11}} = 60.8$$

$$V_{s_{10}} = 62.2$$

Sign 9 was considered previously due to the first LM of VD(10). However, since the second LM is of smaller value, a tentative setting is computed using $j = 16$. This computation yields 65.4 ft/sec. Since 65.4 is less than the previously computed setting of 65.9 it is concluded that the second LM has the stronger influence on vehicles on section 10. Hence sign 9 is reset to $V_{s_9} = 65.4$.

Similarly a tentative setting for sign 8 is computed, using $j = 16$, and the result is 69.0. Sign 8 is not reset because the previously determined setting of 68.7 ft/sec is less than 69.0.

The third LM is found at VD(19). Sign 19 is not considered and the setting for sign 18 is found to be $V_{s_{18}} = 47.6$ using $j = 19$ in Eq.(4-38).

Sign 17 is not considered because VD(16) is less than the speed at the third LM of VD(19). Thus, cars on section 17 will not be forced to decelerate due to the LM of VD(19). For the same reason sign 16 is not considered.

Sign 15 has been previously considered due to a LM further upstream of smaller value, i.e. VD(16). For this reason the setting of sign 15 is considered to be valid. Furthermore, additional scanning of signs further upstream due to this LM is suppressed and the search for the next LM is initiated.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

5.1 Prefatory Remarks

This chapter concludes the study of the proposed advisory speed sign system by (1) presenting the numerical results from the computer simulation program, (2) analyzing and interpreting these results, and (3) assessing the potential success of the system in improving the level of service afforded to drivers on an urban expressway under heavy traffic conditions.

The primary indicator of the degree of comfort and safety for a driver during his trip is the acceleration noise (see Section 4.1). The sign control algorithm has been designed to minimize this quantitative performance index. Another indicator of the improvement in the quality of traffic flow due to sign control is the total stopped time. For the main part, the utility of the system will be judged by the extent to which sign control reduces both the acceleration noise and the total stopped time.

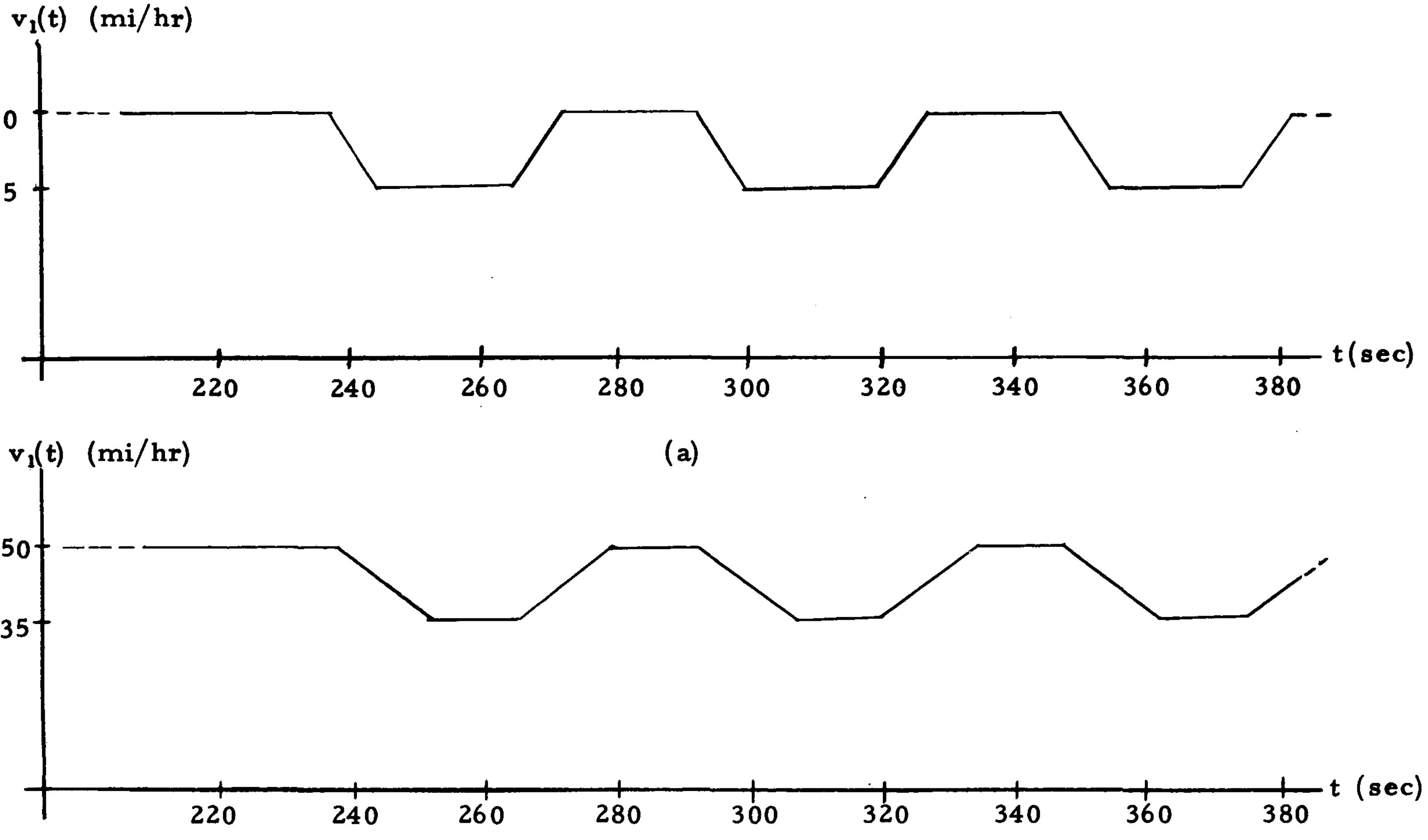
In each of the simulation runs 80 vehicles traverse an eight mile length of roadway. The 80 vehicles occupy approximately two miles of the roadway at any time.

One distinguishing characteristic of a sample population of 80 vehicles is the average headway factor associated with these drivers (see Section 3.2). The average headway factor is determined from the specified demand, D, which is an input parameter in the simulation. At a specified entering flow rate there is no typical sample of 80 vehicles from which a reliable estimate of the improvements due to sign control can be obtained. It is therefore necessary to generate several driver samples at each flow rate and to assess both the performance of the system with the individual samples and the average performance over all the samples.

The effects of sign control on acceleration noise and stopped time are obtained by comparing the results of a simulation run without sign control to those with sign control for the same driver sample. Under sign control the compliance level, which determines the fraction of drivers that heed the sign settings, is varied from 1.0 to 0.2 and the effect of non-perfect compliance is noted. The effect of the flow rate and the compliance level on the duty-cycle of the advisory signs is shown.

5.2 Maneuvers of the lead vehicle

The lead vehicle begins its maneuver shortly after all vehicles have entered the highway. The simulation has been run for two different repetitive maneuvers differing primarily in the magnitudes of the programmed decelerations and accelerations. In both maneuvers the lead vehicle undergoes a constant deceleration, from 50 mi/hr to 35 mi/hr, followed by an interval of constant speed, then a constant acceleration back to 50 mi/hr followed by an interval of constant speed. This motion is repeated with a period of 55 seconds until the vehicle reaches the end of the highway runoff section. The accelerations used in maneuver 1 are ± 3.0 ft/sec^2 whereas maneuver 2 uses ± 1.5 ft/sec^2. These maneuvers, which initiate the responses of the following vehicles, are shown in Fig.5-1.



(a)

(b)

Fig. 5-1 Lead vehicle motion (a) maneuver 1, (b) maneuver 2

5.3 Numerical Results

The results of the individual simulation runs without sign control and those with sign control at 100 percent compliance are shown in Tables 5-1 through 5-8. Each table corresponds to a particular value of demand, D.

Table 5-1, for D = 2300, shows a dramatic reduction in stopped time and acceleration noise due to sign control. The improvement is consistently high* for both lead car maneuvers and for each of the three driver samples. Maneuver 1, being more severe than maneuver 2, yields larger values of stopped time and acceleration noise both with and without sign control. The positive correlation between stopped time and acceleration noise is noted for the different driver samples. Thus, stopped time is also a correlate of the "smoothness" of flow, at least for those high values of D where the stopped time is appreciable. The duty cycle for the advisory signs is observed to vary between 26 percent and 29 percent† with the higher duty cycles associated with the runs having larger values of acceleration noise and stopped time.

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* The percent change calculations in the tables of this chapter tend to de-emphasize the improvements due to sign control. A reduction in acceleration noise from 10 to 5 is a 50% decrease whereas a change from 5 to 10 is a 100% increase.

† Since the vehicles travel at constant velocity before the lead vehicle maneuver begins, several signs near the beginning of the roadway are never set. Omitting these signs from the duty cycle calculation would increase the stated percents by about 25%.

Table 5-2, for D = 2200, similarly shows large reductions in stopped time and acceleration noise for both maneuvers and for all driver samples. However the improvements are not as dramatic as those for D = 2300 and there exists greater variability among the four driver samples.

Referring to Tables 5-3 through 5-8 it is seen that the stopped time is small for D = 2100 and essentially zero for smaller values of D both with and without sign control.

At D = 2100 the average reduction of acceleration noise is still substantial except for driver sample 3 under maneuver 2 for which the reduction is negligible. In Table 5-6, for D = 1800, it is observed that although there is an overall improvement due to sign control, three of the eight runs yield a small increase in acceleration noise.

The system's performance for different values of D is now evaluated on the basis of the percent change in stopped time and acceleration noise averaged over all driver samples for each maneuver. The average stopped time and the average acceleration noise (with and without the signs) and the average percent change* of these quantities are shown in Table 5-9 and Table 5-10 for maneuvers 1 and 2 respectively. For each value of D and for both maneuvers the simulation was run with four different driver samples, except for those few cases noted in the

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*The average percent change is the average of the percent changes for the different driver samples, not the percent change of the average quantities appearing in Tables 5-9 and 5-10.

tables where three driver samples were used.

For maneuver 1 (see Table 5-9) the decrease in stopped time is dramatic for D = 2300 and D = 2200 but essentially negligible for smaller values of D for which vehicles are not forced to stop. The decrease in acceleration noise is substantial for values of D between 2300 and 2000 and is judged to be significant for the other demand rates. The results for maneuver 2 (see Table 5-10) are similar except for the negligible reduction in acceleration noise for D = 1800 and D = 1700.

Comparison of the results for maneuvers 1 and 2 show that, with few exceptions, the entries in Table 5-9 are greater than the corresponding entries in Table 5-10. It is not surprising that the stopped time and acceleration noise are larger for maneuver 1 since it is the more severe maneuver. The fact that the average percent changes are larger for maneuver 1 leads to the conclusion that sign control is comparatively more effective for larger perturbations.

From Table 5-11 it is observed that higher values of D require a higher duty cycle. Maneuver 1 requires a higher duty cycle, on the average, than maneuver 2, although the opposite is true for D = 2200 and D = 2100.

The results presented above have been for 100% compliance, that is, when all drivers respond to the advisory sign settings. In this study it has been hypothesized that sign control improvements will not be substantially eroded under conditions of partial compliance since a driver who responds to a sign forces the following drivers to decelerate. Results for partial compliance are presented in the following discussion.

The results at various compliance levels, for maneuver 1, are presented in Tables 5-12 through 5-16 for demand rates between 2300 and 1900 vehicles per hour[†]. The improvements due to sign control at lower demands are not large enough to warrant simulation runs at intermediate compliance levels.

For D = 2300 and D = 2200 (see Tables 5-12 and 5-13) the stopped time is appreciable without sign control. Stopped time generally increases as the compliance level decreases, yet a considerable improvement is shown at the 20 percent level of compliance. At D = 2100 (see Table 5-14) the stopped time is small and its variation with compliance level follows no pattern. At lower values of D the stopped time is zero or negligible.

[†] The simulation runs without sign control and those with sign control at 100 percent compliance were made, at most of the demand rates, for each of four different driver samples. However the time required for each simulation run precluded generating results for all four driver samples at the other compliance levels.

Tables 5-12 through 5-16 also indicate how the acceleration noise changes as a function of compliance level. Table 5-12 shows that for D = 2300 there is little degradation of performance, even at the 20 percent level of compliance. At D = 2200 the compliance level has minimal effect until it falls below 40%. At lower values of demand the compliance level begins to have a significant effect at a value between 80 and 60 percent. These results are summarized in Table 5-17 which presents the percent change in acceleration noise from the condition of no sign control to the condition of sign control at various levels of compliance. These same results are graphically presented in Fig.5-2.

5-4 Recommendations for Further Study

Based on the models assumed for car following and sign following, and using the algorithm developed in Chapter 4, a significant improvement in system performance has been demonstrated by using advisory sign control. No refinements in the mathematical models can substitute for field tests. It is recommended that a prototype system be constructed and tested, in order to determine the actual level of improvements.

An important consideration for any traffic control system is whether it effects a reduction in travel time. On the simulated highway the travel time of vehicle 1 is unaffected by sign control and the travel times of the other vehicles are completely determined by their time headways at the highway terminus, being unaffected by the dynamics on intermediate sections. On an actual highway with entrances and exits at intermediate points, the travel time of an arbitrary vehicle is profoundly affected by the dynamics of the flow. For example, if a vehicle is approaching its exit and there is a temporary stoppage of traffic between this vehicle and the exit, then this stopped time directly adds to the vehicle's travel time. Thus it is expected that the ability of a sign control system to reduce stopped time in dense traffic will lead to travel time savings on an actual highway. The extent of this reduction in travel time must await a field test.

For major highway incidents such as accidents and disabled vehicles the detectors can readily provide rapid and precise location of the disruption enabling swifter corrective action and thereby decreasing the total delay incurred by upstream vehicles. In addition it is expected that the incidence of rear-end accidents under these circumstances will be substantially reduced due to the advance warning nature of the advisory signs.

Although a cost analysis of the proposed system has not been undertaken it is felt that the system is economically feasible. The Toronto intersection control system, including 1000 detectors, is projected to cost $5 million in capital outlay. Since a 16 mile length of six lane highway would use 1000 detectors, the cost of advisory sign control is estimated to be about $300,000 per mile. This is a small fraction of the cost of constructing a mile of highway in an urban area.

An accurate cost-effective analysis would involve building the system and comparing before-and-after statistics on travel time, throughput, and accidents.

Further investigations should include the effect of advisory sign and detector spacings on improvements afforded by the system. These spacings are directly related to the cost of the system.

Table 5-1 Results without sign control and with sign control at 100% compliance, for D = 2300 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(ft/sec^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change	Without Signs	With Signs	Percent Change	
1	1	328.	21.2	-93.6	38.92	14.11	-63.7	27.2
3	1	321.	18.8	-91.5	28.33	14.71	-48.2	25.2
4	1	707.	94.8	-86.6	40.85	17.58	-57.0	29.2
1	2	165.	27.8	-83.1	26.09	13.81	-47.2	25.9
3	2	199.	62.0	-68.9	26.42	14.10	-46.6	26.7
4	2	462.	49.6	-89.3	36.48	16.34	-55.2	27.6

Table 5-2 Results without sign control and with sign control at 100% compliance, for D = 2200 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(ft/sec^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change	Without Signs	With Signs	Percent Change	
1	1	58.2	9.6	-83.5	18.64	11.49	-38.4	24.5
2	1	372.	64.4	-82.7	25.13	13.99	-44.3	26.9
3	1	46.4	1.0	-97.8	16.80	11.60	-30.9	24.6
4	1	342.	84.6	-75.3	33.91	13.70	-59.6	26.5
1	2	9.8	1.0	-89.8	13.61	11.19	-17.8	24.1
2	2	407.	51.4	-87.4	32.90	13.84	-58.0	27.1
3	2	32.8	11.6	-64.6	15.28	11.61	-24.0	25.4
4	2	64.2	31.6	-50.8	18.32	13.30	-27.4	26.9

Table 5-3 Results without sign control and with sign control at 100% compliance, for D = 2100 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(ft/sec^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change †	Without Signs	With Signs	Percent Change	
1	1	0.0	2.8	-	10.51	8.742	-16.8	21.8
2	1	20.6	34.0	+65.0	16.91	10.87	-35.7	23.9
3	1	1.2	3.0	-	10.67	9.214	-13.6	22.1
4	1	41.4	19.6	-52.8	14.86	10.81	-27.3	24.6
1	2	0.0	1.2	-	9.234	8.026	-13.1	21.0
2	2	61.0	19.0	-68.9	19.40	11.052	-43.0	26.6
3	2	0.8	2.4	-	10.06	9.856	- 2.03	21.1
4	2	0.0	3.6	-	13.26	10.77	-18.8	28.1

† Missing entries in this column indicate that the change is zero or negligble and is treated as zero.

Table 5-4 Results without sign control and with sign control at 100% compliance, for D = 2000 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(\text{ft}/\text{sec}^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change †	Without Signs	With Signs	Percent Change	
1	1	0.0	0.0	-	7.564	6.554	-13.4	19.7
2	1	0.0	1.2	-	11.21	8.735	-22.0	22.4
3	1	0.0	0.0	-	8.581	8.060	-6.07	21.9
4	1	0.0	0.0	-	10.93	8.259	-24.4	22.3
1	2	0.0	0.0	-	6.583	6.217	-5.56	17.6
2	2	0.0	0.0	-	10.66	8.107	-23.9	22.3
3	2	0.0	0.0	-	8.182	7.038	-14.0	19.6
4	2	0.0	0.0	-	10.15	8.120	-20.0	24.0

† Missing entries in this column indicate that the change is zero or negligible and is treated as zero.

Table 5-5 Results without sign control and with sign control at 100% compliance, for D = 1900 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(ft/sec^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change	Without Signs	With Signs	Percent Change	
1	1	0.0	0.0	-	5.697	5.517	-3.16	18.1
2	1	0.0	0.0	-	7.843	6.974	-11.1	18.1
3	1	0.0	0.0	-	6.648	6.006	-9.66	20.1
4	1	0.0	0.0	-	7.158	6.731	-5.97	20.6
1	2	0.0	0.0	-	5.079	4.807	-5.36	15.1
2	2	0.0	0.0	-	7.299	6.306	-13.6	20.4
3	2	0.0	0.0	-	6.581	5.798	-11.9	19.5
4	2	0.0	0.0	-	7.027	6.234	-11.3	19.0

Table 5-6 Results without sign control and with sign control at 100% compliance, for D = 1800 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(ft/sec^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change	Without Signs	With Signs	Percent Change	
1	1	0.0	0.0	-	4.791	4.324	-9.75	17.2
2	1	0.0	0.0	-	5.851	6.199	+5.95	18.5
3	1	0.0	0.0	-	5.618	5.180	-7.79	16.7
4	1	0.0	0.0	-	5.603	4.939	-11.9	17.1
1	2	0.0	0.0	-	4.288	3.909	-8.84	13.2
2	2	0.0	0.0	-	5.552	5.734	+3.28	17.7
3	2	0.0	0.0	-	5.382	5.031	-6.52	16.1
4	2	0.0	0.0	-	4.851	5.009	+3.26	15.6

Table 5-7 Results without sign control and with sign control at 100% compliance, for D = 1700 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(ft/sec^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change	Without Signs	With Signs	Percent Change	
1	1	0.0	0.0	-	3.962	3.494	-11.8	15.1
2	1	0.0	0.0	-	4.911	4.917	+0.1	14.1
3	1	0.0	0.0	-	4.814	4.321	-10.2	16.7
4	1	0.0	0.0	-	4.271	4.291	+0.5	15.5
1	2	0.0	0.0	-	3.542	3.309	-6.58	13.4
2	2	0.0	0.0	-	4.654	4.803	+3.2	16.5
4	2	0.0	0.0	-	4.007	3.980	-0.7	15.5

Table 5-8 Results without sign control and with sign control at 100% compliance, for D = 1600 veh/hr

Driver Sample	Maneuver Number	Stopped Time (sec)			Acceleration Noise $(ft/sec^2)^2$			Duty Cycle with Sign Control (%)
		Without Signs	With Signs	Percent Change	Without Signs	With Signs	Percent Change	
1	1	0.0	0.0	-	3.240	2.787	-14.0	12.9
2	1	0.0	0.0	-	4.386	4.146	-5.5	15.7
4	1	0.0	0.0	-	3.629	3.364	-7.3	14.6

Table 5-9 Results without sign control and with sign control at 100% compliance, averaged over several driver samples, for maneuver 1

	Stopped Time (sec)			Acceleration Noise $(\mathrm{ft/sec}^2)^2$		
Demand D (veh/hr)	Average Without Signs	Average With Signs	Average Percent Change†	Average Without Signs	Average With Signs	Average Percent Change
2300*	418.7	44.9	-90.5	36.03	15.46	-56.3
2200	204.7	39.9	-84.8	23.62	12.70	-43.3
2100	15.8	14.9	-	13.24	9.91	-23.4
2000	0.0	0.3	-	9.57	7.90	-16.5
1900	0.0	0.0	-	6.84	6.31	-7.5
1800	0.0	0.0	-	5.47	5.16	-5.9
1700	0.0	0.0	-	4.49	4.26	-5.4
1600**	0.0	0.0	-	3.75	3.43	-8.9

* Excludes driver sample 2

** Excludes driver sample 3

† The missing entries in this column indicate that the change is zero or negligible and is treated as zero.

Table 5-10 Results without sign control and with sign control at 100% compliance, averaged over several driver samples, for maneuver 2

Demand D (veh/hr)	Stopped Time (sec)			Acceleration Noise $(\text{ft}/\text{sec}^2)^2$		
	Average Without Signs	Average With Signs	Average Percent Change †	Average Without Signs	Average With Signs	Average Percent Change
2300*	275.3	4.65	-80.4	29.66	14.75	-49.6
2200	128.4	23.9	-73.2	20.03	12.49	-31.8
2100	15.45	6.55	-17.2	12.99	9.93	-19.2
2000	0.0	0.0	-	8.89	7.37	-15.9
1900	0.0	0.0	-	6.497	5.786	-10.5
1800	0.0	0.0	-	5.018	4.921	-2.2
1700**	0.0	0.0	-	4.067	4.031	-1.4

* Excludes driver sample 2

** Excludes driver sample 3

† Missing entries in this column indicate that the change is zero

Table 5-11 Average duty cycle of advisory signs at 100% compliance

Demand D (veh/hr)	Duty Cycle (%)	
	Maneuver 1	Maneuver 2 *
2300	27.2	26.7
2200	25.6	25.9
2100	23.1	24.2
2000	21.6	20.9
1900	19.2	18.5
1800	17.4	15.7
1700	15.4	15.1
1600	14.4	-

* Maneuver 2 was not run for D = 1600

Table 5-12 Results at various compliance levels, for maneuver 1, for D = 2300†

Compliance Level (%)	Stopped Time (sec)	Acceleration Noise $(ft/sec^2)^2$	Duty Cycle (%)
100	44.9	15.46	27.2
80	82.7	15.93	27.1
60	76.3	15.72	29.2
40	74.4	16.02	28.1
20	106.6	18.53	29.5
0*	418.6	36.03	-

† Includes driver samples 1, 3, and 4

* Results for no sign control

Table 5-13 Results at various compliance levels, for maneuver 1, for D = 2200†

Compliance Level (%)	Stopped Time (sec)	Acceleration Noise $(ft/sec^2)^2$	Duty Cycle (%)
100	52.9	13.06	26.0
80	54.2	13.70	27.4
60	73.2	13.62	28.4
40	98.5	14.70	29.9
20	117.	16.81	29.6
0*	257.	25.90	-

† Includes driver samples 1, 2, and 4

* Results for no sign control

Table 5-14 Results at various compliance levels, for maneuver 1, for D = 2100 †

Compliance Level (%)	Stopped Time (sec)	Acceleration Noise $(ft/sec^2)^2$	Duty Cycle (%)
100	18.5	10.04	23.0
80	6.3	10.46	24.5
60	28.2	11.36	25.0
40	35.7	11.58	25.3
20	3.1	12.24	25.4
0 *	10.9	13.79	-

† Includes driver samples 2 and 3

* Results for no sign control

Table 5-15 Results at various compliance levels, for maneuver 1, for D = 2000†

Compliance Level (%)	Stopped Time (sec)	Acceleration Noise $(ft/sec^2)^2$	Duty Cycle (%)
100	0.4	7.62	21.3
80	1.1	7.89	20.9
60	0.0	7.86	22.4
40	0.0	8.15	20.7
20	1.9	8.28	21.8
0*	0.0	9.02	-

† Includes driver samples 1, 3, and 4

* Results for no sign control

Table 5-16 Results at various compliance levels, for maneuver 1, for D = 1900[†]

Compliance Level (%)	Stopped Time (sec)	Acceleration Noise $(ft/sec^2)^2$	Duty Cycle (%)
100	0.0	6.41	18.9
80	0.0	6.50	19.5
60	0.0	6.69	19.0
40	0.0	6.65	19.2
20	0.0	6.59	20.3
0*	0.0	6.90	-

[†] Includes driver samples 1,2, and 4

*Results for no sign control

Table 5-17 Percent change in acceleration noise due to sign control at various compliance levels, for maneuver 1

Demand D (veh/hr)	Percent Change in Acceleration Noise				
	Compliance Level				
	100%	80%	60%	40%	20%
2300	-57	-57	-58	-57	-50
2200	-50	-47	-47	-43	-35
2100	-27	-24	-18	-16	-11
2000	-16	-13	-13	-10	- 8
1900	- 7	- 6	- 3	- 4	- 4

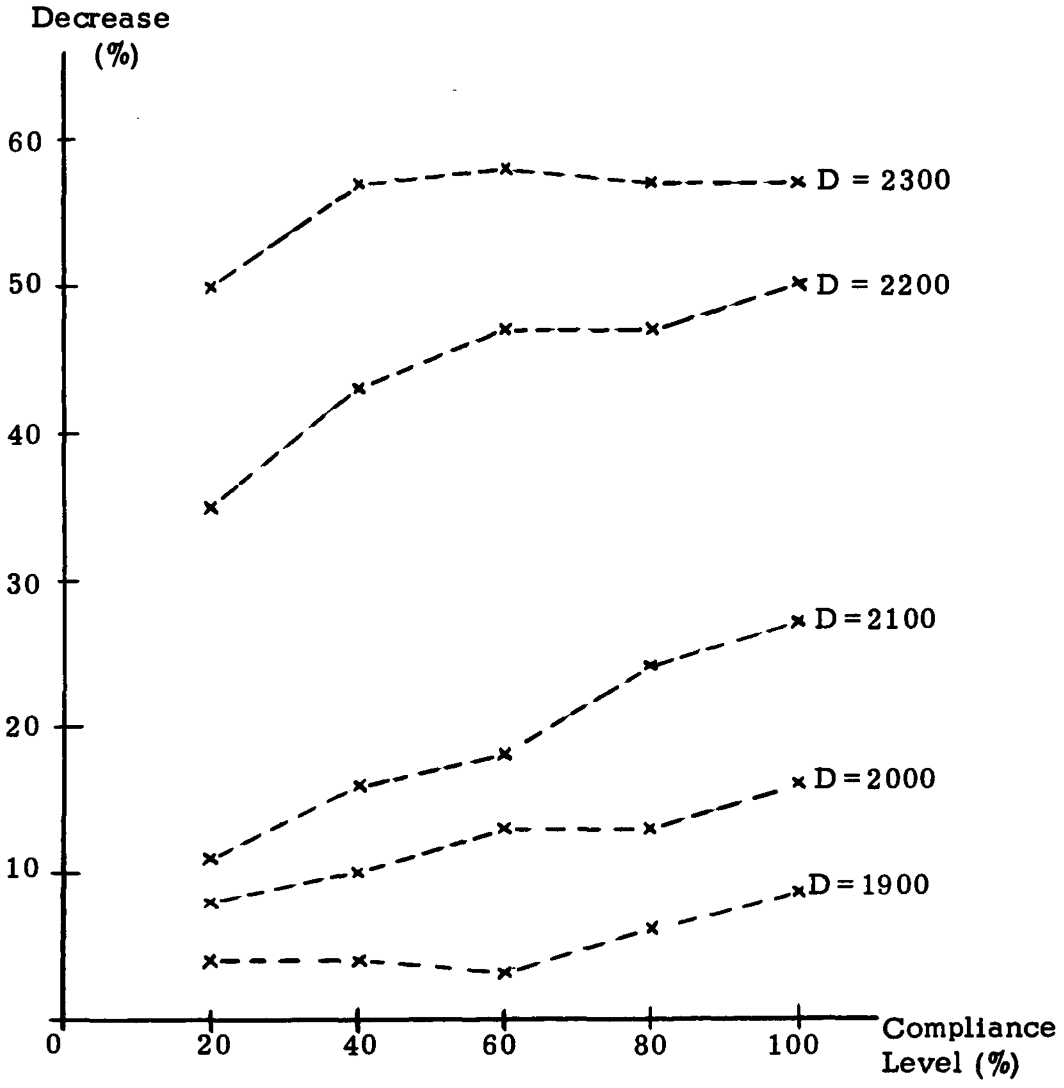
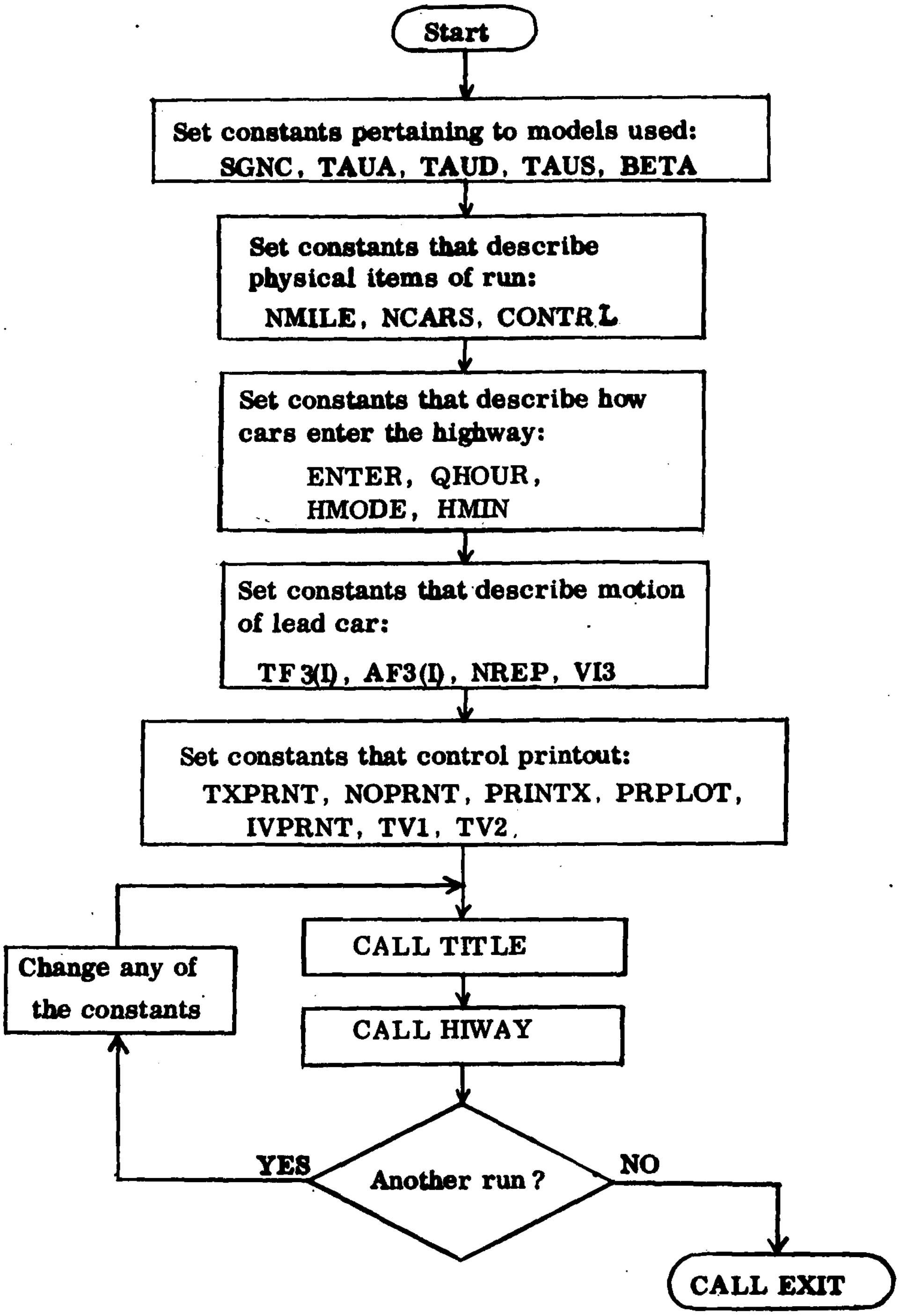


Fig.5-2 Percent decrease in acceleration noise due to sign control at various compliance levels, for maneuver 1

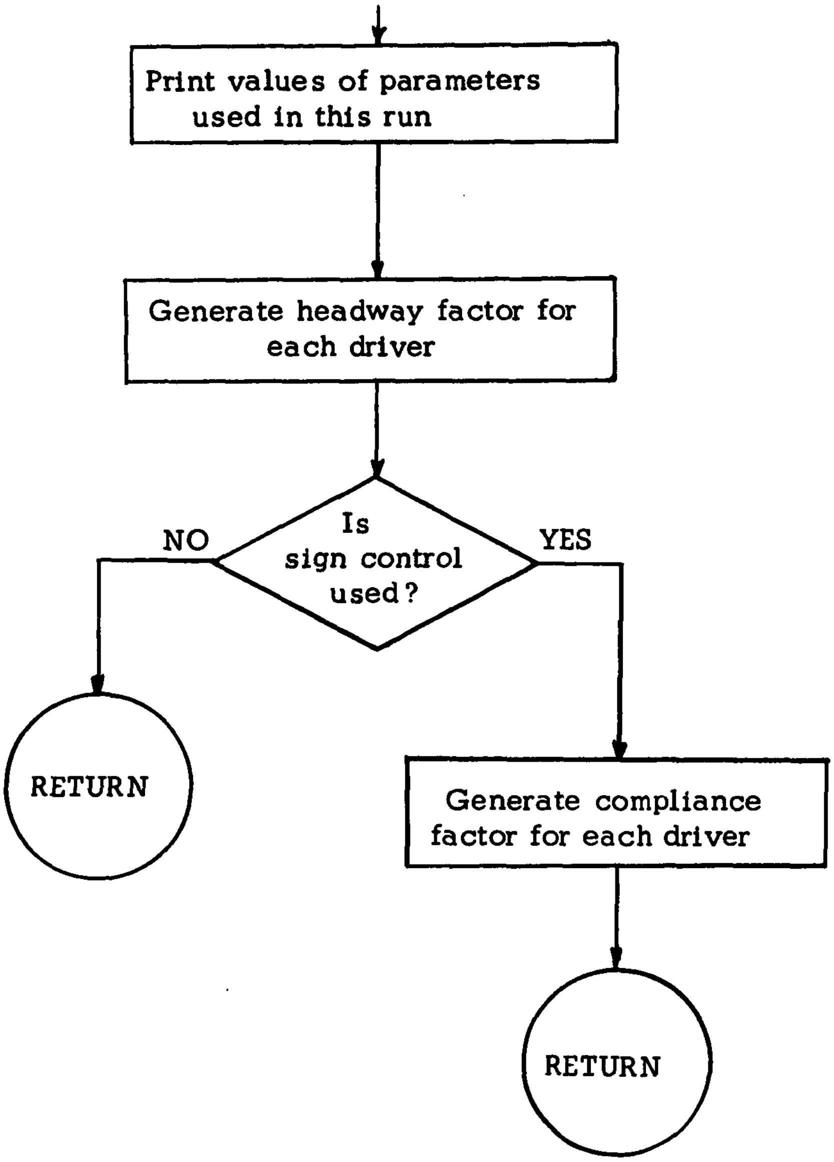
APPENDIX A

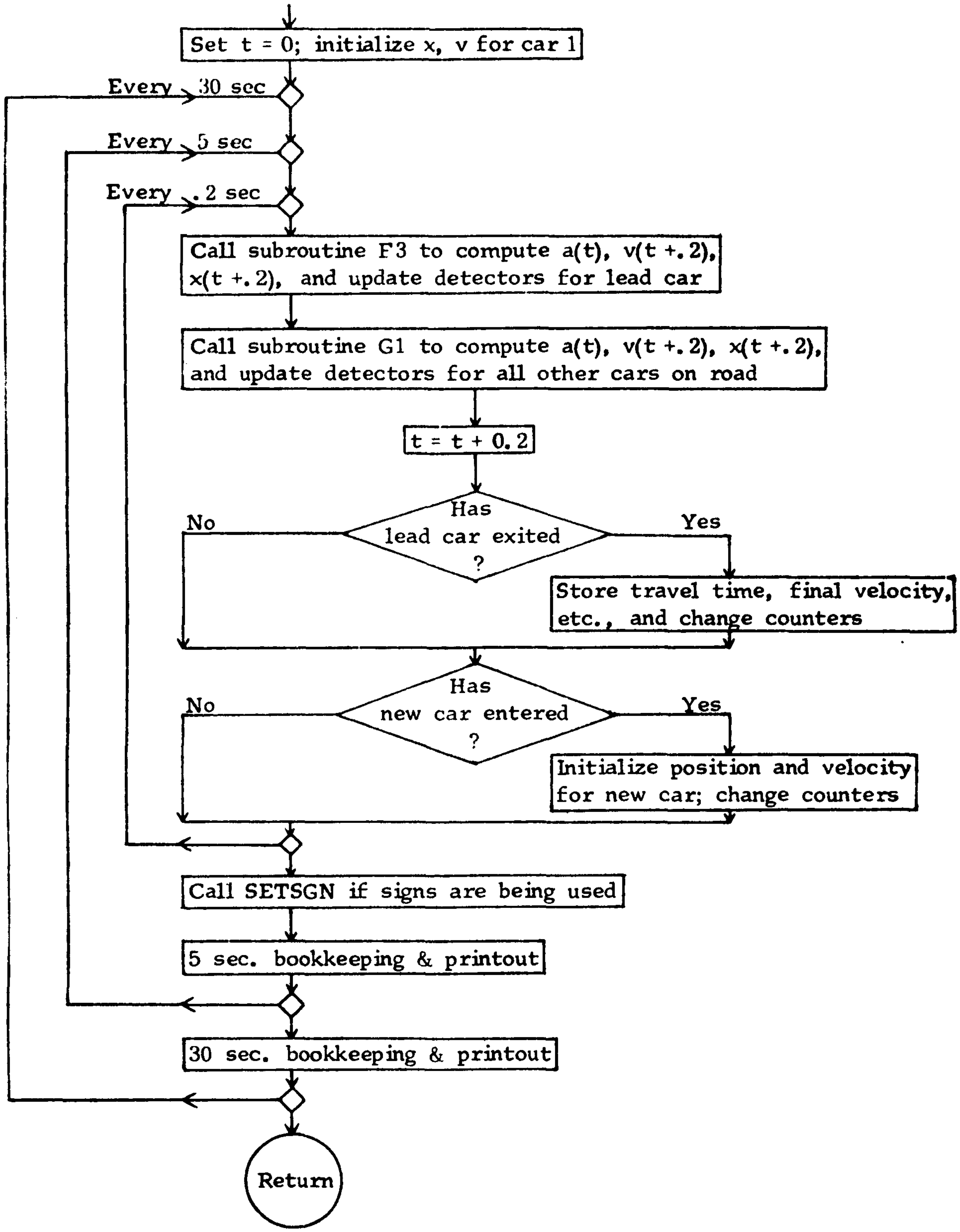
FLOW CHARTS OF THE COMPUTER SIMULATION PROGRAM

Main Program

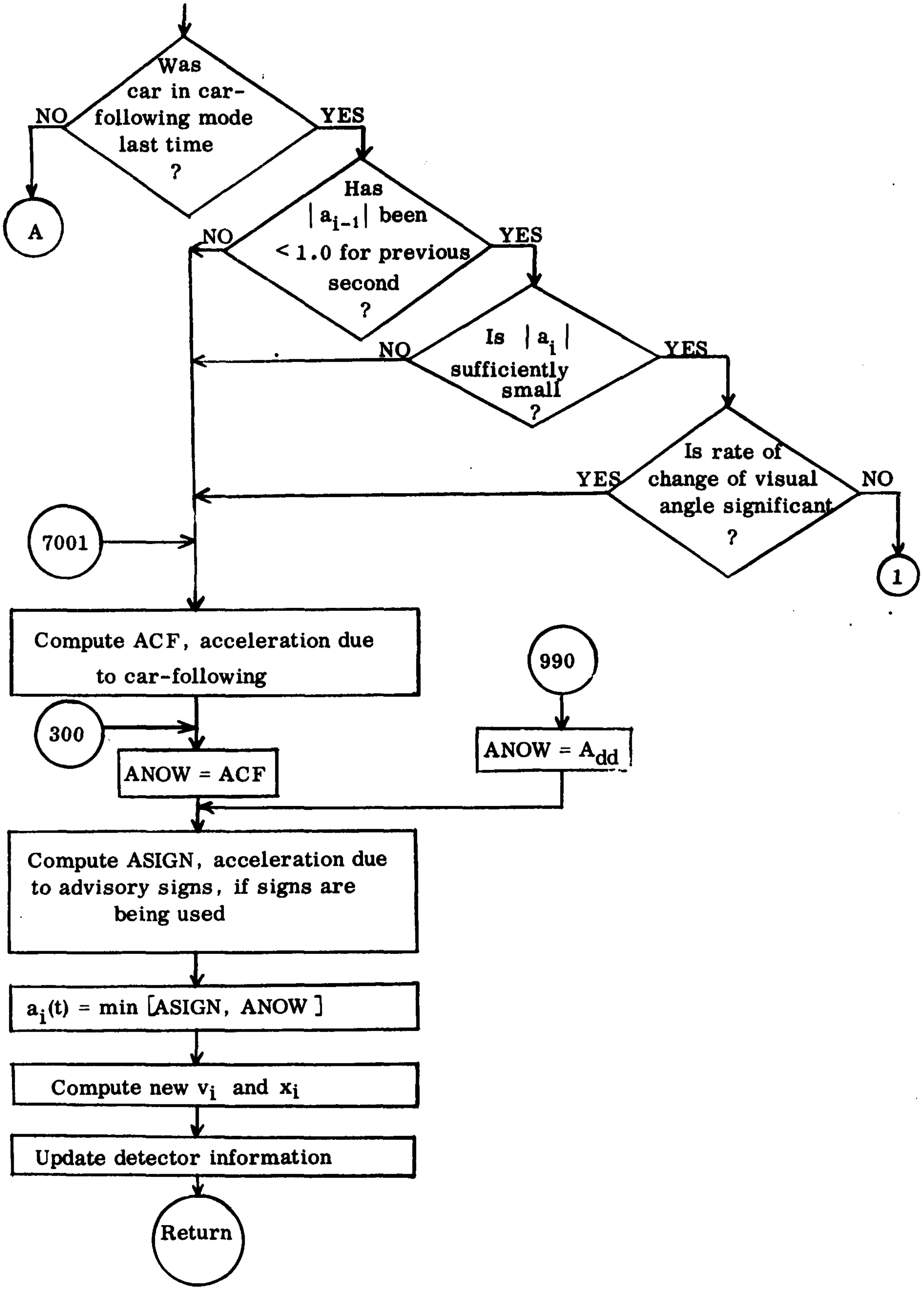


Subroutine TITLE

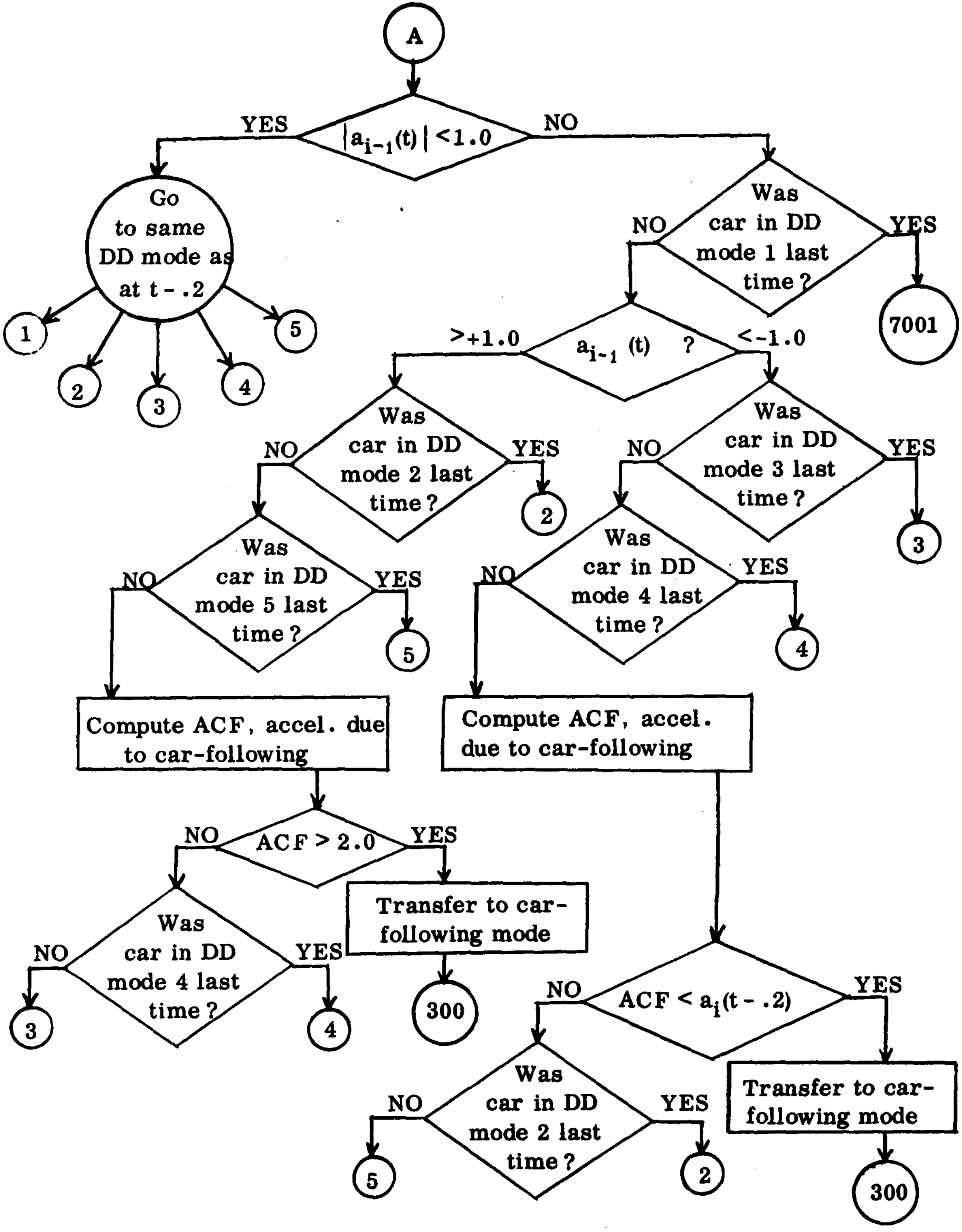



Set t = 0; initialize x, v for car 1
Every 30 sec
Every 5 sec
Every .2 sec
Call subroutine F3 to compute a(t), v(t +.2), x(t +.2), and update detectors for lead car
Call subroutine G1 to compute a(t), v(t +.2), x(t +.2), and update detectors for all other cars on road
t = t + 0.2
Has lead car exited ?
No
Yes
Store travel time, final velocity, etc., and change counters
Has new car entered ?
No
Yes
Initialize position and velocity for new car; change counters
Call SETSGN if signs are being used
5 sec. bookkeeping & printout
30 sec. bookkeeping & printout
Return

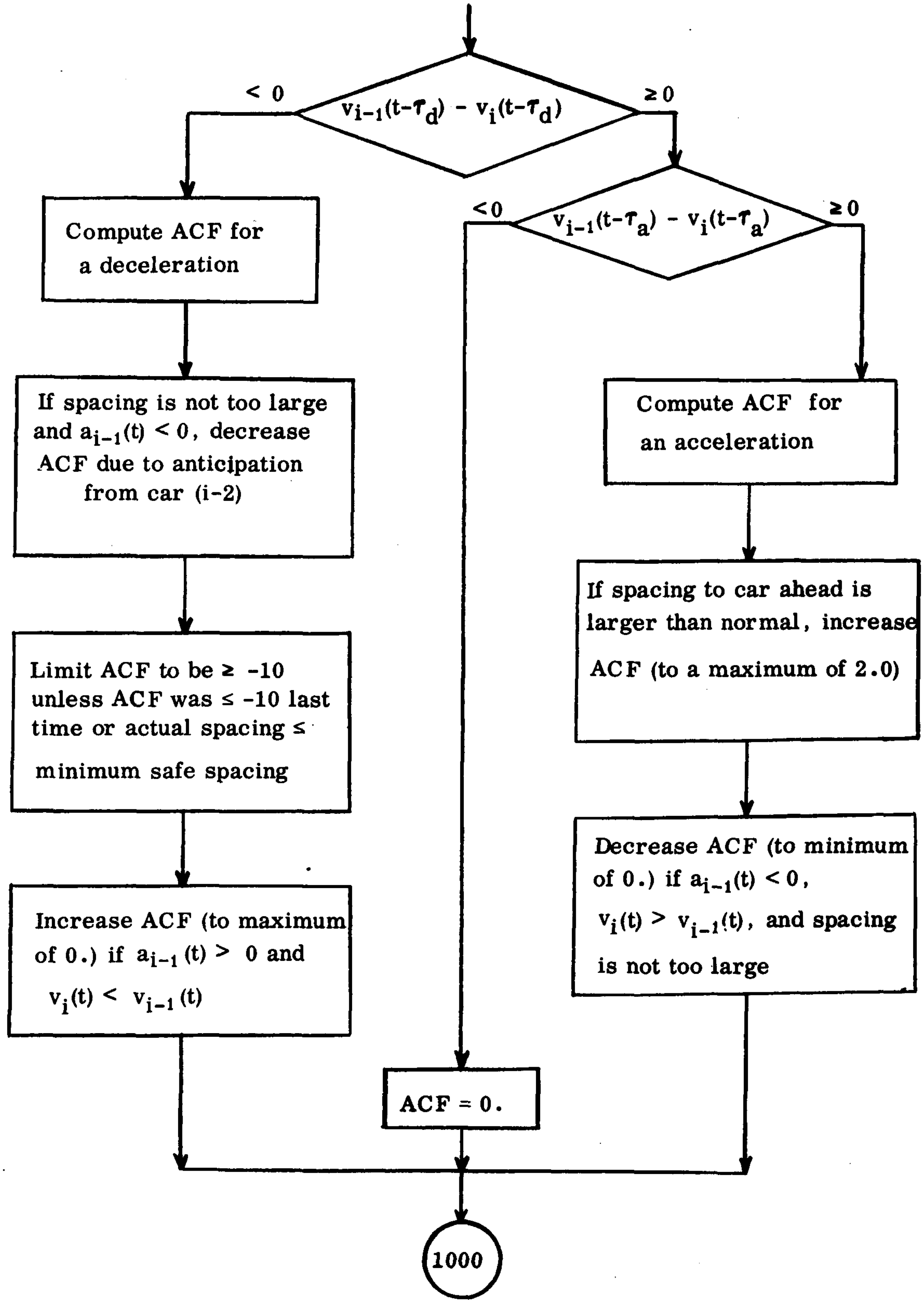
Subroutine G1 --- Vehicle Dynamics



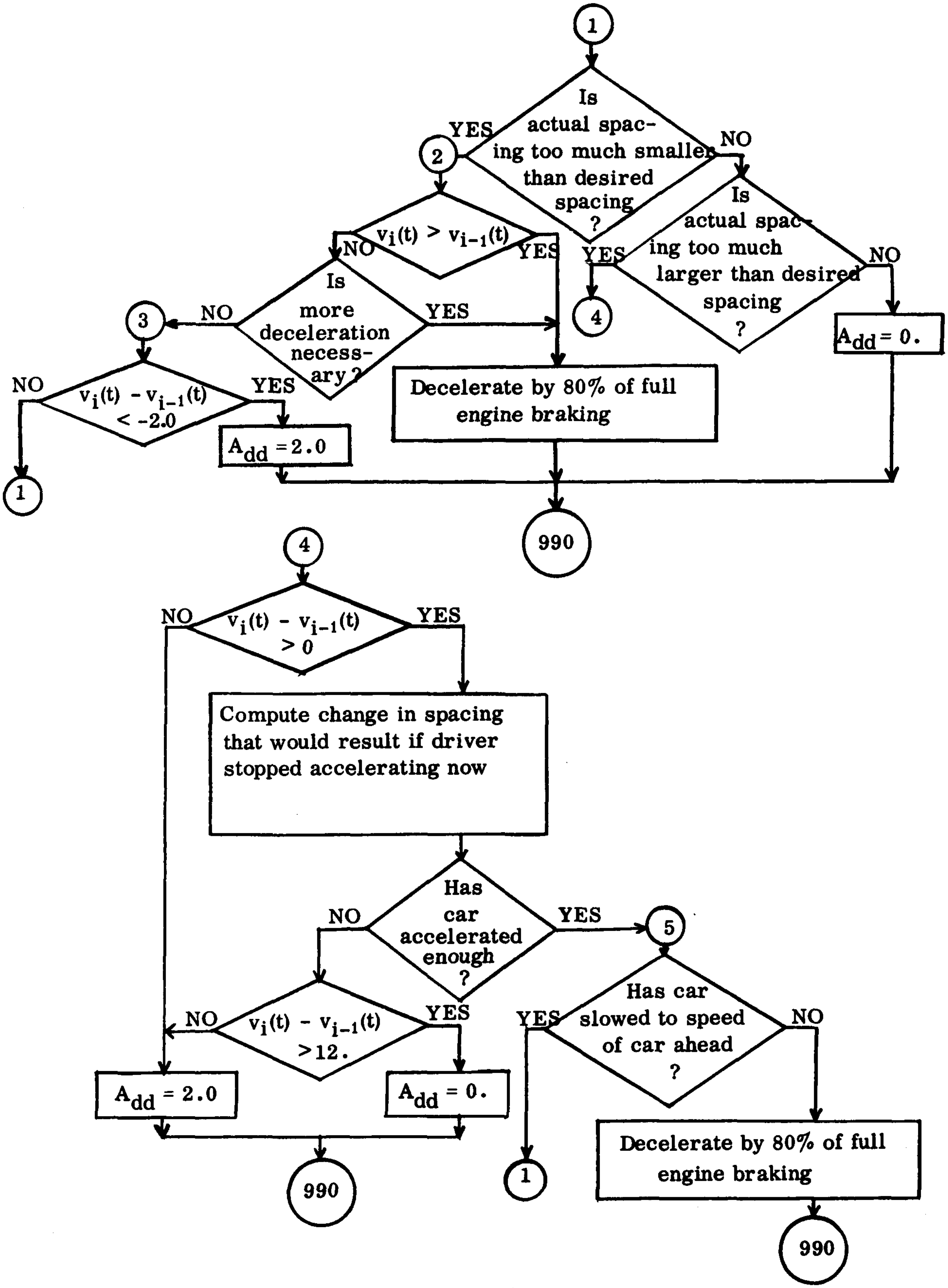
Subroutine G1 --- Vehicle Dynamics



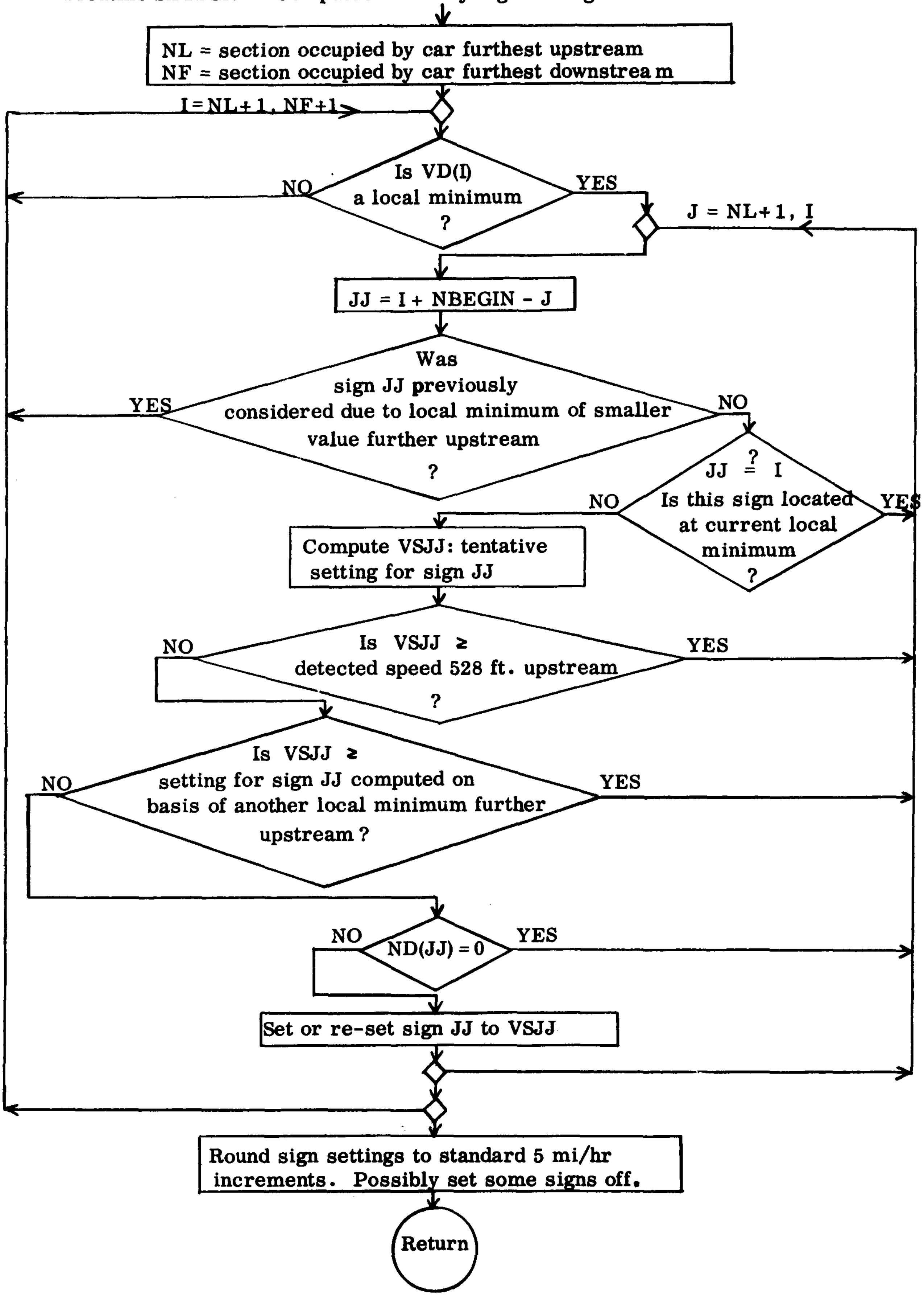
Subroutine G1 --- Acceleration Due to Car-following (ACF)



Subroutine G1 --- Distance-Detection Mode (DD mode)

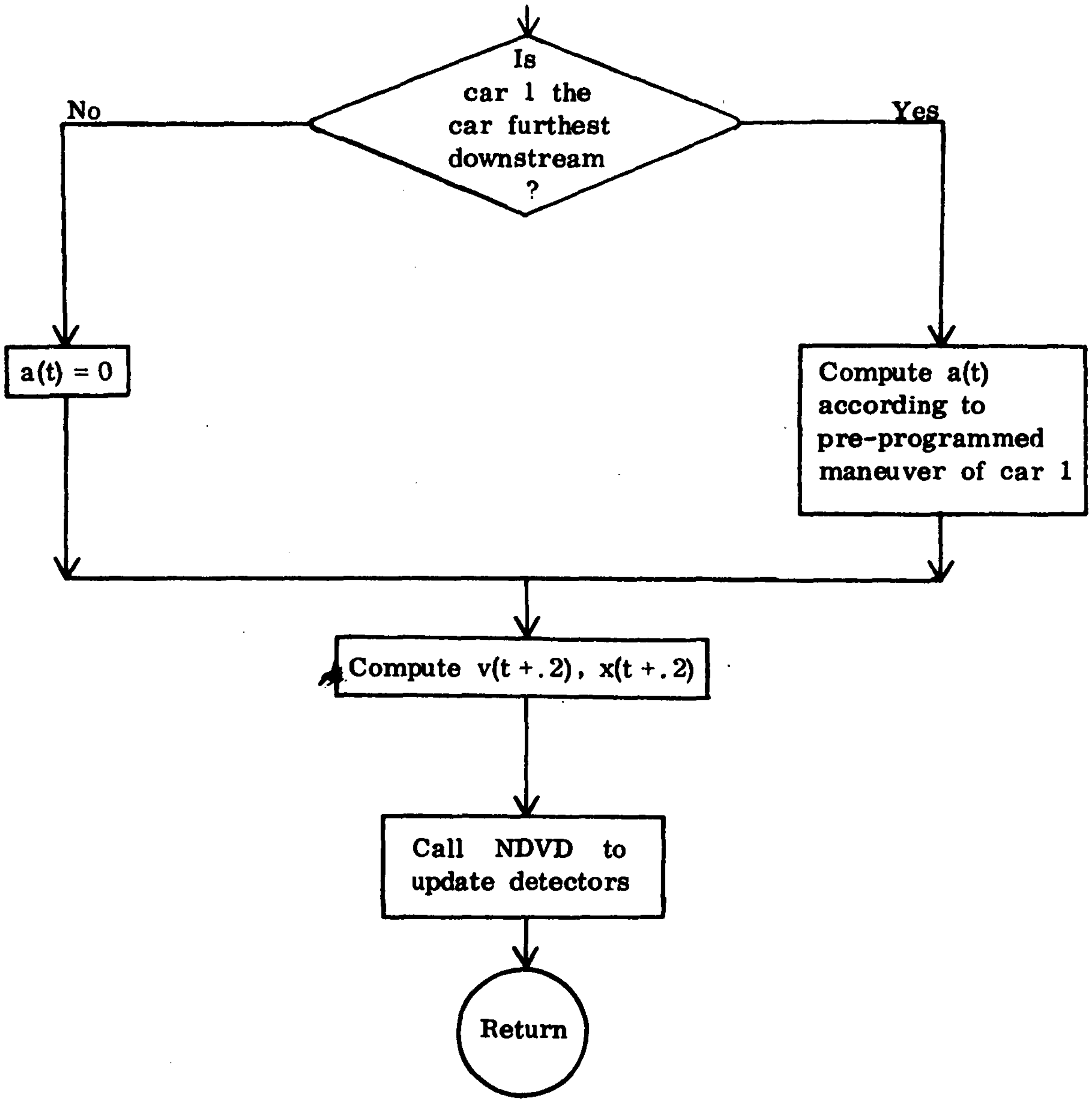


Subroutine SETSGN -- Computes Advisory Sign Settings



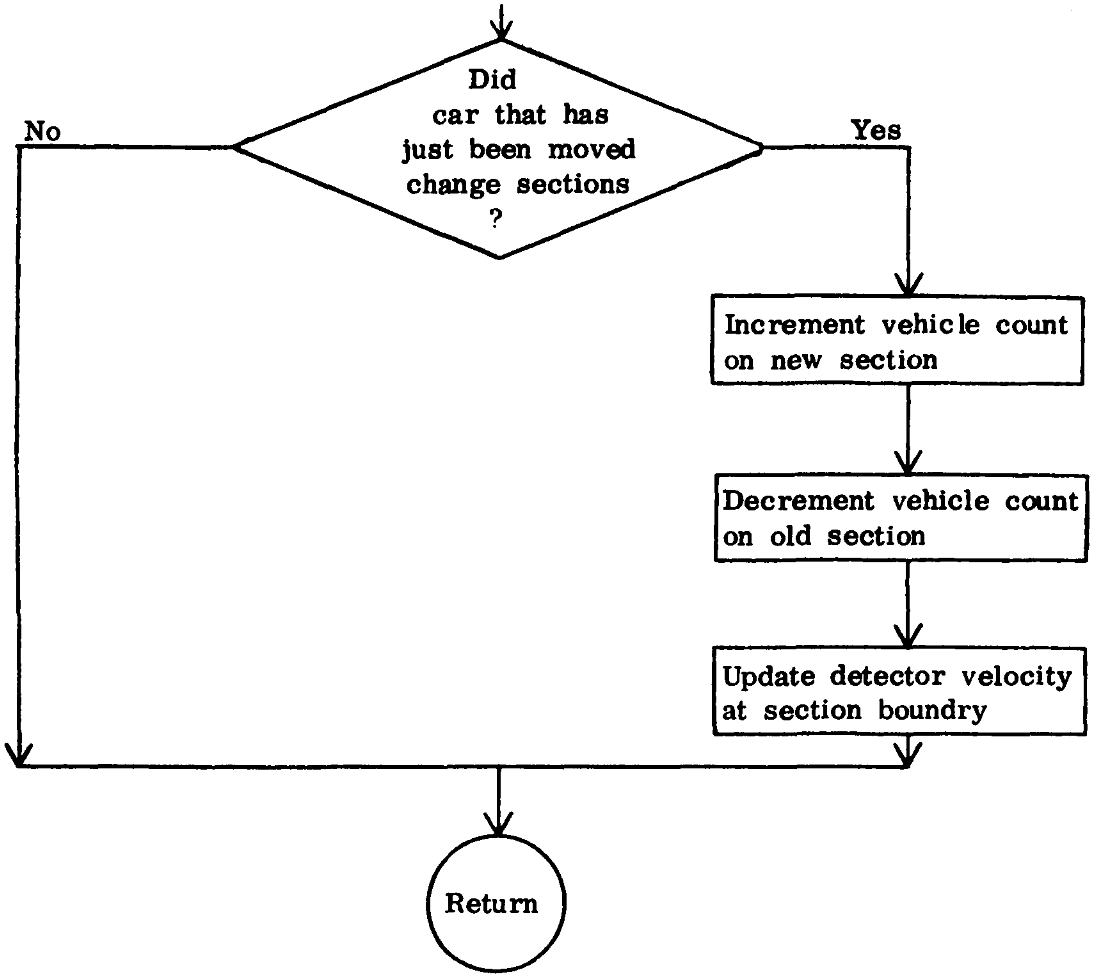
Subroutine F3

This subroutine updates velocity and position for the car that is furthest downstream



Subroutine NDVD

This subroutine updates ND and VD -- Detector Information



APPENDIX B

LISTING OF FORTRAN SIMULATION PROGRAM

```
C   COMMONS USED
C
C   MAIN     ABC    HM   T    ZK
C   TITLE    ABC   G     T    ZK
C   HIWAY   $A C FGHMN   U    Z
C   G1      $A     G MN T
C   F3      $AB    G
C   SETSGN  $A C      N   U
C   NDVD    $      G   N
C   FINISH   ABC F  MN   U    ZK
C   ZAP              M        ZK
C
      IMPLICIT INTEGER(C,I-N)
      INTEGER*2 IBRNCH,IDMODE,COMPLY
      INTEGER ON, OFF,          ENTER, PRINTX
      COMMON /AAAAAA/ NCARS,NMILE,VSTART,TXPRNT,          IBRNCH(350),
     1 CARNOW,         NOPRNT,CONTRL,ON,OFF,BETA,TAUS,KSIGN,LSIGN(100),
     2 HBAR,HDRV(350),COMPLY(350),VSIGN(100,7)
      COMMON /BBBBBB/TF3(5),AF3(4),BASE,NREP,NREPI,VI3
      COMMON /CCCCCC/CBUG1,CROUND,SGNC
      COMMON /HHHHHH/ PRINTX, BOMB,TXPR2,NOPR2
      COMMON /KKKKKK/ESIG2,ETSTOP,ETOTLT,EPER,EPCMP,IEVAV1,IEDX,NENS,
     2               JENS,EQ,ESPACE(10),RR1
      COMMON /MMMMMM/IVPRNT,TV1,TV2,IFIFTH,IFOL,SPACE(10),TSPACE(10)
      COMMON /TTTTTT/ IDMODE(350),TAUA,TAUD,VLIMIT,KA,KD
      COMMON /ZZZZZZ/ENTER,QHOUR,HMIN,HMODE,IR,       HBAR2,PCMPLY,PCMP
      DATA ION, IOFF / 'ON', 'OFF' /
      ON = ION
      OFF = IOFF
C
C          CBUG1 SPECIFIES PRINTOUT OF DETAILS OF SIGN SETTING
C               CBUG1=0   NO PRINTOUT
C               CBUG1=1   PRINTOUT EVERY 5 SECONDS
C
      CBUG1 = 0
C
C          CROUND SPECIFIES ROUNDING OF SIGN SETTINGS
```

```
C              CROUND=0  EXACT SIGN SETTINGS USED                        MAIN  380
C              CROUND=1  ROUND SIGN SETTINGS -- USE MODEL 1              MAIN  390
C                                                                        MAIN  400
C                                                                        MAIN  410
C          PCMPLY = FRACTION OF DRIVERS THAT COMPLY WITH SIGNS           MAIN  420
C                                                                        MAIN  430
      PCMPLY = 1.0                                                       MAIN  440
C                                                                        MAIN  450
C                                                                        MAIN  460
C          SGNC IS A CONSTANT IN ADJUSTING SIGN SETTING                  MAIN  470
C                                                                        MAIN  480
      SGNC = 1200.                                                       MAIN  490
C                                                                        MAIN  500
C     ***** INPUT DATA                                                   MAIN  510
C                                                                        MAIN  520
C          HDRV(I)   = VARIABLE AFFECTING DESIRED DISTANCE               MAIN  530
C          NCARS     = TOTAL # OF CARS TO ENTER THE HIGHWAY              MAIN  540
C          NMILE     = LENGTH OF HIGHWAY (IN MILES)                      MAIN  550
C          BETA    = SENSITIVITY CONST. TO COMPUTE ACC. DUE TO SIGNS     MAIN  560
C          TAUS    = DELAY IN RESPONSE DUE TO SIGNS                      MAIN  570
C                          KSIGN = 5.*TAUS + .1 + 1.  (SET IN HIWAY)     MAIN  580
C                                                                        MAIN  590
      BETA = .2                                                          MAIN  600
      TAUS = 2.0                                                         MAIN  610
      TAUA = 1.4                                                         MAIN  620
      TAUD=1.0                                                           MAIN  630
C                                                                        MAIN  640
C          SET CONSTANTS TC SPECIFY DENSITY FUNCTION FOR HEADWAY FACTOR  MAIN  650
C               HMIN  = MINIMUM HEADWAY FACTOR                           MAIN  660
C               HMODE = MODAL HEADWAY FACTOR                             MAIN  670
C                                                                        MAIN  680
      HMIN = .3                                                          MAIN  690
      HMODE = 1.                                                         MAIN  700
C                                                                        MAIN  710
C                                                                        MAIN  720
C          QHOUR = AVG. ENTERING FLOW RATE  (CARS/HOUR) FOR              MAIN  730
C                         RANDOM ENTERING HEADWAYS                       MAIN  740
```

```
C
      QHOUR = 2200.
C
C          ENTER = 0   IF ENTERING SPACING IS SAME FOR ALL CARS
C                = 1   FOR DISTRIBUTION 1  (SEE TITLE)
C
C
C          DXCAR, VCAR, ANOW, IMODE  ARE PRINTED OUT ONCE EVERY
C             'NOPRNT' CYCLES  (AFTER TNOW = TXPRNT)
C
C          IF  'PRINTX=1'   THEN  XCAR ALSO PRINTED OUT
C
C          IVPRNT CONTROLS PRINTING OF VELOCITY OF CARS EVERY SECOND
C                   IVPRNT = 0   VELOCITIES NOT PRINTED
C                   IVPRNT = 1   VELOCITIES PRINTED
C                       TV1 = TIME TO START PRINTING VELOCITIES
C                       TV2 = TIME TO STOP PRINTING VELOCITIES
C
C          CONTRL = 0  IF NO SIGN CONTROL
C                 = 1  WITH  SIGN CONTROL
C
C
C          NENS SPECIFIES NUMBER OF ENSEMBLE RUNS (MAX OF 10)
C
      NENS = 1
      NENS = 4
C
C          IF YOU WISH RUN TO END AFTER 'X' TRAVEL SECONDS,
C              THEN . . .   'BOMB=X'
C              OTHERWISE... 'BOMB=10000000.'
C
C
C          TXPRNT = TIME WHEN PRINTING OF X,V,A,MODE BEGINS
C          IF YOU DO NOT WISH TO HAVE X, V, A, MODE
C             PRINTED OUT AT ALL, SET TXPRNT = 1000000.
C             BEFORE CALLING HIWAY
C
```

```
C          TXPR2 = TIME TO CHANGE TO PRINTING X,V,A,MODE EVERY 'NOPR2'   MAIN 1120
C               CYCLES                                                    MAIN 1130
C                                                                         MAIN 1140
      TXPRNT=1.E6                                                         MAIN 1150
      TXPR2 = 1.E6                                                        MAIN 1160
C                                                                         MAIN 1170
C                                                                         MAIN 1180
C          IF USING F3 FOR LEAD CAR MANEUVER, SET                         MAIN 1190
C             NREP    = NUMBER OF REPETITIONS OF BASIC MANEUVER           MAIN 1200
C             TF3(I)  = TIME INSTANTS DESCRIBING BASIC MANEUVER           MAIN 1210
C             AF3(I)  = ACCELERATIONS USED IN BASIC MANEUVER (FT/SEC/SEC) MAIN 1220
C             VI3     = INITIAL VELOCITY (MI/HR)                          MAIN 1230
C                                                                         MAIN 1240
      NOPRNT  = 1                                                         MAIN 1250
      NOPR2 = 5                                                           MAIN 1260
      PRINTX = 0                                                          MAIN 1270
      TV1 = 220.                                                          MAIN 1280
      TV2 = 2000.                                                         MAIN 1290
      BOMB = 2000.                                                        MAIN 1300
      TF3(1) = 0.          + 237.                                         MAIN 1310
      TF3(2) = 7.4         + 237.                                         MAIN 1320
      TF3(3) = 27.4        + 237.                                         MAIN 1330
      TF3(4) = 34.8        + 237.                                         MAIN 1340
      TF3(5) = 54.8        + 237.                                         MAIN 1350
      AF3(1) = -3.0                                                       MAIN 1360
      AF3(2) = 0.0                                                        MAIN 1370
      AF3(3) =  3.0                                                       MAIN 1380
      AF3(4) =  0.                                                        MAIN 1390
      NREP = 50                                                           MAIN 1400
      VI3 = 50.                                                           MAIN 1410
      ENTER = 1                                                           MAIN 1420
      CROUND = 1                                                          MAIN 1430
      NMILE = 10                                                          MAIN 1440
      NCARS = 80                                                          MAIN 1450
      IVPRNT = 0                                                          MAIN 1460
      NENS = 4                                                            MAIN 1470
C                                                                         MAIN 1480
```

```
C          QHOUR VARIES, PCMPLY = 1.0
C
      QHOUR = 2000.
      CONTRL = 0
      CALL ZAP
      CONTRL = 1
      CALL ZAP
C
      QHOUR = 1900.
      CONTRL = 0
      IVPRNT = 1
      CALL ZAP
      CONTRL = 1
      CALL ZAP
C
      QHOUR = 1800.
      CONTRL = 0
      IVPRNT = 0
      CALL ZAP
      CONTRL = 1
      CALL ZAP
C
      QHOUR = 1700.
      CONTRL = 0
      CALL ZAP
      CONTRL = 1
      CALL ZAP
C
      QHOUR = 1600.
      CONTRL = 0
      IVPRNT = 1
      CALL ZAP
      CONTRL = 1
      CALL ZAP
C
      QHOUR = 1500.
      IVPRNT = 0
```

```
      CONTRL = 0                                                        MAIN 1860
      CALL ZAP                                                          MAIN 1870
      CONTRL = 1                                                        MAIN 1880
      CALL ZAP                                                          MAIN 1890
C                                                                       MAIN 1900
      QHOUR = 1400.                                                     MAIN 1910
      CONTRL = 0                                                        MAIN 1920
      CALL ZAP                                                          MAIN 1930
      CONTRL = 1                                                        MAIN 1940
      CALL ZAP                                                          MAIN 1950
C                                                                       MAIN 1960
      QHOUR = 1300.                                                     MAIN 1970
      IVPRNT = 1                                                        MAIN 1980
      CONTRL = 0                                                        MAIN 1990
      CALL ZAP                                                          MAIN 2000
      CONTRL = 1                                                        MAIN 2010
      CALL ZAP                                                          MAIN 2020
C                                                                       MAIN 2030
      CALL EXIT                                                         MAIN 2040
      STOP                                                              MAIN 2050
      END                                                               MAIN 2060
```

```
      SUBROUTINE HIWAY                                                  HIWA   10
C                                                                       HIWA   20
C     ***** VARIABLES USED IN THIS PROGRAM (UNITS OF FEET & SECONDS)    HIWA   30
C                                                                       HIWA   40
C          TNOW       = TIME NOW                                        HIWA   50
C          CARONE     = THE CAR THAT IS FARTHEST AHEAD ON THE HIGHWAY NOW HIWA   60
C                       IS THE CARONE-TH CAR TO HAVE ENTERED THE HIGHWAY HIWA   70
C          CYCLE1     = CARONE HAS POSITION CYCLE1 IN THE ARRAYS,       HIWA   80
C                       I.E.  XCAR(CYCLE1,16)= WHERE FURTHEST CAR IS NOW HIWA   90
C          CARZ       = SAME AS ABOVE FOR LAST CAR ON THE ROAD          HIWA  100
C          CYCLEZ     = SAME AS ABOVE FOR LAST CAR ON THE ROAD          HIWA  110
C          CARA, CYCLEA  REFER TO FURTHEST CAR ON HIGHWAY THAT HASN'T   HIWA  120
C             REACHED THE POINT AT WHICH TRAVEL TIME IS RECORDED        HIWA  130
C                                                                       HIWA  140
C          JSTOP(I)   = NUMBER OF INTERVALS I-TH CAR IS AT REST         HIWA  150
C          ATOTAL(I)  = SUM OF ANOW(I)**2                               HIWA  160
C                                                                       HIWA  170
C          NFEET      = NMILE * 5280                                    HIWA  180
C          TRAVEL(I)  = 1. TIME WHEN I-TH CAR ENTERS HIGHWAY            HIWA  190
C                       2. TRAVELLING TIME OF I-TH CAR ON HIGHWAY       HIWA  200
C                                                                       HIWA  210
C          ANOW(I)    =    LAST ACC OF I-TH CAR                         HIWA  220
C          JEXIT(I)   INDICATES WHEN I-TH CAR LEFT THE HIGHWAY          HIWA  230
C                                                                       HIWA  240
      IMPLICIT INTEGER(C,I-N)                                           HIWA  250
      INTEGER*2 JEXIT, JSTOP,ZD(7),ZSIGN(7),COMPLY                      HIWA  260
      INTEGER*2 ND,      IVOUT(350),IDXOUT(350),IBRNCH,NSON,NSFULL,CECT HIWA  270
      INTEGER*2  JSEC,JVSET,IVSEC(100,5)                                HIWA  280
      INTEGER PRINTX  , IX(20),ON,OFF,        ENTER                     HIWA  290
      DIMENSION IDX(20),VV(20)                                          HIWA  300
      COMMON XCAR(3861),VCAR(3861),ANOW(350),CYCLE1,CARONE,TNOW,CARA,   HIWA  310
     1 CARZ, CYCLEZ, CYCLEA                                             HIWA  320
      COMMON /AAAAAA/ NCARS,NMILE,VSTART,TXPRNT,          IBRNCH(350),  HIWA  330
     1 CARNOW,        NOPRNT,CONTRL,ON,OFF,BETA,TAUS,KSIGN,LSIGN(100),  HIWA  340
     2 HBAR,HDRV(350),COMPLY(350),VSIGN(100,7)                          HIWA  350
      COMMON /CCCCCC/CBUG1,CROUND,SGNC                                  HIWA  360
      COMMON /FFFFFF/TOTALT,ATOTAL(350),TRAVEL(350),JEXIT(350),         HIWA  370
```

```
     1             JSTOP(350),IDXOUT,IVOUT
      COMMON /GGGGGG/ ISIGN,JSEC,JVSET,IVSEC,IVP,ITENP,CECT(350)
      COMMON /HHHHHH/ PRINTX, BOMB,TXPR2,NOPR2
      COMMON /MMMMMM/IVPRNT,TV1,TV2,IFIFTH,IFOL,SPACE(10),TSPACE(10)
      COMMCN/NNNNNN/ITEN,ITENM,ITEND2,ND(100,7),I5SEC,VD(100,7)
      COMMON /UUUUUU/ NSON(100),NSFULL(100),NFT(1CC),HTEST,VSTARX
      COMMON /ZZZZZZ/ENTER,QHOUR,HMIN,HMODE,IR,      HBAR2,PCMPLY,PCMP
C
C          CHECK VALUES OF 'ENTER', 'NCARS', 'NMILE'
C
      CHECK = 0
      IF(ENTER.EQ.0.OR.ENTER.EQ.1)GO TO 51
      WRITE(6,50)ENTER
 50   FORMAT(///,1X,'ENTER =',I3,8X,'VALUE OF ENTER IS IN ERROR')
      CHECK = 1
 51   IF(NCARS.LT.350.AND.NCARS.GT.1)GO TO 53
      WRITE(6,52)NCARS
 52   FORMAT(///,1X,'NCARS =',I5,8X,'VALUE OF NCARS IS IN ERROR')
      CHECK = 1
 53   IF(NMILE.GT.0.AND.NMILE.LT.11)GO TO 55
      WRITE(6,54)NMILE
 54   FORMAT(///,1X,'NMILE =',I5,8X,'VALUE OF NMILE IS IN ERROR')
      CHECK = 1
 55   IF(CHECK.NE.0)RETURN
C          IBOMB = NUMBER OF 5 SEC INTERVALS AFTER WHICH PROGRAM WILL
C              BE ABORTED
      IBOMB = BOMB*.2 - .01
C
C
C          INITIALIZE VARIABLES
C
      IFOL = 0
      JSEC=0
      NCARSM = NCARS
      IF( NCARS .GT. 100 ) NCARSM = 100
      VSTARX=VSTART
      DO 701 I=1,10
```

```
      SPACE(I) = 0.0
 701  TSPACE(I) = 0.0
C
C          IFLAG3 = COUNTER FOR PRINTING XCAR, VCAR, ANOW, IMODE
C
      IFLAG3 =-1
      TOTALT = 0.
      NFEET = 5280 * NMILE
      FNFEET = FLCAT(NFEET)
      XFEET = FLCAT(NFEET) * 1.2
      KSIGN=5.*TAUS + 1.5
C
C          HERE TRAVEL(I) IS TIME WHEN I-TH CAR ENTERS HIGHWAY
C          LATER TRAVEL(I) STORES TRAVEL TIME FOR I-TH CAR
C
      TRAVEL(1) = 0.
      ITEN=10*NMILE
      ITENP = ITEN + 1
      ITENM=ITEN-1
      ITEND2=ITEN/2
      CYCLEA = 1
      CARA = 1
      CYCLE1 = 1
      CARONE = 1
      CYCLEZ = 1
      CARZ = 1
      DO 704  I=1,ITEN
      NFT(I)=528*I
      LSIGN(I)=OFF
      NSON(I)=0
      NSFULL(I)=0
      DO 704  J=1,7
      VSIGN(I,J)=9.E10
      ND(I,J)=0
 704  VD(I,J)=9.E10
      DO 700 I = 1, NCARS
      CECT(I) = 0
```

```
      ANOW(I) = 0.
      IBRNCH(I) = 1
      JSTOP(I) = 0.
      ATOTAL(I) = 0.
  700 CONTINUE
      IBRNCH(1) = 6
      HTEST=3.*HBAR-1.3
C
C          TIME STARTS WHEN FIRST CAR ENTERS THE HIGHWAY
C
      TNOW = 0.
C
C          INITIALIZE POSITION & VELOCITY FOR CAR 1
C
      DO 703 J = 1, 11
      XCAR(12-J)=VSTART * .2*FLOAT(J-11)
  703 VCAR(12-J) = VSTART
C
C     IMAX SPECIFIES NUMBER OF VEHICLES FOR PRINTOUT EVERY NOPRNT CYCLES
C
      IMAX = 20
      IF(NCARS .LT. 20) IMAX = NCARS
C
C          START OF MAJOR DO-LOOPS
C
      DO 3000 I30SEC = 1, 120
      DO 3000 I30SEC = 1, 2
      DO 2000 I5SEC  = 2, 7
C
      TNOW=FLOAT(IFIX(TNOW+.002))+.00002
      IF( TNOW .LT. TXPR2 .CR. NOPRNT .EC. NOPR2 ) GO TO 1707
      IFLAG3= -1
      NOPRNT = NOPR2
 17C7 CONTINUE
      IVP = 0
      JVSET = 0
      IF( IVPRNT .EQ. 0) GC TO 707
```

```
      IF(TNOW .LT. TV1  .OR.  TNOW .GT. TV2) GO TO 707                  HIWA 1490
      IVP = 1                                                           HIWA 1500
      DO 706 J = 1,5                                                    HIWA 1510
      DO 706 I = 1, NCARSM                                              HIWA 1520
  706 IVSEC(I,J) = 15999                                                HIWA 1530
  707 ISIGN=I5SEC-1                                                     HIWA 1540
      IF(ISIGN.EQ.1) ISIGN=7                                            HIWA 1550
C                                                                       HIWA 1560
C          INITIALIZE ND AND VD FOR CURRENT VALUE OF I5SEC              HIWA 1570
C                                                                       HIWA 1580
      DO 410 I=1,ITEN                                                   HIWA 1590
      ND(I,I5SEC)=ND(I,ISIGN)                                           HIWA 1600
  410 VD(I,I5SEC)=VD(I,ISIGN)                                           HIWA 1610
C                                                                       HIWA 1620
      IF(CARONE.NE.CARZ .AND. TNOW.GE.TXPRNT .AND. NOPRNT .LT. 6  .AND. HIWA 1630
     2      CARA .LE. IMAX                               ) WRITE(6,705) HIWA 1640
  705 FORMAT(1H1)                                                       HIWA 1650
C                                                                       HIWA 1660
      DO 1000 IFIFTH = 1, 25                                            HIWA 1670
C                                                                       HIWA 1680
C                                                                       HIWA 1690
      IF(CARA .GE. IMAX) GO TO 995                                      HIWA 1700
      IFLAG3 = IFLAG3 + 1                                               HIWA 1710
      IF(IFLAG3.LT.NOPRNT ) GO TO 995                                   HIWA 1720
      IFLAG3 = 0                                                        HIWA 1730
      IF( TNOW .LT. TXPRNT .OR. CARONE .EQ. CARZ ) GO TO 995            HIWA 1740
C                                                                       HIWA 1750
C          PRINT SPACING, VELOCITY, ACCEL., & IBRANCH EVERY NOPRNT      HIWA 1760
C              CYCLES                                                   HIWA 1770
C                                                                       HIWA 1780
C                                                                       HIWA 1790
C          SET VELOCITY AND SPACING FOR THOSE CARS NOT ON HIWAY AT TNOW HIWA 1800
C                                                                       HIWA 1810
      DO 991  J=1,CARA                                                  HIWA 1820
      VV(J) = 10.E10                                                    HIWA 1830
      IX(J)=9999999                                                     HIWA 1840
  991 IDX(J) = 0                                                        HIWA 1850
```

```
      IF(CARZ .GT. IMAX) GC TO 993
      DO 992 J = CARZ, IMAX
      VV(J) = 10.E10
      IX(J)=10.E10
  992 IDX(J) = 0
  993 CONTINUE
C
      CALL STEPH (TNOW, MIN, ISEC, SEC)
C
      XCAR1 = XCAR(CYCLEA)
      J=CARA
      VV(CARA)=VCAR(CYCLEA)
      IX(CARA) = XCAR(CYCLEA) +0.5
      IDX(CARA)=XCAR(CYCLEA)  + 0.5
      I=CYCLEA
  990 I = I + 11
      J = J + 1
      IF(I .GT. 3850) I = I - 3850
      IDX(J) = XCAR1 - XCAR(I) + .5
      IX(J) = XCAR(I) + .5
      VV(J) = VCAR(I)
      XCAR1 = XCAR(I)
      IF(J .LT. CARZ  .AND. J .LT. IMAX) GO TO 990
      WRITE(6,692)(IBRNCH(I),I=1,IMAX)
      WRITE(6,691)(ANOW(I),I=1,IMAX)
      WRITE(6,690) MIN, ISEC, SEC, (IDX(I),I=1,IMAX)
      IF(PRINTX .EQ. 1) WRITE(6,692) (IX(I),I=1,IMAX)
      WRITE(6,691)(VV(I),I=1,IMAX)
  690 FORMAT(//3H T=,I2,1H-,I1,F3.1,I8,19I6)
  691 FORMAT(12X,20F6.1)
 692  FORMAT(12X,20I6)
C
C          COMPUTE ACCELERATION FOR T = TNOW
C          COMPUTE VELOCITY AND POSITION FOR T = TNOW + .2
C
  995 IF(IVP .EQ. 0) GO TO 100
      JVSET=0
```

```
      IF(IFIFTH/5*5.NE.IFIFTH) GO TO 100                                HIWA 2230
      JVSET=1                                                           HIWA 2240
      JSEC=JSEC+1                                                       HIWA 2250
C                                                                       HIWA 2260
C          FIND NEW X, V OF LEAD CAR                                    HIWA 2270
C                                                                       HIWA 2280
 100  CYCLEA=CYCLEA - 1                                                 HIWA 2290
      IF( CYCLEA .EQ. 0 )  CYCLEA=3850                                  HIWA 2300
      CYCLE1 = CYCLE1 - 1                                               HIWA 2310
      CYCLEZ = CYCLEZ - 1                                               HIWA 2320
      IF ( CYCLE1 . NE. 0 ) GO TO 102                                   HIWA 2330
      DO 101 I = 1, 11                                                  HIWA 2340
      XCAR(I+3850) = XCAR(I)                                            HIWA 2350
 101  VCAR(I+3850) = VCAR(I)                                            HIWA 2360
      CYCLE1 = 3850                                                     HIWA 2370
      IF( CYCLEZ .EQ. 0 )  CYCLEZ = 3850                                HIWA 2380
 102  CALL F3                                                           HIWA 2390
C                                                                       HIWA 2400
C          FIND NEW X, V OF THE OTHER CARS                              HIWA 2410
C                                                                       HIWA 2420
      CARNOW=CARONE                                                     HIWA 2430
      IF(CYCLE1 .EQ. CYCLEZ) GO TO 107                                  HIWA 2440
      IF ( CYCLE1 .GT. CYCLEZ ) GO TO 103                               HIWA 2450
      I = CYCLE1                                                        HIWA 2460
      GO TO 106                                                         HIWA 2470
103   I = CYCLE1                                                        HIWA 2480
104   I = I + 11                                                        HIWA 2490
      IF(I .GT. 3850) GO TO 105                                         HIWA 2500
      IF(I .NE. 3850) GO TO 109                                         HIWA 2510
      DO 108 J = 1, 11                                                  HIWA 2520
      XCAR(J+3850) = XCAR(J)                                            HIWA 2530
 108  VCAR(J+3850) = VCAR(J)                                            HIWA 2540
109   CARNO = I - 11                                                    HIWA 2550
      CARNOW=CARNOW+1                                                   HIWA 2560
      CALL G1(CARNO,I)                                                  HIWA 2570
      IF(XCAR(I).GT.FNFEET) GO TO 104                                   HIWA 2580
      IF(VCAR(I).EQ.0.) JSTOP(CARNOW)=JSTOP(CARNOW) +1                  HIWA 2590
```

```
      ATOTAL(CARNOW) = ATOTAL(CARNOW) + ANOW(CARNOW)**2                 HIWA 2600
      GO TO 104                                                         HIWA 2610
  105 CARNO = I - 11                                                    HIWA 2620
      I = I - 3850                                                      HIWA 2630
      IF( I .GT. CYCLEZ ) GO TO 107                                     HIWA 2640
      CARNOW=CARNOW+1                                                   HIWA 2650
      CALL G1(CARNO,I)                                                  HIWA 2660
      IF(XCAR(I).GT.FNFEET) GO TO 106                                   HIWA 2670
      IF(VCAR(I)     .EQ.0.) JSTOP(CARNOW) = JSTOP(CARNOW) + 1          HIWA 2680
      ATOTAL(CARNOW) = ATOTAL(CARNOW) + ANOW(CARNOW)**2                 HIWA 2690
  106 I = I + 11                                                        HIWA 2700
      IF ( I .GT. CYCLEZ )  GO TO 107                                   HIWA 2710
      CARNO = I - 11                                                    HIWA 2720
      CARNOW=CARNOW+1                                                   HIWA 2730
      CALL G1(CARNO,I)                                                  HIWA 2740
      IF(XCAR(I).GT.FNFEET) GO TO 106                                   HIWA 2750
      IF(VCAR(I).EQ.0.) JSTOP(CARNOW)=JSTOP(CARNOW) +1                  HIWA 2760
      ATOTAL(CARNOW) = ATOTAL(CARNOW) + ANOW(CARNOW)**2                 HIWA 2770
      GO TO 106                                                         HIWA 2780
  107 IF(CYCLEZ .EQ. 0) CYCLEZ = 3850                                   HIWA 2790
C                                                                       HIWA 2800
C          INCREMENT TIME                                               HIWA 2810
C                                                                       HIWA 2820
      TNOW = TNOW + .2                                                  HIWA 2830
C                                                                       HIWA 2840
C          A CAR LEAVES THE HIGHWAY                                     HIWA 2850
C                                                                       HIWA 2860
      IF( XCAR(CYCLEA) .LT. FNFEET ) GO TO 201                          HIWA 2870
C                                                                       HIWA 2880
C          HERE TRAVEL(CARA  ) = TRAVEL TIME OF CARA  -TH CAR ON HIGHWAY HIWA 2890
C                                                                       HIWA 2900
      TRAVEL(CARA  ) = TNOW - TRAVEL(CARA  )                            HIWA 2910
      JEXIT(CARA)=HFIX(5.*TNOW +.001)                                   HIWA 2920
      IVOUT(CARA) = HFIX( VCAR(CYCLEA) + 0.5 )                          HIWA 2930
      TOTALT = TOTALT + TRAVEL(CARA  )                                  HIWA 2940
      IF(CARA .EQ.NCARS ) GO TO 1300                                    HIWA 2950
      CARA = CARA + 1                                                   HIWA 2960
```

```
      XOUT = XCAR(CYCLEA)                                               HIWA 2970
      CYCLEA = CYCLEA + 11                                              HIWA 2980
      IF(CYCLEA .GT. 3850) CYCLEA = CYCLEA - 3850                       HIWA 2990
      IDXOUT(CARA) = HFIX( XOUT - XCAR(CYCLEA) + 0.5 )                  HIWA 3000
  201 CONTINUE                                                          HIWA 3010
      IF( XCAR(CYCLE1).LT. XFEET ) GO TO 202                            HIWA 3020
      CARONE = CARONE + 1                                               HIWA 3030
      CYCLE1 = CYCLE1 + 11                                              HIWA 3040
      IF(CYCLE1 .GT. 3850) CYCLE1 = CYCLE1 - 3850                       HIWA 3050
C                                                                       HIWA 3060
  202 IF( CARZ .EQ. NCARS )  GO TO 205                                  HIWA 3070
      IF(XCAR(CYCLEZ).LT.HDRV(CARZ+1)*VCAR(CYCLEZ)+20.) GO TO 1000      HIWA 3080
C                                                                       HIWA 3090
C           A CAR HAS ENTERED THE HIGHWAY WITHIN THE LAST .2 SECONDS    HIWA 3100
C                                                                       HIWA 3110
      DFOL=HDRV(CARZ+1)*VCAR(CYCLEZ)+20.                                HIWA 3120
      CARZ = CARZ + 1                                                   HIWA 3130
      TRAVEL(CARZ)=TNOW                                                 HIWA 3140
      CYCLEZ = CYCLEZ+ 11                                               HIWA 3150
      IF ( CARZ - CARONE .GE. 350 )  GO TO 901                          HIWA 3160
C           UPDATE ND AND SET CECT FOR ENTERING CAR                     HIWA 3170
      CECT(CARZ)=1                                                      HIWA 3180
      ND(1,I5SEC)=ND(1,I5SEC) +1                                        HIWA 3190
C                                                                       HIWA 3200
      IF ( CYCLEZ .GT. 3850 )  GO TO 204                                HIWA 3210
      DO 203 J = 1, 11                                                  HIWA 3220
      I = CYCLEZ + J - 1                                                HIWA 3230
      XCAR(I) = XCAR(I-11) -DFOL                                        HIWA 3240
  203 VCAR(I) = VCAR(I-11)                                              HIWA 3250
      VSTARX = VCAR(CYCLEZ)                                             HIWA 3260
      GO TO 205                                                         HIWA 3270
  204 CYCLEZ = CYCLEZ - 3850                                            HIWA 3280
      DO 206 J = 1, 11                                                  HIWA 3290
      I = CYCLEZ + J - 1                                                HIWA 3300
      XCAR(I) = XCAR(I+3839) - DFOL                                     HIWA 3310
  206 VCAR(I) = VCAR(I+3839)                                            HIWA 3320
      VSTARX = VCAR(CYCLEZ)                                             HIWA 3330
```

```
C
  205 CONTINUE
C
 1000 CONTINUE
C
C          DO THIS EVERY 5 SECONDS
C
C
C          FOR PURPOSES OF EASE IN READING PRINTOUT
C          SET VD(I,I5SEC) = 9.E10 IF NO CARS ARE ON PREVIOUS SECTIONS
C
      IF( ND(1,I5SEC) .NE. 0 ) GO TO 321
      DO 320 I=2,ITEN
      IF( ND(I,I5SEC) .NE. 0 ) GO TO 321
  320 VD(I-1,I5SEC) = 9.E10
      VD(ITEN,I5SEC) = 9.E10
  321 CONTINUE
C
C          CHANGE SIGNS
C
      IF( CONTRL .EQ. 1 ) CALL SETSGN
C
C
C          PRINTING OF VELOCITY OF ALL CARS -- IF IVPRNT = 1
C
      IF(IVP   .EQ.0) GO TO 1999
      NT5=IFIX(TNOW+.001)
      NT4=NT5-1
      NT3=NT4-1
      NT2=NT3-1
      NT1=NT2-1
      WRITE(6,250) NT1,NT2,NT3,NT4,NT5,NT1,NT2,NT3,NT4,NT5
  250 FORMAT(1H1,60X,'VELOCITY' // 37X,'NEGATIVE VALUE MEANS CAR IS RESP
     2ONDING TO A SIGN' // 9X, 5('T=',I3,5X), 15X, 5('T=',I3,5X) //)
      LZ=50
      IF(CARZ.LT.50)LZ=CARZ
      DO 253 I=1,LZ
```

```
      WRITE(6,251)  I,(IVSEC(I,J),J=1,5)
  251 FORMAT( 1X,I3,6X,5(I4,6X))
      IPL=I+50
      IF(IPL.GT. CARZ) GO TO 253
      WRITE(6,252)  IPL,(IVSEC(IPL,J),J=1,5)
  252 FORMAT(1H+,67X,I3,4X,5( I4,6X))
  253 CONTINUE
      JSEC=0
C
C
 1999 IBOMB = IBOMB - 1
      IF(IBOMB .LT. 0) RETURN
 2000 CONTINUE
C
C
C          DO THIS EVERY 30 SECONDS
C
C          WRITE ND & VD & VSIGN
C
      CALL STEPH(TNOW,MIN,ISEC,SEC)
      WRITE(6,680) MIN, ISEC, SEC
  680 FORMAT(1H1,10X,'*** TIME =',I3,' MIN.',I2,F3.1,' SEC.'//5H MILE,
     1 6('  ND    VD  VSIGN   '),' FEET'/)
      IBB = XCAR(CYCLEZ)/528.0 + 1.0
      IBB=IBB-7
      IF(IBB.LT.1)IBB=1
      IAA = XCAR(CYCLEA)/528.0 + 1.0
      DO 681 I = IBB, IAA
      X = FLOAT(I)/10.
      IIX = I * 528
      ZD(2)=VD(I,2)*.6818182+.0001
      ZD(3)=VD(I,3)*.6818182+.0001
      ZD(4)=VD(I,4)*.6818182+.0001
      ZD(5)=VD(I,5)*.6818182+.0001
      ZD(6)=VD(I,6)*.6818182+.0001
      ZD(7)=VD(I,7)*.6818182+.0001
      ZSIGN(2)=VSIGN(I,2)*.683
```

```
      ZSIGN(3)=VSIGN(I,3)*.683                                          HIWA 4080
      ZSIGN(4)=VSIGN(I,4)*.683                                          HIWA 4090
      ZSIGN(5)=VSIGN(I,5)*.683                                          HIWA 4100
      ZSIGN(6)=VSIGN(I,6)*.683                                          HIWA 4110
      ZSIGN(7)=VSIGN(I,7)*.683                                          HIWA 4120
      WRITE(6,684) X, (ND(I,J),ZD(J),ZSIGN(J),J=2,7),IIX                HIWA 4130
 684  FORMAT(1X,F4.1,6(I4,2X,I4,3X,I3,4X),I5)                           HIWA 4140
      VSIGN(I,1)=VSIGN(I,7)                                             HIWA 4150
681   CONTINUE                                                          HIWA 4160
      DO 219  I = 1, ITEN                                               HIWA 4170
      ND(I,1) = ND(I,7)                                                 HIWA 4180
  219 VD(I,1) = VD(I,7)                                                 HIWA 4190
C                                                                       HIWA 4200
 3000 CONTINUE                                                          HIWA 4210
      WRITE(6,603)                                                      HIWA 4220
  603 FORMAT(//18H ** ONE HOUR IS UP)                                   HIWA 4230
      RETURN                                                            HIWA 4240
C                                                                       HIWA 4250
C             ALL CARS HAVE LEFT THE HIGHWAY                            HIWA 4260
C                                                                       HIWA 4270
C                                                                       HIWA 4280
 1300 CALL FINISH                                                       HIWA 4290
C                                                                       HIWA 4300
      RETURN                                                            HIWA 4310
  901 WRITE(6,604)                                                      HIWA 4320
  604 FORMAT(//20H ** 350 CARS ON ROAD)                                 HIWA 4330
      RETURN                                                            HIWA 4340
      END                                                               HIWA 4350
```

```
      SUBROUTINE TITLE
      IMPLICIT INTEGER(C,I-N)
      INTEGER*2 IBRNCH,IDMODE,JSEC,JVSET,IVSEC(100,5),CECT,COMPLY
      INTEGER ON, OFF         , ENTER
      COMMON /AAAAAA/ NCARS,NMILE,VSTART,TXPRNT,          IBRNCH(350),
     1 CARNOW,       NOPRNT,CONTRL,ON,OFF,BETA,TAUS,KSIGN,LSIGN(100),
     2 HBAR,HDRV(350),COMPLY(350),VSIGN(100,7)
      COMMON /BBBBBB/TF3(5),AF3(4),BASE,NREP,NREPI,VI3
      COMMON /CCCCCC/CBUG1,CROUND,SGNC
      COMMON /GGGGGG/ ISIGN,JSEC,JVSET,IVSEC,IVP,ITEMP,CECT(350)
      COMMON /TTTTTT/ IDMODE(350),TAUA,TAUD,VLIMIT,KA,KD
      COMMON /ZZZZZZ/ ENTER,QHOUR,HMIN,HMODE,IR,      HBAR2,PCMPLY,PCMP
      COMMON /KKKKKK/ESIG2,ETSTOP,ETOTLT,EPER,EPCMP,IEVAV1,IEDX,NENS,
     2              JENS,EQ,ESPACE(10),RR1
      Y = 5280./3600.
      KA = 5.*TAUA + 1.5
      KD = 5.*TAUD + 1.5
      WRITE(6,601) NMILE, NCARS
  601 FORMAT(1H1,20X,'*** HIGHWAY SIMULATION PROGRAM ***'//4X,'INPUT DAT
     1A FOR THIS RUN'/10X,'NMILE =',I4,'  = LENGTH OF HIGHWAY IN MILES'/
     2 10X,'NCARS =',I4,'  = TOTAL NUMBER OF CARS TO ENTER THE HIGHWAY')
      VSTART = VI3*Y
      VLIMIT=VSTART+14.667
      BASE = 0.0
      NREPI=0
C
C           PRINT HEADING FOR F3
C
      WRITE(6,612) TF3,AF3,NREP,VI3
  612 FORMAT(1H0,5X,'THIS RUN USES SUBROUTINE F3'////
     2       6X,'TF3(I) =',5F12.2///
     3       6X,'AF3(I) =',4F12.2///
     4       6X,'NREP =',I5///
     5       6X,'INITIAL VELOCITY = VI3 =',F8.1,' MI/HR'///)
      TF3(1) = TF3(1) - 0.02*RR1
      TF3(2) = TF3(2) - 0.02*RR1
      TF3(3) = TF3(3) - 0.02*RR1
```

```
      TF3(4) = TF3(4) - 0.02*RR1                                        TITL 380
      TF3(5) = TF3(5) - 0.02*RR1                                        TITL 390
      RR1 = 0.0                                                         TITL 400
C                                                                       TITL 410
      QSEC = QHOUR/3600.                                                TITL 420
      HBAR = 1./QSEC - 20./VSTART                                       TITL 430
      HDRV(1) = 0.                                                      TITL 440
      IDMODE(1) = 0                                                     TITL 450
      DO 201 I = 2, NCARS                                               TITL 460
      IDMODE(I) = 0                                                     TITL 470
      HDRV(I) = HBAR                                                    TITL 480
  201 CONTINUE                                                          TITL 490
      IF(ENTER.EQ.0) GO TO 999                                          TITL 500
      IF(ENTER .GT. 1) GO TO 999                                        TITL 510
C                                                                       TITL 520
C           HEADWAY FACTORS COMPUTED                                    TITL 530
C                                                                       TITL 540
      TBAR=1./QSEC                                                      TITL 550
      HEIGHT=2./(3.*HBAR-2.*HMIN-HMODE)                                 TITL 560
      HMAX=3.*HBAR-HMIN-HMODE                                           TITL 570
      HRVSUM=0.                                                         TITL 580
C           SET IS=IR --- SAME STARTING VALUE FOR ALL RUNS              TITL 590
      IS=IR                                                             TITL 600
      DO 104 I = 2, NCARS                                               TITL 610
      CALL RANDU(IS,IY,Z)                                               TITL 620
      IS = IY                                                           TITL 630
      IF(Z.GT.(HMODE-HMIN)/(HMAX-HMIN)) GO TO 103                       TITL 640
      HDRV(I)=SQRT((HMAX-HMIN)*(HMODE-HMIN)*Z)+HMIN                     TITL 650
      GO TO 104                                                         TITL 660
  103 HDRV(I)= -SQRT((HMAX-HMODE)*(HMAX-HMIN)*(1.-Z))+HMAX              TITL 670
  104 HRVSUM=HRVSUM+HDRV(I)                                             TITL 680
      HBAR2=HRVSUM/FLOAT(NCARS-1)                                       TITL 690
      WRITE(6,620) QHOUR,TBAR,HBAR,HBAR2,HMIN,HMODE,HMAX,HEIGHT         TITL 700
  620 FORMAT('0THIS RUN IS MADE WITH RANDOMLY GENERATED HEADWAYS'///    TITL 710
     2  5X,'QHOUR   = AVERAGE FLOW =',F5.0,' VEHICLES/HOUR'/            TITL 720
     3  5X,'TBAR    = 1/QSEC = AVG. TIME HEADWAY =',F5.2,' SECONDS'/    TITL 730
     4  5X,'HBAR    = AVERAGE HEADWAY FACTOR DESIRED =',F6.3/           TITL 740
```

```
    5  5X,'HBAR2  = AVERAGE HEADWAY FACTOR GENERATED =',F6.3////        TITL  750
    6  ' FOR THE DENSTIY FUNCTION USED'//                                TITL  760
    7  5X,'HMIN   = MINIMUM HEADWAY FACTOR =',F5.2,' (GIVEN)'/           TITL  770
    8  5X,'HMODE  = MODAL HEADWAY FACTOR   =',F5.2,' (GIVEN)'/           TITL  780
    9  5X,'HMAX   = MAXIMUM HEADWAY FACTOR =',F5.2,' (CALCULATED)'/      TITL  790
    A  5X,'HEIGHT = MAX OF DENSITY FUNCTION =',F6.3,' (CALCULATED)'///) TITL  800
      WRITE(6,630)                                                       TITL  810
  630 FORMAT(////24X,'F(H)'/                                             TITL  820
    2            25X,'+'/                                                TITL  830
    3            19X,'HEIGHT+-------------*'/                            TITL  840
    4            25X,'+',10X,'* ''   *'/                                 TITL  850
    5            25X,'+',8X, '*   ''      *'/                            TITL  860
    6            25X,'+',6X,'*     ''',8X,'*'/                           TITL  870
    7            25X,'+++++*++++++++++++++++++++++*++++++ H'/            TITL  880
    8            28X,'HMIN',4X,'HMODE',8X,'HMAX'//1H1)                   TITL  890
  999 IF( CONTRL .EQ. 0 ) GO TO 9999                                     TITL  900
C                                                                        TITL  910
C          COMPUTE SIGN COMPLIANCE FACTOR FOR EACH DRIVER                TITL  920
C                                                                        TITL  930
      CMP=0                                                              TITL  940
      IS=2*IR-37                                                         TITL  950
      DO 105 I=2,NCARS                                                   TITL  960
      CALL RANDU(IS,IY,Z)                                                TITL  970
      IS=IY                                                              TITL  980
      COMPLY(I)=0                                                        TITL  990
      IF( Z .LT. PCMPLY ) COMPLY(I)=1                                    TITL 1000
  105 CMP=CMP+COMPLY(I)                                                  TITL 1010
      PCMP=FLOAT(CMP)/FLOAT(NCARS-1)                                     TITL 1020
 9999 RETURN                                                             TITL 1030
      END                                                                TITL 1040
```

```
      SUBROUTINE G1 (CARNO,CARFOL)                                      G1      10
C                                                                       G1      20
C          COMPUTE NEW VALUES X(T=TNCW+.2) & V(T=TNOW+.2) FOR CARNOW-TH  G1      30
C              VEHICLE                                                  G1      40
C                                                                       G1      50
C          CARNO = LOCATION IN ARRAY OF NEW VALUE FOR (CARNOW -1)-TH CAR G1     60
C          CARFOL=    ''    ''  ''    ''  ''    ''    '' CARNOW-TH CAR  G1      70
C          ANOW  = OLD ACCEL.  (AT T=TNOW)                              G1      80
C                                                                       G1      90
      IMPLICIT INTEGER(C,I-N)                                           G1     100
      INTEGER*2  JSEC,JVSET,IVSEC(100,5),COMPLY                         G1     110
      INTEGER*2 ND,       IBRNCH,IDMODE,CECT                            G1     120
      INTEGER ON, OFF                                                   G1     130
      COMMON XCAR(3861),VCAR(3861),ANOW(350),CYCLE1,CARONE,TNOW,CARA,   G1     140
     1 CARZ, CYCLEZ, CYCLEA                                             G1     150
      COMMON /AAAAAA/ NCARS,NMILE,VSTART,TXPRNT,          IBRNCH(350),  G1     160
     1 CARNOW,        NOPRNT,CONTRL,ON,OFF,BETA,TAUS,KSIGN,LSIGN(100),  G1     170
     2 HBAR,HDRV(350),COMPLY(350),VSIGN(100,7)                          G1     180
      COMMON /GGGGGG/ ISIGN,JSEC,JVSET,IVSEC,IVP,ITENP,CECT(350)        G1     190
      COMMON /MMMMMM/IVPRNT,TV1,TV2,IFIFTH,IFOL,SPACE(10),TSPACE(10)    G1     200
      COMMON/NNNNNN/ITEN,ITENM,ITEND2,ND(100,7),I5SEC,VD(100,7)         G1     210
      COMMON /TTTTTT/ IDMODE(350),TAUA,TAUD,VLIMIT,KA,KD                G1     220
C                                                                       G1     230
C                                                                       G1     240
C          IBRNCH = 1, 2, 3, 4, 5     DISTANCE DETECTION MODE           G1     250
C          IBRNCH = 10                CAR FOLLOWING MODE                G1     260
C          IBRNCH = 11, 12, 13,...., 16  CAR FOLLOWING  +               G1     270
C                           ACC OF CAR IN FRONT HAS BEEN LESS THAN 1.0  G1     280
C                           FOR  (IBRNCH-10)  INTERVALS  (OF 0.2 SECS.) G1     290
C          IBRNCH = 50+                 SIGN FOLLOWING                  G1     300
C                                       ACTUAL IBRNCH = IBRNCH - 50     G1     310
C                                                                       G1     320
C                                                                       G1     330
C     ***************************************************************** G1     340
C                                                                       G1     350
C          IDMODE(I) CCNTROLS MAX. CECELERATION OF CAR I                G1     360
C              IDMODE = 0 MAX. DECEL. LIMITED TO -10                    G1     370
```

```
C                 IDMODE = 1 MAX DECEL. NOT LIMITED SINCE SPACING IS
C                              UNSAFE
C
C           AAA    = NEW VALUE OF ACCEL. FOR (CARNOW-1)-TH CAR
C
C           COMPUTE ACTUAL & DESIRED SPACINGS
C
      H = HDRV(CARNOW)
      DELTAV = VCAR(CARFOL+1) - VCAR(CARNO+1)
      SA = XCAR(CARNO+1) - XCAR(CARFOL+1) - 20.
      SD = H*VCAR(CARNO+1)
      DA = SA + 20.
      DD = SD + 20.
      SAOVSD = 1.0
      IF(SD .GT. 5.0) SAOVSD = SA/SD
      AAA = ANOW(CARNOW-1)
C
C           SEE WHICH MODE THIS CAR WAS IN (LAST TIME)
C
      IF( IBRNCH(CARNOW) .GT. 50 )  IBRNCH(CARNOW) = IBRNCH(CARNOW) - 50
      IBR = IBRNCH(CARNOW)
      ASSIGN 300 TO IBACK
      IF(IBR .GE. 10) GO TO 7000
C
C           LAST TIME CAR WAS IN DISTANCE DETECTION MODE (MODE ZERO)
C           CHECK TO SEE IF CAR REMAINS IN DISTANCE DETECTION MODE
C
      IF( ABS(AAA) .LE. 1.) GO TO (1,2,3,4,5),IBR
      IF( IBR .NE. 1 )  GO TO 250
      IBRNCH(CARNOW) = 10
      GO TO 7001
 250  IF(AAA .LT. -1.) GO TO 252
C
C           CAR AHEAD HAS ACCELERATION .GT. +1.0
C
      IF(IBR .EQ. 2) GO TO 2
      IF(IBR .EQ. 5) GO TO 5
```

```
      ASSIGN 254 TO IBACK
      GO TO 7001
 254  IF(ACF .GT. 2.0) GO TO 258
      IF(IBR .EQ. 4) GO TO 4
      GO TO 3
C
C          CAR AHEAD HAS ACCELERATION .LT. -1.0
C
 252  IF(IBR .EQ. 3) GO TO 3
      IF(IBR .EQ. 4) GO TO 4
      ASSIGN 256 TO IBACK
      GO TO 7001
 256  IF(ACF .LT. ANOW(CARNOW) )  GO TO 258
      IF(IBR .EQ. 2) GO TO 2
      GO TO 5
 258  IBRNCH(CARNOW) = 10
      GO TO 300
C
C
C        ++++++++++++++++++++++++++++++++++++++++
C        + ENTER DISTANCE DETECTION MODE        +
C        ++++++++++++++++++++++++++++++++++++++++
 1    CONTINUE
      Q = DA/DD
      IF(Q .LT. 0.85 + 1./(VCAR(CARNO+1)+10.)) GO TO 2
      IF(Q .GT. 1.2) GO TO 4
C
C          ACTUAL SPACING WITHIN 0.1 OF DESIRED SPACING
C
      ANOW(CARNOW)=0.
      IBRNCH(CARNOW) = 1
      GO TO 990
C
C          FOLLOWING TOO CLOSE
C
 2    CONTINUE
      IF(DELTAV .GT. 0.) GO TO 22
```

```
C
C          TOO CLOSE BUT SEPARATION IS INCREASING
C
      IF(DO-DA .GT. .25*DELTAV*DELTAV) GO TO 22
C
C          TOO CLOSE -- V2 .LT. V1 -- ACCELERATE UNTIL V2 = V1
C
 21   ANOW(CARNOW) = 2.
      IBRNCH(CARNOW) = 3
      GO TO 990
C
C          TOO CLOSE -- DECELERATE BY ENGINE BRAKING - FOOT OFF GAS
C                       USE 80 PER-CENT OF FULL ENGINE BRAKING
C
 22   ANOW(CARNOW) = (-0.03114286*VCAR(CARFOL+1) - 0.38955)*0.80
      IF(VCAR(CARFOL+1) .LT. 27.629) ANOW(CARNOW) = -1.0
      IBRNCH(CARNOW) = 2
      GO TO 990
  3   CONTINUE
      IF(DELTAV .LT. -.2) GO TO 21
      ANOW(CARNOW) = 0.
      IBRNCH(CARNOW) = 1
      GO TO 990
C
C          FOLLOWING TOO FAR
C
  4   CONTINUE
      IF(DELTAV .LE. 0.) GO TO 42
C
C          COMPUTE CHANGE IN SPACING THAT WOULD RESULT
C          IF DRIVER STOPPED ACCELERATING AT TNOW
C
      SAMSD = SA - SD
      IF( VCAR(CARFOL+1) .LE. 27.629) GO TO 46
      IF( VCAR(CARNO+1) .LT. 27.629) GO TO 45
      BPAV1 = (0.03114286*VCAR(CARNO+1) + 0.38955)*0.80
      ARG =(0.03114286 * VCAR(CARFOL+1) + 0.38955) / BPAV1*0.80
```

```
      DS2=(DELTAV-BPAV1*ALOG(ARG)/.03114286/.8)/.03114286/.8
      GO TO 47
 45   BPAV1 = (.03114286*27.629 + 0.38955)*0.80
      ARG =(0.03114286 * VCAR(CARFOL+1) + 0.38955) / BPAV1*0.80
      DS2 = ( VCAR(CARFOL+1) - 27.629 -BPAV1 * ALOG(ARG) / 0.80/
     1   0.03114286)/.03114286/.8 + (27.629 -VCAR(CARNO+1))*(27.629-
     2   VCAR(CARNO+1))*0.5
      GO TO 47
 46   DS2=-DELTAV*.2 - .2*.2*.5
C
C          SHOULD DRIVER REMOVE FOOT FROM GAS NOW?
C
 47   IF( SAMSD .GT. DS2 ) GO TO 42
C
C          USE 80 PER-CENT OF FULL ENGINE BRAKING
C
 41   ANOW(CARNOW) = (-0.03114286*VCAR(CARFOL+1) - 0.38955)*0.80
      IF(VCAR(CARFOL+1) .LT. 27.629) ANOW(CARNOW) =-1.0
      IBRNCH(CARNOW) = 5
      GO TO 990
 42   ANOW(CARNOW) = 2.
      IF( DELTAV .GT.12.0 ) ANOW(CARNOW)=0.
      IBRNCH(CARNOW) = 4
      GO TO 990
C          FOOT OFF GAS -- V2 .GT. V1 -- STAY IN MODE 5 UNTIL  V2=V1
C                                                            (APPROX.)
 5    CONTINUE
      IF(DELTAV .GT. -.1*ANOW(CARNOW) ) GO TO 41
      ANOW(CARNOW) = 0.
      IBRNCH(CARNOW) = 1
      GO TO 990
C        -----------------------------------------
C        - END OF DD MODE                        -
C        -----------------------------------------
C
C          LAST TIME CAR WAS IN CAR-FOLLOWING MODE
C
```

```
 7000 IF(ABS(AAA) .GT. 1.) IBRNCH(CARNOW) = 9
      IBRNCH(CARNOW) = IBRNCH(CARNOW) + 1
      IF( IBRNCH(CARNOW) .LT. 17) GO TO 7001
C
C          CHECK IF ANOW IS O.K. FOR CARNOW-TH CAR TO ENTER DD MODE
C
      IF(ANOW(CARNOW).LT.(-.03114286 *VCAR(CARFOL+1)-.38955)*.8.OR.
     1     ANOW(CARNOW).GT.2.) GO TO 7002
      IF(ABS(DELTAV)/(SA+1.)/(SA+1.) .GT. 2.E-4) GO TO 7002
      IBRNCH(CARNOW) = 1
      GO TO 1
C        ++++++++++++++++++++++++++++++++++++++++
C        + ENTER CAR FOLLOWING MODE  (MODE ONE)  +
C        ++++++++++++++++++++++++++++++++++++++++
7002  IBRNCH(CARNOW) = IBRNCH(CARNOW) - 1
 7001 DELVD = VCAR(CARNO+KD) - VCAR(CARFOL+KD)
      DELVA = VCAR(CARNO+KA) - VCAR(CARFOL+KA)
      IF(DELVD.LT.0.) GO TO 102
      IF(DELVA.LT.0.) GO TO 101
C
C          CAR EXPECTING TO ACCELERATE
C
      AMAX = 12.4 - 0.0913*VCAR(CARFOL+1)
      ACF = AMAX
      IF(DELVA.LT.2.*AMAX*H   ) ACF = DELVA/H*(1.-.25/H*DELVA/AMAX)
      IF(ACF .GT. 2.0) GO TO 93
C
C          IN C.F. MODE AND ANOW(CARNOW) .GE. 0.   .AND.  .LT. 2.0
C          CHECK IF ACCEL. SHOULD BE INCREASED DUE
C          TO LARGE FOLLOWING DISTANCE.
C          ADD TERM TO ACCEL. IF SA/SD .GT. 1.2
C
      IF(SAOVSD .LT. 1.2) GO TO 94
      FA = 2.0
      IF(SAOVSD .LT. 1.4) FA = (SAOVSD-1.2)*10.
      IF(ACF .GT. FA) GO TO 93
      ACF = FA
```

```
C
C          CORRECT ACCEL. IF SA/SD .LT. 1.6 .AND. ANOW(CARNOW-1) .LT. 0.
C                                                 .AND. DELTAV .GT. 0.
C
 93   IF(SAOVSD .GT. 1.6) GO TO 1000
 94   IF( DELTAV .LT. 0. .OR. AAA .GT. 0. )  GO TO 1000
      IF(AAA .LT. -4.0) GO TO 101
      ACF = (1.0 + AAA/4.0)*ACF
      GO TO 1000
 101  ACF = 0.
      GO TO 1000
C
C          CAR EXPECTING TO DECELERATE
C
 102  FACTOR = 1.0
      IF( VCAR(CARNO+1) .LE. 20.0 )  GO TO 107
      AOV = 20.0 / VCAR(CARNO+1)
      FACTOR = AOV + (1.-AOV)/SAOVSD
 107  PDELVD = FACTOR * DELVD/H
      IF(AAA .GE. 0. .OR. SAOVSD .GT. 1.6) GO TO 108
      PDELVD = PDELVD + SQRT((1.6-SAOVSD)/9.6)*AAA
 108  IF(PDELVD .GE. -10.) GO TO 103
C          SSAFE = 1/(2*AMAX)*( V1**2 - V2**2 + (AMAX-A2)*
C                                          (2*V2*TAU+A2*TAU**2)
C                         HERE TAU = 0.45 SEC.
      IF( IDMODE(CARNOW) .EQ. 1) GO TO 104
      SSAFE = 1./48.*(VCAR(CARFOL+1)**2 - VCAR(CARNO+1)**2 + (24.*ANOW(
     1CARNOW))*(.9*VCAR(CARFOL+1)+0.2025*ANOW(CARNOW)))
      IF(SA.LT.SSAFE) GO TO 105
      ACF = -10.
      GO TO 106
 105  IDMODE(CARNOW) = 1
      GO TO 104
 103  IDMODE(CARNOW) = 0
 104  ACF = PDELVD
 106  IF( DELTAV .GT. 0. .OR. AAA .LT. 0. )  GO TO 1000
      IF( AAA .GT. 4.0 )  GO TO 101
```

```
      ACF = ( 1.0 - AAA/4.0 )*ACF
C        -----------------------------------------
C        - END OF CF MODE                        -
C        -----------------------------------------
 1000 CONTINUE
C **
C **
      GO TO IBACK,(254,256,300)
C **
C **
300   ANOW(CARNOW) = ACF
C        *****************************************
C        * COMPUTE ACCELERATION DUE TO SIGNS     *
C        *****************************************
 990  IF( CONTRL.EQ.0 .OR. COMPLY(CARNOW).EQ.0 ) GO TO 992
C          LOCATE SIGN THAT DRIVER SAW TAUS SECONDS AGO
      NSIGN = XCAR(CARFOL + KSIGN)/528. + 1.
      IF( NSIGN .LT. 1 ) GO TO 992
      IF( NSIGN .GT. ITEN ) GO TO 992
C          WAS VSIGN CHANGED WITHIN LAST TAUS SECONDS
      IF( IFIFTH .LT. KSIGN ) GO TO 980
C          VSIGN WAS NOT CHANGED WITHIN LAST TAUS SECONDS
      IF( LSIGN(NSIGN) .EQ. OFF ) GO TO 992
      MSIGN = ISIGN
      GO TO 985
C          VSIGN WAS CHANGED WITHIN LAST TAUS SECONDS
 980  MSIGN = ISIGN - 1
      IF( MSIGN .EQ. 1 ) MSIGN = 7
C          WAS NSIGN ON DURING PREVIOUS 5 SEC INTERVAL
      IF( VSIGN(NSIGN,MSIGN) .GT. 1.E8 ) GO TO 992
C
C          ASIGN = ACCELERATION DUE TO SIGNS
C
 985  ASIGN = BETA*( VSIGN(NSIGN,MSIGN)-VCAR(CARFOL+KSIGN))
      IF( ASIGN .GE. ANOW(CARNOW) )  GO TO 992
      IFCL=1
      ANOW(CARNOW)=ASIGN
```

```
      IBRNCH(CARNOW) = IBRNCH(CARNOW) + 50
C
C        ************************************************************
C           UPDATE SECTION -- ANOW(CARNOW) HAS JUST BEEN COMPUTED
C        ************************************************************
C
 992  VCAR(CARFOL) = VCAR(CARFOL+1) + .2*ANOW(CARNOW)
      IF(VCAR(CARFOL).LT.VLIMIT) GO TO 510
      ANOW(CARNOW)=(VLIMIT-VCAR(CARFOL+1))*5.
      VCAR(CARFOL)=VLIMIT
      GO TO 991
510   IF(VCAR(CARFOL) .GE. 0.) GO TO 991
      VCAR(CARFOL) = 0.
      ANOW(CARNOW) = -5.*VCAR(CARFOL+1)
 991  XCAR(CARFOL)  =XCAR(CARFOL+1)+VCAR(CARFOL+1)*.2 + .02*ANOW(CARNOW)
      IF(XCAR(CARNO) - XCAR(CARFOL) .GE. 20.) GO TO 200
      XCAR(CARFOL) = XCAR(CARNO) - 20.
      VCAR(CARFOL) = 5.*(XCAR(CARFOL)-XCAR(CARFOL+1))
      ANOW(CARNOW) = 5.*(VCAR(CARFOL) - VCAR(CARFOL+1))
C
C           UPDATE ND AND VD --  DETECTOR INFORMATION
C
 200  C1=DECT(CARNOW)
      C2=XCAR(CARFOL)/528. + 1.
      IF(C2 .EQ. C1) GO TO 601
      DECT(CARNOW)=C2
      IF(C2 .GT. ITENP) GO TO 601
      ND(C1,I5SEC)=ND(C1,I5SEC) - 1
      VD(C1,I5SEC)=VCAR(CARFOL)
      IF(C2 .EQ. ITENP) GO TO 601
 600  ND(C2,I5SEC)=ND(C2,I5SEC) + 1
C
C
 601  IF(MOD(CARNOW,10).NE.0.OR.CARNOW.LT.CARA) GO TO 602
      JSP = CARNOW/10
      SPACE(JSP) = SPACE(JSP) + XCAR(CARNO) - XCAR(CARFOL)
      TSPACE(JSP) = TSPACE(JSP) + 1.0
```

```
602  IF(JVSET .EQ. 0 .OR. CARNOW .GT. 100) RETURN                         G1    3340
     IVSEC(CARNOW,JSEC) = HFIX(VCAR(CARFCL) + .5)                         G1    3350
     IF(IFCL.EQ.1) IVSEC(CARNOW,JSEC)=-IVSEC(CARNOW,JSEC)                 G1    3360
     IFCL = 0                                                             G1    3370
     RETURN                                                               G1    3380
     END                                                                  G1    3390
```

```
      SUBROUTINE ZAP
      INTEGER ENTER
      COMMON /KKKKKK/ESIG2,ETSTOP,ETOTLT,EPER,EPCMP,IEVAV1,IEDX,NENS,
     2               JENS,EQ,ESPACE(10),RR1
      COMMON /MMMMMM/IVPRNT,IV1,IV2,IFIFTH,IFOL,SPACE(10),TSPACE(10)
      COMMON /ZZZZZZ/ENTER,QHOUR,HMIN,HMODE,IR,      HBAR2,PCMPLY,PCMP
      DIMENSION IRENS(10)
      DATA IRENS/692739,688379,362991,443107,967765,619915,727273,
     2          866531,209831,747299/
      RR1 = 1.0
      ESIG2=0.
      ETSTOP=0.
      ETOTLT=0.
      EQ=0.
      EPER=0.
      EPCMP=0.
      IEVAV1=0
      IEDX=0
      IF(IVPRNT .EQ. 1 ) IVSAVE = 1
      DO 50  I= 1,10
   50 ESPACE(I) = 0.0
C
      DO 100 JENS=1,NENS
      IR=IRENS(JENS)
      CALL TITLE
      CALL HIWAY
      IVPRNT = 0
  100 CONTINUE
      IF( IVSAVE .EQ. 1 ) IVPRNT = 1
      RETURN
      END
```

```
      SUBROUTINE SETSGN
      IMPLICIT INTEGER(C,I-N)
      INTEGER*2  ND,IBRNCH,NSON,NSFULL,LMTAG(100),COMPLY
      INTEGER ON, OFF
      DIMENSION    HOKK(100)
      COMMON XCAR(3861),VCAR(3861),ANOW(350),CYCLE1,CARONE,TNOW,CARA,
     1 CARZ, CYCLEZ, CYCLEA
      COMMON /AAAAAA/ NCARS,NMILE,VSTART,TXPRNT,          IBRNCH(350),
     1 CARNOW,        NOPRNT,CONTRL,ON,OFF,BETA,TAUS,KSIGN,LSIGN(100),
     2 HBAR,HDRV(350),COMPLY(350),VSIGN(100,7)
      COMMON /CCCCCC/CBUG1,CROUND,SGNC
      COMMON/NNNNNN/ITEN,ITENM,ITEND2,ND(100,7),I5SEC,VD(100,7)
      COMMON /UUUUUU/ NSON(100),NSFULL(100),NFT(100),HTEST,VSTARX
      DATA Y/7.333333/
      IF( CBUG1 .EQ. 0 ) GO TO 201
      CALL STEPH( TNOW,MIN,ISEC,SEC )
      WRITE(6,900)MIN,ISEC,SEC
  900 FORMAT(1H1,'T=',I2,'-',I1,F3.1,////)
      DO 200 K=1,NMILE
      K2 = 10*K
      K1 = K2 - 9
      IF( K .EQ. 6 ) WRITE(6,914)
  914 FORMAT(1H1)
  200 WRITE(6,901)(I,I=K1,K2),(I,I=K1,K2),(ND(I,I5SEC),I=K1,K2),
     1(VD(I,I5SEC),I=K1,K2),(NFT(I),I=K1,K2)
  901 FORMAT(3X,10(10X,'S',I2)/1X,'*',10(12X,'*')/1X,'*',10(1X,'SECTION
     1',I2,1X,'*')/1X,'*',10(3X,'ND=',I2,4X,'*')/3X,10(8X,F5.1)/
     2  3X,10(8X,I5)////)
  201 CONTINUE
C
C          LOCATE SECTION OCCUPIED BY FIRST CAR AND BY LAST CAR
C                 LAST CAR ON SECTION NL
C                FIRST CAR ON SECTION NF
C
      NL=XCAR(CYCLEZ)/528.+1.
      NF=XCAR(CYCLEA)/528.+1.
      IF( CBUG1.EQ. 1 ) WRITE(6,910)NF,NL
```

```
  910 FORMAT(1X,'FIRST CAR IS ON SECTION',I3,'   LAST CAR IS ON SECTION'
     1,I3)
C
C           SET ALL SIGNS OFF
C
      DO 300 I=1,ITEN
      LMTAG(I) = 9999
      VSIGN(I,I5SEC)=1.E10
  300 LSIGN(I)=OFF
C
C           CHECK IF SIGN 1 SHOULD BE SET
C           ARE THERE ANY CARS ON SECTION 1
C
      IF(CARZ.EQ.NCARS.OR.NL.NE.1.OR.NF.EQ.1)  GO TO 320
C           SECTION 1 IS NOT EMPTY
      IF( VSTARX.GT.VD(1, I5SEC).AND.VD(2,I5SEC).GE.VD(1,I5SEC))GO TO 310
      GO TO 320
C           SET SIGN 1
  310 VSIGN(1,I5SEC)=VD(1,I5SEC)
      LSIGN(1)=ON
      NSON(1)= NSON(1)+1
      LMTAG(1) = VD(1,I5SEC)
      IF( CBUG1 .EQ. 1 ) WRITE(6,902) VSIGN(1,I5SEC)
  902 FORMAT(1X,'SIGN 1 IS SET TO',F5.1)
C
C          LOOK FOR LOCAL MINIMUM
C           FIRST CHECKPOINT IS VD(NL+1)
C
  320 LM=NL+1
      IF( CBUG1 .EQ. 1 .AND. LSIGN(1) .EQ. OFF) WRITE(6,903)
  903 FORMAT(1X,'SIGN 1 WILL NOT BE SET')
C
C           DETERMINE LAST CHECKPOINT LMLAST
C
      LMLAST=NF-1
      IF(CARA.NE.1 .AND. NF.EQ.ITEN) LMLAST=NF
C
```

```
C          ARE THERE MORE DETECTORS TO BE CHECKED?
C
      IF(LMLAST-LM.LE.-1) GO TO 600
C
      IF( CBUG1 .EQ. 1 ) WRITE(6,904) LM
 904  FORMAT(1X,'CHECK FOR LOCAL MINIMUM STARTING AT VD(',I2,')')
      IF( CBUG1 .EQ. 1 ) WRITE(6,905) LMLAST
 905  FORMAT(1X,'LAST CHECKPOINT IS VD(',I3,')'// )
C
C
C          CHECK FOR LOCAL MINIMA FROM STATIONS LM TO LMLAST
C
      DO 500 I=LM,LMLAST
      IF(I.EQ.LMLAST) GO TO 330
      IF(VD(I-1,I5SEC).GT.VD(I,I5SEC).AND.VD(I+1,I5SEC).GE.VD(I,I5SEC))
     2                       GO TO 340
      GO TC 500
C          CHECK FOR LOCAL MINIMUM FOR VD(LMLAST,I5SEC)
 330  IF(VD(I,I5SEC).LT.VD(I-1,I5SEC)) GO TO 340
      GO TO 500
C
C          LOCAL MINIMUM FOUND -- SET SIGNS BACK TO SIGN 1 OR SIGN NL+1
C
 340  NBEGIN=NL+1
      IF(LSIGN(1).EQ.ON) NBEGIN=1
C
C
      IF( CBUG1 .EQ. 1 ) WRITE(6,906) I,NBEGIN
 906  FORMAT( 1X,'LOCAL MIN. FOUND AT VD(',I3,').  SET SIGNS BACK TO SIGN
     1',I4)
      DO 400 J=NBEGIN,I
      JJ=I+NBEGIN-J
C
C          CHECK LMTAG(JJ) ---  WAS SIGN JJ PREVIOUSLY CONSIDERED
C          DUE TO LOCAL MINIMUM OF SMALLER VALUE FURTHER UPSTREAM
C
      IF( LMTAG(JJ) .LT. VD(I,I5SEC) ) GC TO 384
```

```
C                                                                       SETS 1120
C                                                                       SETS 1130
C          SKIP SIGN SETTING AT LOCAL MINIMUM                           SETS 1140
C                                                                       SETS 1150
      IF( J .EQ. NBEGIN ) GO TO 385                                     SETS 1160
C                                                                       SETS 1170
C          LMTAG(JJ) NOT CHANGED FOR SIGN LOCATED AT LOCAL MINIMUM     SETS 1180
C                                                                       SETS 1190
      LMTAG(JJ) = VD(I,I5SEC)                                           SETS 1200
C                                                                       SETS 1210
C          CALCULATIONS FOR SETTING JJ-TH SIGN                          SETS 1220
      IF(JJ.GT.1) VIM1=VD(JJ-1,I5SEC)                                   SETS 1230
      IF(JJ.EQ.1) VIM1=VSTARX                                           SETS 1240
C          COMPUTE INITIAL SPACING OVER THE JCARS VEHICLES              SETS 1250
      KK=I-JJ+1                                                         SETS 1260
      S1=FLOAT(KK)*528.                                                 SETS 1270
C          COMPUTE ESTIMATED FINAL SPACING                              SETS 1280
      S2 = 0.                                                           SETS 1290
      KJ = 0                                                            SETS 1300
      DO 393 K=JJ,I                                                     SETS 1310
      KJ=KJ+1                                                           SETS 1320
      ND4=ND(K,I5SEC)                                                   SETS 1330
      FND4=FLOAT(ND4)                                                   SETS 1340
      VDK=VD(K,I5SEC)                                                   SETS 1350
      IF( K .EQ. 1 ) VDM=VSTARX                                         SETS 1360
      IF( K .NE. 1 ) VDM=VD(K-1,I5SEC)                                  SETS 1370
      VKBAR=(VDK+VDM)*0.5                                               SETS 1380
      IF( ND4 .GT. 15 .OR. VDK .LT. 10. ) GO TO 391                     SETS 1390
      IF( ND4 .EQ. 0 ) GO TO 396                                        SETS 1400
      HDK=(528./FND4 - 20.)/VKBAR                                       SETS 1410
      IF(HDK.LT.HTEST)GO TO 341                                         SETS 1420
      HDK=HTEST                                                         SETS 1430
      IF(CBUG1.EQ.1) WRITE(6,941) K                                     SETS 1440
941   FORMAT(' ','*** HDK(',I2,') IS TOO LARGE... REPLACED BY HTEST')   SETS 1450
341   HDKK(KJ)=HDK                                                      SETS 1460
      DK=(HDK*VD(I,I5SEC)+20.)*FND4                                     SETS 1470
      GO TO 392                                                         SETS 1480
```

```
 396  HDKK(KJ) = 0.                                                          SETS 1490
      DK = 0.                                                                SETS 1500
      GO TO 392                                                              SETS 1510
 391  DK=(HBAR*VD(I,I5SEC)+20.)*FND4                                         SETS 1520
      HDKK(KJ)=HBAR                                                          SETS 1530
 392  S2=S2+DK                                                               SETS 1540
 393  CONTINUE                                                               SETS 1550
C           COMPUTE OPTIMUM ACCELERATION ON SECTION JJ (NEGATIVE)            SETS 1560
      DV = VIM1-VD(I,I5SEC)                                                  SETS 1570
      IF(DV .LE. 0.) GO TO 374                                               SETS 1580
      DV2=DV*DV                                                              SETS 1590
      DS = S2 - S1                                                           SETS 1600
      IF(DS.GT.0.) GO TO 377                                                 SETS 1610
      TSIGN = - DS * 2. / DV                                                 SETS 1620
      AOPT =-DV/TSIGN                                                        SETS 1630
C           COMPUTE SETTING FOR JJ-TH SIGN                                   SETS 1640
      SARG = VIM1*VIM1 + SGNC*AOPT                                           SETS 1650
      IF(SARG .GT. 0.) GO TO 375                                             SETS 1660
      VSJJ = 0.                                                              SETS 1670
      GO TO 376                                                              SETS 1680
 374  IF(CBUG1 .EQ. 1) WRITE(6,930) JJ,I,DV                                  SETS 1690
 930  FORMAT(9X,'SIGN',I4,' NOT SET SINCE DV=VIM1-VD(',I3,')=',F6.1,         SETS 1700
     2   ' IS NEGATIVE' //  )                                                SETS 1710
      GO TO 400                                                              SETS 1720
 377  IF(CBUG1.EQ.1) WRITE(6,921) JJ,DS                                      SETS 1730
 921  FORMAT(9X,'SIGN',I3,' NOT SET SINCE DS = S2 - S1 =',F5.1,              SETS 1740
     2 ' IS POSITIVE'//)                                                     SETS 1750
      GO TO 400                                                              SETS 1760
 375  VSJJ = SQRT(SARG)                                                      SETS 1770
 376  CONTINUE                                                               SETS 1780
      TMIN=528./VDM                                                          SETS 1790
      IF(TSIGN.GT.TMIN) GO TO 397                                            SETS 1800
      WRITE(6,922) JJ,TNOW,TSIGN,TMIN,DV,DS,S1,AOPT,VSJJ                     SETS 1810
 922  FORMAT( /1X,125('*'),/1X,'SIGN',I3,3X,'TNOW=',F6.1,3X,'TSIGN=',        SETS 1820
     2 F5.1,' .LT. TMIN=',F5.1,3X,'DV=',F5.1,3X,'DS=',F5.0,                  SETS 1830
     3 3X,'S1=',F6.0,3X,'AOPT=',F6.2,3X,'VSJJ(TENT.)=',F5.1,' FT/SEC')       SETS 1840
      VSJJ=VD(JJ,I5SEC)                                                      SETS 1850
```

```
      WRITE(6,923) JJ,VSJJ                                              SETS 1860
  923 FORMAT(1X,'SET SIGN',I3,' TO',F5.1,' FT/SEC = VALUE FROM DETECTOR  SETS 1870
     2AT LOCATION OF SIGN'/1X,125('*')/ )                               SETS 1880
  397 IF( CBUG1 .EQ. 0 ) GO TO 202                                      SETS 1890
      JJM = JJ - 1                                                      SETS 1900
      WRITE(6,915) JJ,JJM,VIM1,VC(I,I5SEC),S1,S2,DS                     SETS 1910
  915 FORMAT(6X,'NOW SETTING SIGN',I3,' FOR IMAGINARY CAR LOCATED AT SIG SETS 1920
     2N',I3,/9X,'ASSUMED INITIAL VELOCITY =',F5.1,'  AND ASSUMED FINAL V SETS 1930
     3ELOCITY =',F5.1,/11X,'INITIAL SPACING =',F6.0,' FEET AND'         SETS 1940
     4 ' FINAL SPACING =',F6.0,' FEET',5X,'S2 - S1 =',F6.0)             SETS 1950
      WRITE(6,916)  ( IA,HDKK(IA-JJ+1),  IA=JJ,I )                      SETS 1960
  916 FORMAT( (11X,7('H(',I2,')=',F4.2,3X) ) )                          SETS 1970
      WRITE(6,917) DV,DV2,TSIGN,AOPT,SARG,VSJJ                          SETS 1980
  917 FORMAT(                                                           SETS 1990
     211X,'DV =',F6.2,' FT/SEC',5X,'DV*DV =',F7.2,' TSIGN=',F5.1,' SEC.' SETS 2000
     3,5X,'AOPT =',F6.2,' FT/(SEC)**2',5X,'SARG =',F8.1/ 9X,'COMPUTED SI SETS 2010
     4GN SETTING = VSJJ =',F6.1,' FT/SEC')                              SETS 2020
  202 CONTINUE                                                          SETS 2030
      IF( VSJJ .LT. VIM1 ) GO TO 380                                    SETS 2040
      IF( CBUG1 .EQ. 1 ) WRITE(6,911)                                   SETS 2050
  911 FORMAT(6X,'SIGN NOT SET BECAUSE COMPUTED SETTING IS GREATER THAN S SETS 2060
     2PEED OF CAR 528 FEET UPSTREAM' // )                               SETS 2070
      GO TO 400                                                         SETS 2080
  380 IF( VSJJ .LT. VSIGN(JJ,I5SEC) ) GO TO 381                         SETS 2090
      IF( CBUG1 .EQ. 1 ) WRITE(6,912)                                   SETS 2100
  912 FORMAT(6X,'SIGN NOT SET BECAUSE COMPUTED SETTING IS GREATER THAN P SETS 2110
     2REVIOUS SETTING' // )                                             SETS 2120
      GO TO 400                                                         SETS 2130
  381 IF( ND(JJ,I5SEC) .NE. 0 ) GO TO 382                               SETS 2140
      IF( CBUG1 .EQ. 1 ) WRITE(6,913) JJ                                SETS 2150
  913 FORMAT(6X,'SIGN NOT SET BECAUSE THERE ARE NO CARS ON SECTION',I3 / SETS 2160
     2/ )                                                               SETS 2170
      GO TO 400                                                         SETS 2180
  385 IF( CBUG1 .EQ. 1 ) WRITE(6,920)                                   SETS 2190
  920 FORMAT(1X,'SKIP SETTING OF SIGN LOCATED AT LOCAL MINIMUM'//)      SETS 2200
      GO TO 400                                                         SETS 2210
  384 IF( CBUG1 .EQ. 1 ) WRITE(6,918) JJ,LMTAG(JJ)                      SETS 2220
```

```
 918  FORMAT(6X,'SIGN',I3,' HAS BEEN PREVIOUSLY CONSIDERED DUE TO LOCAL  SETS 2230
     2MINIMUM FURTHER UPSTREAM OF SMALLER VALUE, I.E.',I4,' FT/SEC' //   SETS 2240
     3  1X,'**STOP SCANNING SIGNS AND LOOK FOR OTHER LOC. MINIMA FURTHER SETS 2250
     4 DOWNSTREAM' // )                                                 SETS 2260
      GO TO 500                                                         SETS 2270
C          SET JJ-TH SIGN                                               SETS 2280
 382  VSIGN(JJ,I5SEC)=VSJJ                                              SETS 2290
      IF( CBUG1 .EQ. 0 ) GO TO 383                                      SETS 2300
      IF( LSIGN(JJ) .EQ. OFF) WRITE(6,908) JJ,VSJJ                      SETS 2310
      IF( LSIGN(JJ) .EQ. ON ) WRITE(6,909)JJ,VSJJ                       SETS 2320
 908  FORMAT(11X,'SET SIGN',I3,' TO',F6.1// )                           SETS 2330
 909  FORMAT(11X,'RE-SET SIGN',I3,' TO',F6.1// )                        SETS 2340
 383  IF(I.NE.JJ .OR. VSJJ.GT.VD(JJ,I5SEC)-2.) GO TO 203                SETS 2350
      VSIGN(JJ,I5SEC)=VD(JJ,I5SEC)-2.                                   SETS 2360
      IF(CBUG1.EQ.1) WRITE(6,931) JJ,VSIGN(JJ,I5SEC)                    SETS 2370
 931  FORMAT(11X,'SIGN',I4,' IS AT LOCAL MINIMUM.  RE-SET SIGN TO',     SETS 2380
     2  F6.1// )                                                        SETS 2390
 203  CONTINUE                                                          SETS 2400
      IF( LSIGN(JJ) .EQ. ON ) GO TO 400                                 SETS 2410
      LSIGN(JJ)=ON                                                      SETS 2420
      NSON(JJ) = NSON(JJ)+1                                             SETS 2430
 400  CONTINUE                                                          SETS 2440
 500  CONTINUE                                                          SETS 2450
 600  DO 700 I=1,ITEN                                                   SETS 2460
      IF( ND(I,I5SEC) .EQ. 0 ) GO TO 700                                SETS 2470
      NSFULL(I)= NSFULL(I)+1                                            SETS 2480
 700  CONTINUE                                                          SETS 2490
      IF( CROUND .EQ. 0 ) GO TO 950                                     SETS 2500
C                                                                       SETS 2510
C          ROUND SIGN SETTING -- POSSIBLY SET SOME OFF                  SETS 2520
C                                                                       SETS 2530
      IF(CBUG1 .EQ. 1) WRITE(6,801)                                     SETS 2540
 801  FORMAT(  1X,'RESULTS OF ROUNDING'/ )                              SETS 2550
      DO 720 I=1,ITEN                                                   SETS 2560
      VSIG=VSIGN(I,I5SEC)                                               SETS 2570
      IF(LSIGN(I) .EQ. OFF ) GO TO 720                                  SETS 2580
      IF( I .EQ. 1 ) VIM=VSTARX                                         SETS 2590
```

```
      IF( I .NE. 1 ) VIM=VD(I-1,I5SEC)                                  SETS 2600
      IF( VIM - VSIG .GT. 3.666667 ) GO TO 710                          SETS 2610
C           VD-VSIGN IS SMALL --- SET SIGN I OFF                        SETS 2620
 705  LSIGN(I)=OFF                                                      SETS 2630
      VSIGN(I,I5SEC)=9.E10                                              SETS 2640
      NSON(I)=NSON(I)-1                                                 SETS 2650
      IF(CBUG1.EQ.1) WRITE(6,702) I                                     SETS 2660
 702  FORMAT(8X,'VIM - VSIGN IS LESS THAN 3.666667 --- SET SIGN',I4,   SETS 2670
     2  ' OFF')                                                         SETS 2680
      GO TO 720                                                         SETS 2690
C           ROUND SIGN I                                                SETS 2700
 710  VSIGN(I,I5SEC) = FLOAT( IFIX(VSIG/Y+.5) )*Y                       SETS 2710
      IF( CBUG1 .EQ.1) WRITE(6,703) I, VSIGN(I,I5SEC)                   SETS 2720
 703  FORMAT(1X,'SIGN',I4,' ROUNDED TO',F6.1)                           SETS 2730
      IF( VIM-VSIGN(I,I5SEC) .LT. 3.666667 ) GO TO 705                  SETS 2740
 720  CONTINUE                                                          SETS 2750
C                                                                       SETS 2760
C                                                                       SETS 2770
 950  CONTINUE                                                          SETS 2780
C           CHECK WHETHER SIGN SEEN BY CARZ SHOULD BE SET               SETS 2790
      IF( LSIGN(NL) .EQ. ON ) GO TO 1C00                                SETS 2800
      IF( NL .EQ. ITEN ) GO TO 1000                                     SETS 2810
      IF( LSIGN(LM) .EQ. OFF ) GC TO 1000                               SETS 2820
      VSIGN(NL,I5SEC) = VSIGN(LM,I5SEC)                                 SETS 2830
      LSIGN(NL) = ON                                                    SETS 2840
      NSON(NL) = NSCN(NL) + 1                                           SETS 2850
      IF( CBUG1 .EQ. 1 ) WRITE(6,831) VSIGN(NL,I5SEC),LM                SETS 2860
 831  FORMAT( /1X,'SET SIGN SEEN BY LAST CAR ON ROAD TO',F6.1,'.  SAME A SETS 2870
     1S SIGN',I4//)                                                     SETS 2880
 1000 CONTINUE                                                          SETS 2890
      RETURN                                                            SETS 2900
      END                                                               SETS 2910
```

```
      SUBROUTINE STEPH(XIN,I1,I2,FT1)                                   STEP  10
C          XIN = INPUT IN SECONDS                                       STEP  20
C          I1 = # OF MINUTES                                            STEP  30
C          I2 = # OF 10 SECONDS                                         STEP  40
C          FT1 = SECONDS & FRACTION OF SECOND                           STEP  50
C                                                                       STEP  60
      I1= XIN / 60. +.0001                                              STEP  70
      F = XIN - 60.*FLOAT(I1)                                           STEP  80
      I2 = F / 10.                                                      STEP  90
      FT1= F - 10.*FLOAT(I2)                                            STEP 100
      IF( FT1 .LE. 0.0 )  FT1 = +0.0                                    STEP 110
      IF(FT1.LT. 9.95) GO TO 111                                        STEP 120
      FT1 = 0.0                                                         STEP 130
      I2 = I2 + 1                                                       STEP 140
      IF(I2 .LE. 5) GO TO 111                                           STEP 150
      I2 = 0                                                            STEP 160
      I1 = I1 + 1                                                       STEP 170
111   RETURN                                                            STEP 180
      END                                                               STEP 190
```

```
      SUBROUTINE F3
      IMPLICIT INTEGER (C,I-N)
      INTEGER*2 JSEC, JVSET, IVSEC(100,5),CECT,IBRNCH,COMPLY
      INTEGER ON, OFF
      COMMON XCAR(3861),VCAR(3861),ANOW(350),CYCLE1,CARONE,TNOW,CARA,
     1 CARZ, CYCLEZ, CYCLEA
      COMMON /AAAAAA/ NCARS,NMILE,VSTART,TXPRNT,          IBRNCH(350),
     1 CARNOW,        NOPRNT,CONTRL,ON,OFF,BETA,TAUS,KSIGN,LSIGN(100),
     2 HBAR,HDRV(350),COMPLY(350),VSIGN(100,7)
      COMMON /BBBBBB/TF3(5),AF3(4),BASE,NREP,NREPI,VI3
      COMMON /GGGGGG/ ISIGN,JSEC,JVSET,IVSEC,IVP,ITENP,CECT(350)
C
C           THIS SUBROUTINE UPDATES THE CARONE-TH CAR
C                I.E.  THE FURTHEST CAR ON HIGHWAY OR EXTENSION
C
C           LEAD CAR GOES ACCORDING TO CONSTANTS TF3(I) AND AF3(I)
C           TNOW REPRESENTS OLD TIME
C           COMPUTED VALUE OF 'ACC' REPRESENTS ACCEL. AT TNOW
C           COMPUTED VALUES OF 'XCAR' & 'VCAR' ARE FOR T=TNOW+.2
C
      IF( CARONE .NE. 1 ) GO TO 60
   50 IF( TNOW.GT.TF3(1) .AND. NREPI.NE.NREP ) GO TO 100
   60 ANCW(CARONE)=0.
      GO TO 600
  100 IF( TNOW .GT. TF3(2)+BASE ) GO TO 200
      ANOW(CARONE)=AF3(1)
      GO TO 600
  2CC IF( TNOh .GT. TF3(3)+BASE ) GO TO 300
      ANOW(CARONE)=AF3(2)
      GO TO 600
  300  IF( TNOW .GT. TF3(4)+BASE ) GO TO 400
      ANOW(CARONE)=AF3(3)
      GO TO 600
  400 IF( TNOh .GT. TF3(5)+BASE ) GC TC 5CO
      ANOW(CARONE)=AF3(4)
      GO TO 6CO
  500 NREPI = NREPI + 1
```

```
      BASE = BASE + TF3(5) - TF3(1)
      GO TO 50
C            UPDATE XCAR AND VCAR
 600  VCAR(CYCLE1)=VCAR(CYCLE1+1) + ANOW(CARONE)*0.2
      XCAR(CYCLE1) = XCAR(CYCLE1+1) + VCAR(CYCLE1+1)*0.2 + ANOW(CARONE)*
     2  0.02
C
C            UPDATE DETECTORS
C
      CALL NDVD
C
      IF(JVSET .EQ. 0.OR. CARONE .GT. 100) RETURN
      IVSEC(CARONE,JSEC) = HFIX(VCAR(CYCLE1)+0.5)
      RETURN
      END
```

```
      SUBROUTINE NDVD
C
C          UPDATE ND AND VD -- DETECTOR INFORMATION
C          THIS SUBROUTINE IS CALLED BY F3
C
      IMPLICIT INTEGER (C,I-N)
      INTEGER*2 ND,      CECT,JSEC,JVSET,IVSEC(10C,5)
      COMMON XCAR(3861),VCAR(3861),ANOW(350),CYCLE1,CARONE,TNOW,CARA,
     2  CARZ,CYCLEZ,CYCLEA
      COMMON /GGGGGG/ ISIGN,JSEC,JVSET,IVSEC,IVP,ITENP,CECT(350)
      COMMON/NNNNNN/ITEN,ITENM,ITEND2,ND(100,7),I5SEC,VD(100,7)
      C1 = CECT(CARONE)
      C2=XCAR(CYCLE1)/528. + 1.
      IF(C2 .EQ. C1) GO TO 601
      CECT(CARONE) = C2
      IF(C2 .GT. ITENP) GO TO 601
      IF(C2 .EQ. 1) GO TO 600
      ND(C1,I5SEC) = ND(C1,I5SEC) - 1
      VD(C1,I5SEC) = VCAR(CYCLE1)
      IF(C2 .EQ. ITENP) GO TO 601
  600 ND(C2,I5SEC) = ND(C2,I5SEC) + 1
  601 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FINISH
      IMPLICIT INTEGER (C,I-N)
      INTEGER*2 JSTOP, JEXIT, ND,COMPLY
      INTEGER*2 IDXOUT(350),IVOUT(350),IBRNCH,NSON,NSFULL
      INTEGER ON, OFF, ENTER
      COMMON /AAAAAA/ NCARS,NMILE,VSTART,TXPRNT,          IBRNCH(350),
     1 CARNOW,        NOPRNT,CONTRL,ON,OFF,BETA,TAUS,KSIGN,LSIGN(100),
     2 HBAR,HDRV(350),COMPLY(350),VSIGN(100,7)
      COMMON /BBBBBB/TF3(5),AF3(4),BASE,NREP,NREPI,VI3
      COMMEN /CCCCCC/CBUG1,CROUND,SGNC
      COMMON /FFFFFF/TOTALT,ATOTAL(350),TRAVEL(350),JEXIT(350),
     1               JSTOP(350),IDXOUT,IVOUT
      COMMON /KKKKKK/ESIG2,ETSTOP,ETOTLT,EPER,EPCMP,IEVAV1,IEOX,NENS,
     2               JENS,EQ,ESPACE(10),RR1
      COMMON /MMMMMM/IVPRNT,TV1,TV2,IFIFTH,IFOL,SPACE(10),TSPACE(10)
      COMMON/NNNNNN/ITEN,ITENM,ITEND2,ND(100,7),I5SEC,VD(100,7)
      COMMON /UUUUUU/ NSON(100),NSFULL(100),NFT(100),HTEST,VSTARX
      COMMON /ZZZZZZ/ENTER,QHOUR,HMIN,HMODE,IR,      HBAR2,PCMPLY,PCMP
C
      IF(NENS.GT.1)WRITE( 6,498) JENS,NENS
  498 FORMAT(1H1,'THIS RUN IS NUMBER',I2,' OF AN ENSEMBLE OF',I2,' RUNS'
     2       )
      IF(NENS.EQ.1) WRITE(6,499)
  499 FORMAT(1H1)
      WRITE(6,500) NCARS,NMILE
  500 FORMAT(1X ,'THIS RUN IS MADE WITH',I4,' CARS FOR',I3, ' MILES')
      WRITE(6,503)
  503 FORMAT(/1X,'THE LEAD CAR UNDERGOES REPETITIVE MANEUVERS USING SUBR
     2OUTINE F3')
      IF( ENTER .EQ. 1 ) GO TO 505
      PARMX=HBAR *VSTART+20.
      PARMT=HBAR+20./VSTART
      PARMQ=VSTART/PARMX*3600.
      QQ=PARMQ
      WRITE(6,5040) ENTER
 5040 FORMAT( //1X,'ENTER=',I2)
      WRITE(6,504) PARMX,PARMT,PARMQ
```

```
  504 FORMAT(  1X,'CARS ENTER THE HIGHWAY AT EQUAL SPACING OF', F6.1,
     2 ' FEET (TIME HEADWAY =', F6.2,' SEC), CORRESPONDING TO A FLOW OF'
     3 , F6.0,' VEH/HR' )
      GO TO 507
  505 TBAR2=HBAR2+20./VSTART
      QBAR2=3600./TBAR2
      QQ=QBAR2
      PARMX2=HBAR2*VSTART+20.
      WRITE(6,506) HBAR2,TBAR2,PARMX2,QBAR2
  506 FORMAT(//1X,'CARS ENTER THE HIGHWAY WITH RANDOM SPACINGS ( HBAR2 =
     2', F5.2, ' )  WITH AVERAGE TIME HEADWAY TBAR2 =', F5.2, ' , AVERAG
     3E SPACING OF', F6.1, ' FEET'  / 1X, 'CORRESPONDING TO A FLOW OF QB
     4AR2 =', F6.0, ' VEH/HR' )
  507 IF( CONTRL .EQ. 1 ) GO TO 509
      WRITE(6,508) CONTRL
  508 FORMAT(//1X,'CONTRL =',I2,' THIS RUN IS WITHOUT SIGN CONTROL' )
      GO TO 514
  509 WRITE(6,5091) CONTRL
 5091 FORMAT(//1X,'CONTRL =',I2,' THIS RUN IS WITH SIGN CONTROL' )
      IF( CROUND .EQ. 0 ) WRITE(6,510) CROUND
  510 FORMAT(/1X, 'CROUND =', I2, 3X, 'EXACT SIGN SETTINGS USED --- NO R
     2OUNDING' )
      IF( CROUND .NE. 0 ) WRITE(6,511) CROUND,CROUND
  511 FORMAT(/1X,'CROUND =',I2,3X,'SIGNS ROUNDED USING ALGORITHM',I2)
      WRITE(6,517) SGNC
  517 FORMAT(//1X,'SGNC   =',F7.1,3X,'VALUE OF CONSTANT USED TO COMPUTE
     2SIGN SETTINGS' )
  514 CONTINUE
C
      TAVG = TOTALT / NCARS
      IDXOUT(1) = 0
      ISUMV = IVOUT(1)
      ISUMDX = IDXOUT(1)
      DO 803 I = 2, NCARS
      ISUMV = ISUMV + IVOUT(I)
  803 ISUMDX = ISUMDX + IDXOUT(I)
      IVAVG = ISUMV/NCARS
```

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      ZIG=IVAVG                                                         FINI 750
      ZIG=ZIG*3600./5280.                                               FINI 760
      IVAVG1=ZIG                                                        FINI 770
      IDXAVG = ISUMDX/(NCARS-1)                                         FINI 780
      WRITE(6,611)                                                      FINI 790
 611  FORMAT(1H1,65X,'STOPPED',10X,'SPEED AT EXIT', 8X,'SPACING'        FINI 800
     1  ,7X,'HDRV'                                                      FINI 810
     2/67X,'TIME',12X,'FT/SEC  MI/HR', 7X,'EXIT',3X,'ENTER'/)           FINI 820
      TSTOPT=0.                                                         FINI 830
      DO 804 I = 1,NCARS                                                FINI 840
      CALL STEPH(TRAVEL(I),IT1,IT11,FT1)                                FINI 850
      JEXI = JEXIT(I)                                                   FINI 860
      TEXIT = FLOAT(JEXI    )/5.                                        FINI 870
      CALL STEPH(TEXIT   ,IT2,IT22,FT2)                                 FINI 880
      JSTO = JSTOP(I)                                                   FINI 890
      TSTOP = FLOAT(JSTO    )/5.                                        FINI 900
      TSTOPT=TSTOPT+TSTOP                                               FINI 910
      CALL STEPH(TSTOP   ,IT3,IT33,FT3)                                 FINI 920
      ZT4 = IVOUT(I)                                                    FINI 930
      IT4 = IFIX( ZT4*3600./5280.+.5 )                                  FINI 940
      HEADIN = HDRV(I)*VSTART + 20.                                     FINI 950
 804  WRITE(6,607) I, IT1, IT11, FT1 ,IT2, IT22, FT2, IT3, IT33, FT3,   FINI 960
     1 IVOUT(I),IT4,IDXOUT(I),HEADIN,HDRV(I)                            FINI 970
 607  FORMAT(' CAR(',I2,')  TOOK',I3,1H-,I1,F3.1,8X,'TIME OF EXIT =',I3, FINI 980
     11H-,I1,F3.1,13X,I3,1H-,I1,F3.1, 9X,I6  ,3X,I5  ,5X,I6  ,F7.0,F8.2) FINI 990
      CALL STEPH(TOTALT,IT1,IT11,FT1)                                   FINI 1000
      CALL STEPH(TAVG,IT2,IT22,FT2)                                     FINI 1010
      IT11 = 10*IT11 + FT1                                              FINI 1020
      FT2 = 10*IT22 + FT2                                               FINI 1030
      WRITE(6,602) IT1, IT11, IT2, FT2, IVAVG, IVAVG1, IDXAVG, TSTOPT   FINI 1040
 602  FORMAT(//' TOTAL TRAVEL TIME =',I5,' MIN.',I3,' SEC.'//' AVERAGE T FINI 1050
     1RAVEL TIME =',I4,' MIN.',F5.1,' SEC.'//' AVERAGE SPEED AT EXIT =', FINI 1060
     2I6  ,' FT/SEC  =',I6  ,' MI/HR'//' AVERAGE SPACING AT EXIT =',I6  FINI 1070
     3  ,' FT.'//' TOTAL STOPPED TIME =',F6.1,' SECONDS')               FINI 1080
      WRITE(6,605)                                                      FINI 1090
 605  FORMAT(1H1,10X,'ACCELERATION',20X,'STANDARD DEVIATION'/14X,'NOISE' FINI 1100
     1//12X,'SIGMA**2',28X,'SIGMA'/9X,'(FT/SEC-SEC)**2',14X,'(FT/SEC-SEC FINI 1110
```

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     2)',3X,'(UNITS OF G)'/)
      TSIG2 = 0.
      DO 805 I = 2,NCARS
      JSTO = JSTOP(I)
      TSTOP=FLOAT(JSTO)/5.
      JEXI = JEXIT(I)
      TEXIT = FLOAT(JEXI) / 5.
      SIGMA2 = .2/(TEXIT-TF3(1)-TSTOP)*ATOTAL(I)
      SIGMA = SQRT(SIGMA2)
      GS = SIGMA / 32.174
      TSIG2 = TSIG2 + SIGMA2
      WRITE(6,606) I, SIGMA2, SIGMA, GS
606   FORMAT(' CAR',I3,F12.3,F29.4,F14.3)
805   CONTINUE
      AVSIG2 = TSIG2/FLOAT(NCARS-1)
      AVSIG = SQRT(AVSIG2)
      AVSIG1 = AVSIG/32.174
      WRITE(6,608) TSIG2, AVSIG2, AVSIG, AVSIG1
608   FORMAT(//' TSIG2 = TOTAL ACC. NOISE (EXCLUDING CAR 1) =',F8.3,' (F
     1T/SEC-SEC)**2'//' AVSIG2 = TSIG2/(NCARS-1) = AVER. ACC. NOISE =',
     2F7.3,' (FT/SEC-SEC)**2'//' AVSIG = SQRT(AVSIG2) = STANDARD DEVIATI
     3ON OF ACC. NOISE =',F6.3,' FT/SEC-SEC =',F5.3,' G')
      WRITE(6,906)
906   FORMAT(1H1,'AVERAGE SPACING FOR EVERY TENTH VEHICLE'//)
      IND = NCARS/10
      DO 610 JSP = 1,IND
      SPACE(JSP) = SPACE(JSP)/TSPACE(JSP)
      JCAR = JSP*10
      WRITE(6,907) JCAR,SPACE(JSP)
907   FORMAT(3X,'CAR',I4,3X,'AV. SPACING =',F7.2,' FT.')
610   ESPACE(JSP) = ESPACE(JSP) + SPACE(JSP)
      IF( CONTRL .EQ. 0 ) GO TO 704
      WRITE(6,900)
900   FORMAT(1H1,23X,'DUTY CYCLE FOR ADVISORY SIGNS'//2X, 'DUTY CYCLE
     2= 100 * (TIME SIGN K IS ON) / (TIME SECTION K IS NON-EMPTY)' ///
     3 17X, 'NUMBER OF 5 SEC. INTERVALS' /
     4 10X, 'SIGN',6X, 'SIGN',8X,'SECTION IS', 5X,'DUTY CYCLE   SIGN'/
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     5 9X,'NUMBER     IS ON       NON-EMPTY      (PERCENT)   NUMBER'//) FINI 1490
      INN1=0                                                            FINI 1500
      INN2=0                                                            FINI 1510
      DO 700 I=1,ITEN                                                   FINI 1520
      IN1= NSON(I)                                                      FINI 1530
      IN2= NSFULL(I)                                                    FINI 1540
      PER= FLOAT(IN1)/FLOAT(IN2) * 100.                                 FINI 1550
      INN1=INN1+IN1                                                     FINI 1560
      INN2=INN2+IN2                                                     FINI 1570
  700 WRITE(6,901)  I, IN1, IN2, PER, I                                 FINI 1580
  901 FORMAT( 11X, I3, 6X, I3, 11X, I3, 10X, F6.1, 7X, I3 )             FINI 1590
      PER=FLOAT(INN1)/FLOAT(INN2)*100.                                  FINI 1600
      WRITE(6,902) PER                                                  FINI 1610
  902 FORMAT(///1X,'(SIGN-ON TIME) / (SECTION NON-EMPTY TIME) * 100 =', FINI 1620
     2 F6.1, '  (PERCENT)' )                                            FINI 1630
      WRITE(6,903)                                                      FINI 1640
  903 FORMAT(1H1,40X,'COMPLIANCE FACTORS'/60X,'FACTOR=1   CAR FOLLOWS SI FINI 1650
     2GN'/60X,'FACTOR=0   CAR IGNORES SIGN'//1X,5('CAR NO.   FACTOR',7X) FINI 1660
     3 //)                                                              FINI 1670
      WRITE(6,904) (I,COMPLY(I),I=2,NCARS)                              FINI 1680
  904 FORMAT((3X,5(I3,7X,I1,12X)))                                      FINI 1690
      WRITE(6,905) PCMPLY,PCMP                                          FINI 1700
  905 FORMAT(///1X,'PCMPLY =',F5.3,'   DESIRED FRACTION OF COMPLYING CAR FINI 1710
     2S'/ 1X,'PCMP   =',F5.3,'   ACTUAL  FRACTION OF COMPLYING CARS')   FINI 1720
  704 IF( NENS .EQ. 1 ) RETURN                                          FINI 1730
      ESIG2 = ESIG2 + AVSIG2                                            FINI 1740
      ETSTOP = ETSTOP + TSTOPT                                          FINI 1750
      ETOTLT = ETOTLT + TOTALT                                          FINI 1760
      EQ = EQ + QQ                                                      FINI 1770
      IEVAV1 = IEVAV1 + IVAVG1                                          FINI 1780
      EPER = EPER + PER                                                 FINI 1790
      EPCMP = EPCMP + PCMP                                              FINI 1800
      IEDX = IEDX + IDXAVG                                              FINI 1810
      IF( JENS .LT. NENS ) RETURN                                       FINI 1820
C           COMPUTE ENSEMBLE AVERAGES                                   FINI 1830
      FNENS = FLOAT(NENS)                                               FINI 1840
      ESIG2 = ESIG2/FNENS                                               FINI 1850
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      ETSTOP = ETSTOP/FNENS                                             FINI 1860
      ETOTLT = ETOTLT/FNENS                                             FINI 1870
      EQ = EQ/FNENS                                                     FINI 1880
      IEVAV1 = FLOAT(IEVAV1)/FNENS + 0.5                                FINI 1890
      EPER = EPER/FNENS                                                 FINI 1900
      EPCMP = EPCMP/FNENS                                               FINI 1910
      IEDX = FLOAT(IEDX)/FNENS + 0.5                                    FINI 1920
C          WRITE HEADING DESCRIBING ENSEMBLE OF RUNS                    FINI 1930
      WRITE(6,699) NENS,NCARS,NMILE,      ENTER,EQ,CONTRL               FINI 1940
  699 FORMAT( 1H1,20X,'ENSEMBLE STATISTICS FOR',I2,' RUNS'//            FINI 1950
     2  1X,'NCARS=',I4 / ' NMILE=',I3 / ' SUBROUTINE F3',               FINI 1960
     3  ' USED FOR LEAD CAR' / ' ENTER=',I2 /                           FINI 1970
     4  ' Q=',F6.0 / ' CONTRL=',I2 )                                    FINI 1980
      WRITE(6,707)                                                      FINI 1990
  707 FORMAT(//' AV. SPACING FOR EVERY TENTH CAR' )                     FINI 2000
      DO 705 I=1,IND                                                    FINI 2010
      JCAR = I*10                                                       FINI 2020
      ESPACE(I) = ESPACE(I)/FNENS                                       FINI 2030
      WRITE(6,706) JCAR,ESPACE(I)                                       FINI 2040
  706 FORMAT(5X,'CAR',I4,'   AV. SPACING =',F7.2)                       FINI 2050
  705 CONTINUE                                                          FINI 2060
      IF(CONTRL.EQ.1) WRITE(6,701) SGNC                                 FINI 2070
  701 FORMAT(/1X,'SGNC=',F6.0)                                          FINI 2080
C          WRITE ENSEMBLE AVERAGES                                      FINI 2090
      WRITE(6,702) ESIG2,ETSTOP,ETOTLT,IEVAV1,IEDX                      FINI 2100
  702 FORMAT(///10X,'ENSEMBLE AVERAGES' //1X,'SIGMA SQUARED=',F6.3//    FINI 2110
     2  1X,'TOTAL STOPPED TIME =',F6.1,' SEC.'//                        FINI 2120
     3  1X,'TOTAL TRAVEL TIME =',F7.1,' SEC.'//                         FINI 2130
     4  1X,'AV. SPEED AT EXIT =',I4,' MI/HR' //                         FINI 2140
     5  1X,'AV. SPACING AT EXIT =',I4,' FT.' //)                        FINI 2150
      IF( CONTRL .EQ. 0 ) RETURN                                        FINI 2160
      WRITE(6,703) EPER, EPCMP                                          FINI 2170
  703 FORMAT(1X,'SIGN DUTY CYCLE=',F5.1,' PER-CENT'//                   FINI 2180
     2  1X,'COMPLIANCE FACTOR=',F6.3 )                                  FINI 2190
      RETURN                                                            FINI 2200
      END                                                               FINI 2210
```

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AUTOBIOGRAPHICAL STATEMENT

Mr. Stephen Kleinman was born in New York City in 1941.

After graduating from the Bronx High School of Science he attended Rensselaer Polytechnic Institute and received the Bachelor of Electrical Engineering degree in 1962. He pursued his interests in switching circuits and logical design at Columbia University where he attained the Master of Science degree in Electrical Engineering in 1964.

At this time Mr. Kleinman accepted an appointment as Lecturer on the staff of the Electrical Engineering Department of The City College of the City University of New York. After two years of teaching a wide range of courses he returned to graduate study at The City College. His current interest is in the application of system theory to urban problems.

Mr. Kleinman is a member of the IEEE, Eta Kappa Nu, The Highway Research Board, and the Operations Research Society of America.