THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

THE DEVELOPMENT OF AN ELECTRONICALLY CONTROLLED URBAN HIGHWAY SYSTEM

A Student Design Project

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Preface

The ever increasing congestion of the urban highway is beginning to threaten its continued use as an efficient vehicle artery. Even today the overcrowded conditions on freeways and expressways are seriously impairing the efficiency of these systems and are, in fact, beginning to destroy the realization of their intended purpose.

Congested conditions lead to loss of tempers, risky driving habits, and subsequent injury and loss of life. When the number of injuries and deaths caused here are added to the rising rates already recorded on America's highways, a solution to the traffic congestion problem is clearly indicated.

We are, therefore, making this proposal for an electronically controlled urban highway system as an attempt to relieve this congestion, increase the system's efficiency, and eliminate the weakest link in the safety chain by removing the role of the driver in vehicle control.

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Introduction

A. Goal Statement

The goal of this group is to develop a system for the total electronic control of an urban highway. More specifically, the project includes proposals for increasing the efficiency and safety of the existing expressways within the city without excessive modification of the present highway system and without undue cost to the car owner. Since in the urban system the problems encountered are of a different nature than those found in the turnpike system, and since the development of a controlled highway of the urban type has not been considered by a previous design group, it was decided that the proposals made by this group would be of a general nature. Emphasis was placed on the development of all of the phases of system so that a complete system could be proposed. Because of time restrictions on the one hand and the magnitude of the problem on the other, specific equipment design and, hence, precise economic and realibility analysis will, in general, not be found in this report. It is felt, however, that the system proposals and economic analysis included here are, respectively, substantially sound and well within the correct order of magnitude.

B. Problem Analysis and Sub-System Specifications

1. Control

In the design of any automatic highway system, the first specification that must be made is the amount of control to be provided in addition to, or replacing that of, the driver. In a turnpike system the spacing between vehicles is large enough (around 300 feet) to allow the driver to remain partially involved in the control process. Here, for example, the vehicle speed and spacing may be automatically controlled, but the driver could still continue to perform such functions as lane changing, entering, and exiting without providing a threat to the smooth operation or safety of the system. On the urban expressway, however, the greatly increased traffic density, along with a larger number of exits per mile, rules out the possibility of driver participation in vehicle control. As will be seen later in this report, it will eventually be necessary to operate the system at a high speed and density in order to produce the necessary flow rate, and the average driver would not be able to perform under these conditions without reaching a state of excessive fear or actual panic. Even if the driver were not to become so psychologically impaired, his reaction time would still exceed safe limits and collision would inevitably occur.

Once it has been established that total control is necessary, the actual method of control must be determined. Again looking at the turnpike system, it can be seen that there is large enough vehicular spacing, or headway, for the driver to move freely onto the highway and from lane to lane. Here it is not necessary to alter the speed and positioning of other vehicles to allow him to merge with traffic. There arises, however, this necessity under the conditions of the urban freeway. There now must be an external controlling agent common to provide the coordination necessary for merging, lane changing, and exiting operations. When this need is coupled with the realization of the problems of safety and control in high velocity, high density traffic, central control is obviously indicated.

In this age of logic circuits and high speed electronics, what could better provide central control than a computer? As long as it is not excessively burdened, a computer's "reaction time" is so much shorter than that of man that it becomes negligibly small. Memory banks could be designed to provide almost instantaneously the logic circuitry with a "picture" of the entire traffic pattern in a given stretch of highway. With only a short time delay, the computer could receive "requests" for entering and exiting, process them, and initiate action toward their fulfillment.

The function of the computer, then, is to provide the entire regulation of the vehicular traffic pattern. Specifically, the computer would have to:

1. Maintain uniform speed control according to pre-set parameters
2. Maintain spacing according to pre-set parameters
3. Be able to provide different acceleration and deceleration command signals to each vehicle while still preserving the ability to uniformly accelerate or decelerate all vehicles on the highway.
4. Control traffic coordination in such a way as to allow vehicles to move from lane to lane
5. Control entering and exiting
6. Regulate lateral density distribution

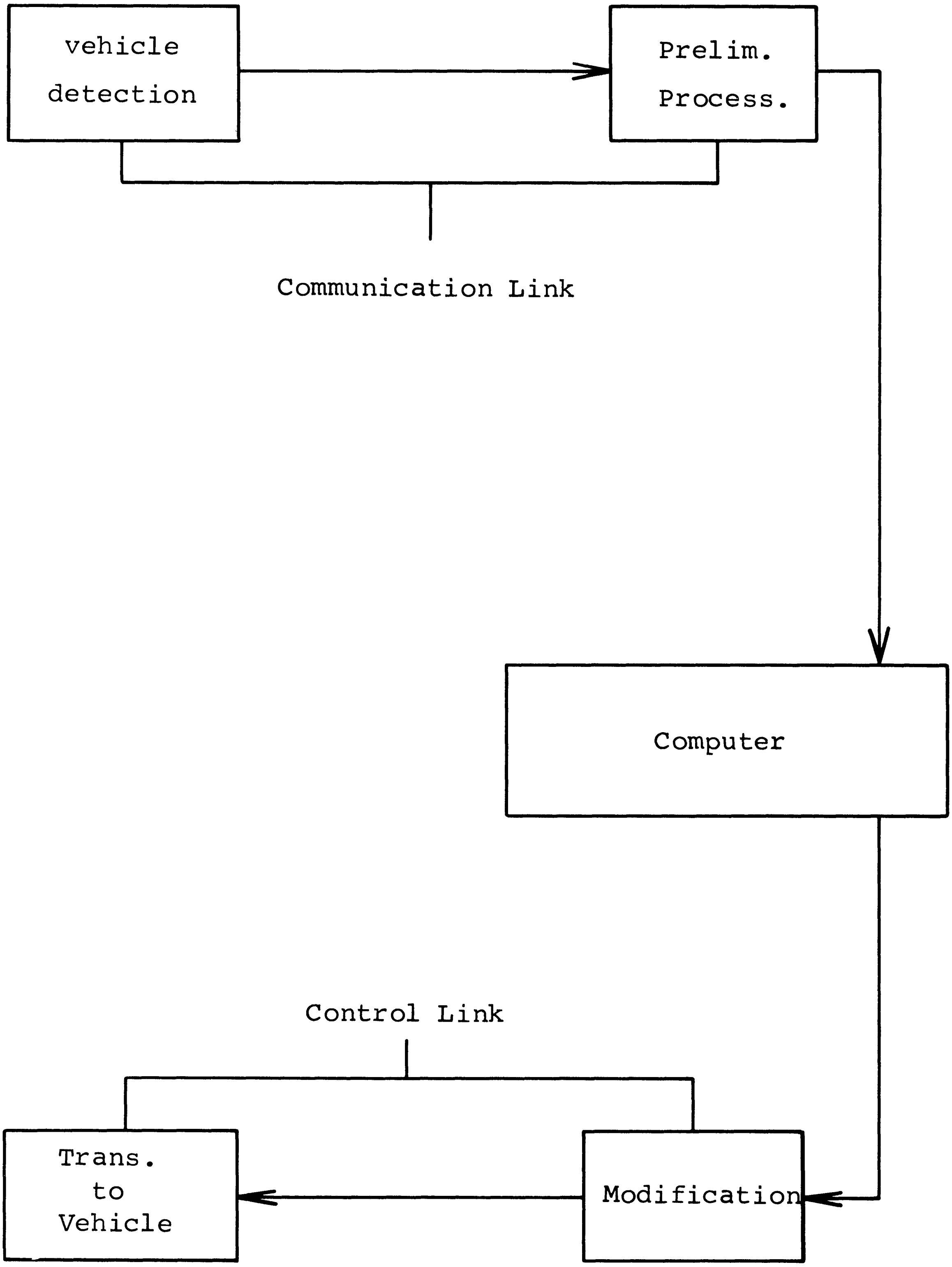
In additon to these computer tasks, the system must provide

1. A means for steering control
2. The proper acceleration and deceleration control without discomfort to vehicle passengers
3. A method for the placing of "requests" and a method for the subsequent relay of this "request" to the computer for processing

2. Information

The accomplishment of each of these tasks implies the need for the attainment and transmission of information concerning vehicle speed and position. In the electronically controlled urban highway system, this vehicular information is obtained at the highway and is then relayed to the computer. The computer processes this information and subsequently generates the necessary command signals for traffic control. These command signals are then relayed back to the highway, transmitted from the highway to the individual vehicle and, as a final step in the information flow process, converted from electrical signals to the necessary alternations in vehicle position, speed, acceleration or deceleration. The diagram on the next page illustrates this information flow scheme. The relaying of information to the computer will forthwith be referred to as the "communication link" and the transmission of command signals to the highway will be referred to as the "control link". Both of these links are illustrated in the diagram, Figure 1.

The structure of this report is modeled after this information flow scheme. After a preliminary study of steering



Information Flow Scheme

Figure 1

control and spacing theory, the report begins with the study of the communication and control links. (Because of their similarities these two links will be discussed in the same chapter). Next, the computer and its operation is discussed and, finally, a study of on-vehicle equipment is made. An economic analysis of the system along with proposals for its phasing-in and discussion of realiability is included at the end of the report.

3. Subsystem Assignments

Each phase of the information flow scheme corresponds to a specific sub-system. The breakdown of the system into sub-systems and the student assignments were as follows:

Group Leader	Thomas L. Steding
Assistant Group Leader	Duane E. Engstrom
Detection	Robert C. Abbott Thomas L. Steding Dale E. McIvor
Communication and Control Links	Dale E. McIvor
Computer Operation	Duane E. Engstrom Candace J. Windeler
Vehicle Equipment	Thomas R. Ward
Vehicle Exiting	Robert C. Abbott

Economic reliability and safety analysis along with the proposals for phasing in included the participation of all group members.

C. General System Specifications

1. Capacity

This system is designed for a maximum working density ratio (vehicle occupancy) of 1:2, or 33 per cent. Provision, however, is made for utilizing a smaller occupancy during the light traffic. When the average length of an automobile is considered to be 17.5 feet, as it will be throughout this report, an occupancy of 33 per cent sets the spacing between vehicles at 35 feet. With this spacing and with traffic moving at 70 mile per hour, the system is capable of handling a maximum of 7000 automobiles per lane per hour as opposed to a maximum of 2000 cars per lane per hour attained on the Detroit John C. Lodge expressway under the present, uncontrolled system. Also, without actual mechanical alteration of the system, the vehicle occupancy may be increased to a maximum of 78 per cent, thus setting the vehicle headway at 5 feet. At 70 miles per hour this occupancy provides for a maximum flow rate of approximately 16,500 automobiles per lane per hour.

It is predicted that the number of vehicles on the American highway will roughly triple by the year 2000. If the percentage of vehicle owners using urban freeways also increases by the year 2000, one can roughly estimate that there will be then approximately five times the number of vehicles using urban freeways as there are today. Reference to the above figures shows that the controlled urban system can easily accomodate this increasing number of vehicles.

Also, these vehicles will be now moving at a speed of 70 miles per hour as opposed to a maximum flow rate speed of 30 to 40 miles per hour found on today's uncontrolled urban freeway. When the system is phased in entirely the computer will take command of vehicles at the top of the entrance ramps and will not relinquish control until the vehicle is brought to a stop at the end of an exit ramp. Ample warning, both visual and audible, will be given to the driver that manual control of the vehicle will soon be returned.

2. Allowable Vehicle Types

The system is being designed such that eventually there will be no uncontrolled vehicles allowed on the freeway. There is provision, however, for their presence during the time that the system is being phased in. (This provision is discussed later). It is now felt that when the system becomes fully automatic, trucks can not be allowed on the freeway. Their acceleration and deceleration rates are too low and their susceptibility to velocity changes due to slight grade variations is too great for their inclusion in a system which demands high vehicular flexibility. This problem, however, is only a matter of minimum tolerable acceleration/deceleration rates and does not appear to be insurmountable. Since the manual shifting of gears when accelerating over a wide range of velocity (such as when merging from an entrance ramp) would severly affect required acceleration rates, it is felt that automobiles with standard transmissions would also have to be excluded from the fully controlled system. Again, however, this problem is only a matter of tolerable limits, these limits now being that of maximum allowable acceleration fluctuations due to the necessary closing of the throttle during the gear shifting process. The system may eventually be made sufficiently flexible so as to be able to accomodate both trucks and standard transmission automobiles. Their presence is allowable during the time that the system is being phased in, as will be discussed later.

3. Steering Control

Before analysis of detection and control can be started a reliable method of steering control must be developed. It has been decided by the members of this group that inasmuch as a reliable steering control system has already been developed by the previous semester's group, further design in this area will not be attempted. It was felt that because of time restrictions, our efforts would yield more profitable results in the many unexplored areas of the urban system. Also, since the turnpike systems group has worked on the extended development of this system, duplication of effort would only result.

A very brief description of this steering system will be given here. Further information can be obtained through reference to either the Electronic Controls For An Automatically Controlled Highway System report of this semester or to the Automatically Controlled Highway System report of the Fall Semester of 1965.

The report of Fall Semester describes the system as utilizing a buried cable in the center of a lane as a reference for the path of the vehicle. The cable is electrically excited so as to create a low intensity field symmetrical with the lane. Two tuned coils are mounted on the vehicle under body and are placed at an equal distance on either side of the vehicle's center line. The intensity of the signals generated in the coils by the field of the cable are compared and their difference activates a steering servo-mechanism. The addition of a third coil to increase system stability is also suggested, but the details will not be covered here.

For the purposes of the urban expressway, a short segment has been taken out of the center line cable at five foot intervals. What results from this is essentially a series of five foot cable sections, each separated from adjacent sections. These sections will be used as antennae for the transmission of command signals originating from the computer while retaining their use for steering control. A carrier wave impressed on these cable sections will provide the necessary field for steering control while the modulating signal will represent the information transmitted to the vehicle.

Chapter I

VELOCITY AND SPACING THEORY

A. Introduction

Before examining some of the system specifications, it is necessary to acquire an understanding of the methods used for vehicle velocity determination and spacing control. Both of these operations can best be understood by first discussing them on a theoretical manner. As the members of this group quickly discovered, there appears to be a wide variety of methods that can be used for velocity determination and spacing control, and the greatest problem was in finding the method that is most efficient and requires a minimum amount of alterations on the existing highway system. It is felt that the method described below fulfills these requirements best through the use of equipment for more than one task. Specifically, it will be seen that the equipment that is necessary for vehicle detection is also used for both velocity determination and spacing control.

B. Theory of Vehicle Detection

Vehicle detection is accomplished through the spacing of "detection units" buried just below the surface of the highway. (These detection units will be discussed in chapter II). These units are placed in the center of each lane of the highway and are spaced at regular intervals along the lane. The distance between detection units has been taken as five feet so as a compromise between accuracy of determination of a vehicle's position on the highway and excessive highway modification and installment costs. As shown in Figure 2, the detection units are placed in the small space between antennae, or steering cable sections, and the necessary wiring for the units and the antennae can either be taken directly off the highway for each detector-antenna unit or run along the cable slots and taken off at larger intervals. The former approach will be followed through here, mostly for ease of illustration, but the latter approach may eventually be necessary in order to reduce the amount of highway modification.

The output of these detectors is a binary signal indicating that the space above a specific unit is either "occupied" or "unoccupied". Because of the necessary interval between detectors, there is a corresponding uncertainty in the actual position of a vehicle. Assuming that the detector is "triggered" when the leading edge of a vehicle is just over the detector, which, as will be seen later, is nearly the case, then an "occupied" signal from a specific detector and an "unoccupied" signal from the next detector in the lane could indicate the presence of the leading edge of that vehicle as being anywhere within the shaded area of Figure 3. This uncertainty must be taken into consideration when specifying the method to be used for spacing control.

C. Theory of Velocity Determination

As a vehicle passes over successive detection points along the highway, it triggers the detectors at various intervals of time. The time interval between the triggering of two adjacent detectors is inversely proportional to the average velocity of the vehicle between the two points. If the detector spacing is constant of proportionality between the vehicle's velocity and the time in-

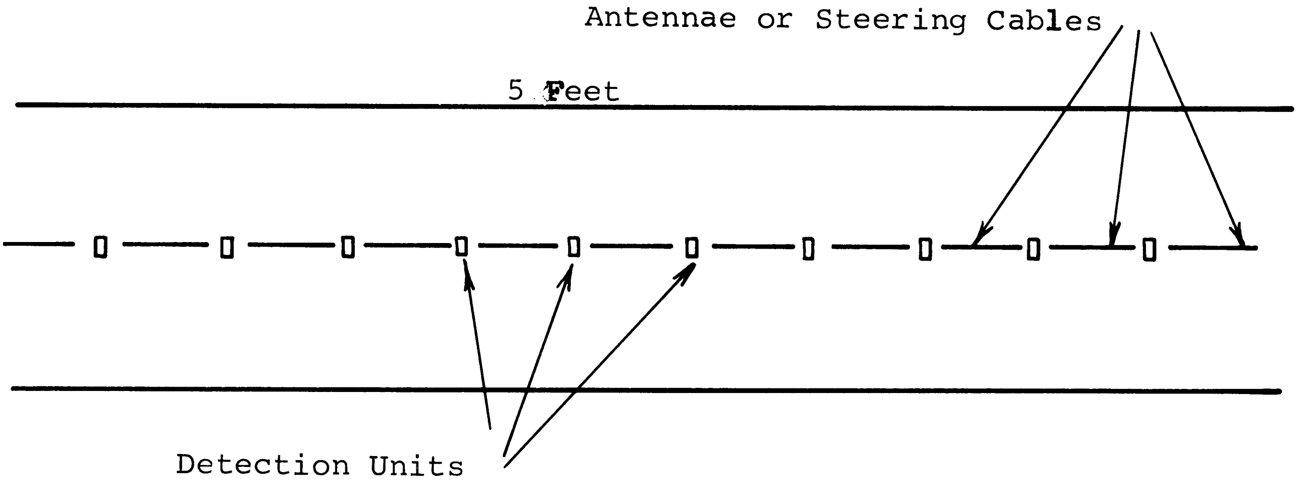
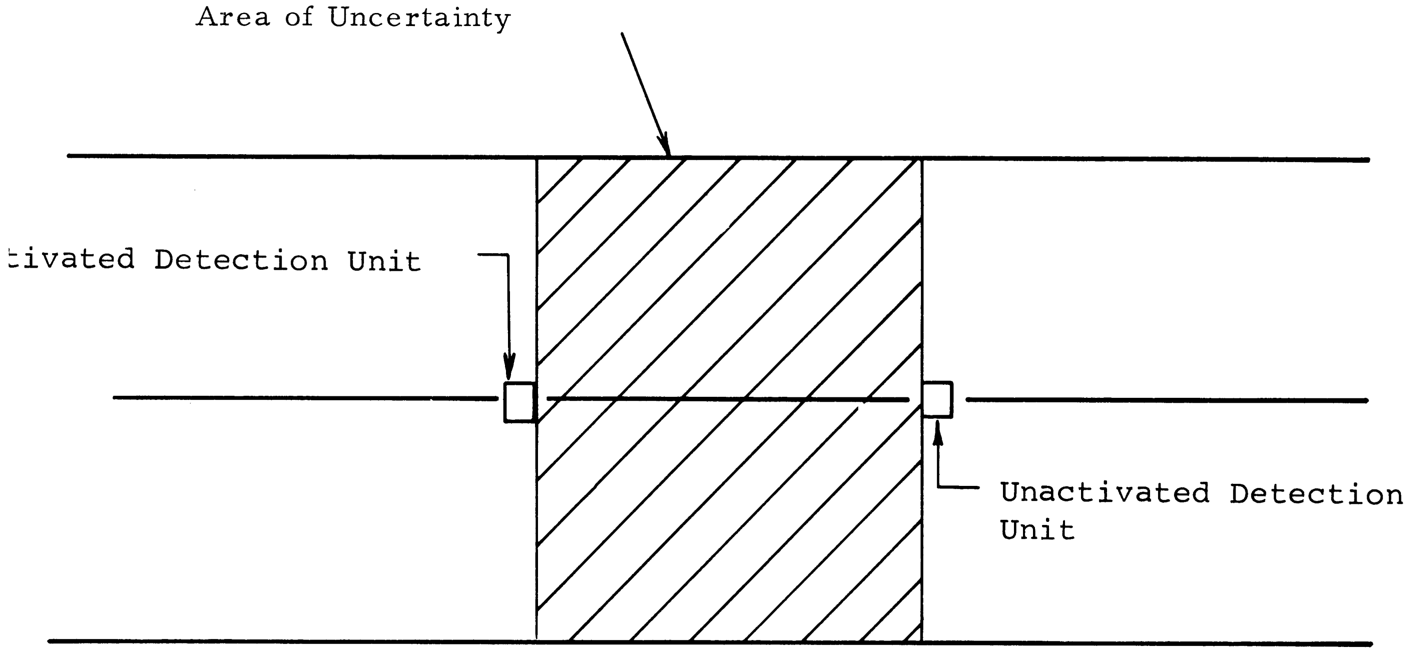


Diagram of A Single Lane Showing Detection Units and Antennae

Figure 2



Uncertainty in Vehicular Position Determination

Figure 3

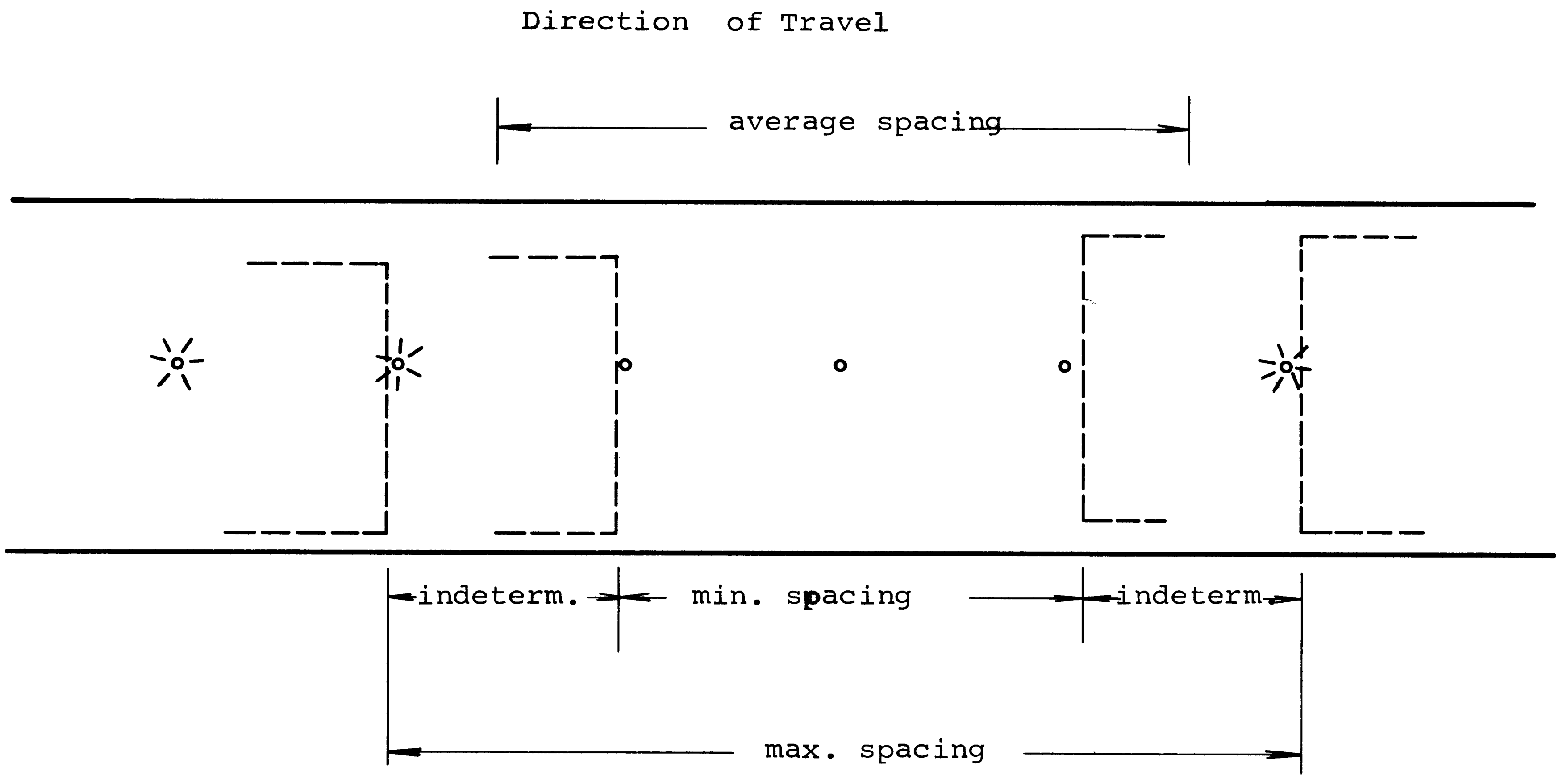
terval between detector outputs is also constant for that highway. Thus, velocity determination is accomplished by measuring the time interval involved as the successive detection points are triggered by the presence of a vehicle. The actual method by which this measurement is made is discussed in detail in Chapter II.

The velocity reading taken from the highway in the above manner, of course, an approximation, the degree of which is dependent upon the amount of velocity change occuring between two detection points. Even when a relatively large deceleration rate is occuring between two points, the error is the velocity as measured is tolerable. For example, if a vehicle passes over one detection point with a velocity of 30 miles per hour, or 44 feet per second, and is decelerating at a rate of 25 feet per second, the loss in velocity before it reaches the next detection point is approximately 3 feet per second. Therefore, the car would be going about 1 1/2 feet per second slower when it passed the second detection than is indicated by the reading of the average velocity. This is about a 3 per cent error and is, as will become more apparent later, well within the allowable error of the system.

D. Theory of Spacing

As in velocity determination, the detection units play a leading role in the method by which spacing control is accomplished. Here, the computer requires that a pre-determined number of detection points remain unoccupied between two adjacent vehicles traveling in the same lane. If one of the two vehicles were to drift so as to reduce the spacing below the minimum allowed spacing, the computer take corrective action in the form of either decelerating the trailing vehicle or accelerating the lead vehicle. The computer senses this violation of spacing minimums by noting that the number of unoccupied detectors between the vehicles is below the minimum allowed. It should be noted here that the minimum spacing determined for any particular highway is only a limit and not a required condition, i.e., the computer does not try to bunch the vehicles on the highway if they are not originally traveling with minimum spacing.

With a spacing of five feet between detectors, the minimum vehicle spacing, therefore, is 5(N-1) feet, where N is the number of unoccupied detectors that are required to exist between vehicles in the same lane. Since the detectors are essentially points on the highway, the minimum value that N could have and still prevent collision is two. It is correct to say, then, that the minimum vehicle spacing that can be set on this system is five feet, but this is not the average spacing that would occur with N equal to two. As mentioned earlier, there is an uncertainity in the actual position of a vehicle. This uncertainity is equal to the distance between detectors, here being five feet. Referring to Figure 4, it can be seen that the total uncertainity in the spacing between two vehicles is twice the uncertainity in one vehicle's position, or, here, ten feet. Therefore, the average spacing is always five feet more than the minimum spacing and is equal to 5 x N feet. For example, for N equal to two, the minimum spacing is five feet but the average spacing is ten feet. It can now be seen that it is necessary to distinguish between maximum flow rate and average flow rate for a highway with any specific N. The maximum flow rate is only an extreme condition



✳ - - actuated detector

○ - - unactuated detector

Diagram showing extremes in possible positions of two cars when three detection points between the two cars are unactuated.

Figure 4

where all the vehicles are traveling at exactly minimum spacing, this condition being possible, but not very probable.

Chapter II

Communication and Control Links

A. Communication Link

1. Vehicle Detection

Probably the greatest obstacle to the realization of an electronically controlled highway system is the development of an economically feasible, yet reliable method for vehicle detection. There has been in the past an array of systems proposed for vehicle detection which have employed such concepts as radar, ultrasonics, and the laser. None of these systems, however, have shown themselves to be satisfactory solutions to the detection problem. Some are limited by weather conditions or continual maintenance requirements, but most of these proposals were simply found to be economically unfeasible.

At the time of this group's formation and, in fact, throughout most of this semester, it was considered that the best existing solution for the detection problem was the utilization of loops buried in the road. The inductance of the loop is changed when a sufficient mass of ferromagnetic material, such as an automobile, passed over.

A rather expensive phase detection unit was then used to sense this inductance fluctuation and in turn, could relay a binary information signal ("occupied" or "unoccupied") to the computer. This system is both highly accurate and reliable but its cost is extremely large. The companies making these units cite a price around $100 per unit. Since, as mentioned earlier, there must be one detection unit for each five feet of highway, the total cost, then would be approximately $100,000 per lane-mile. This figure does not include installation costs.

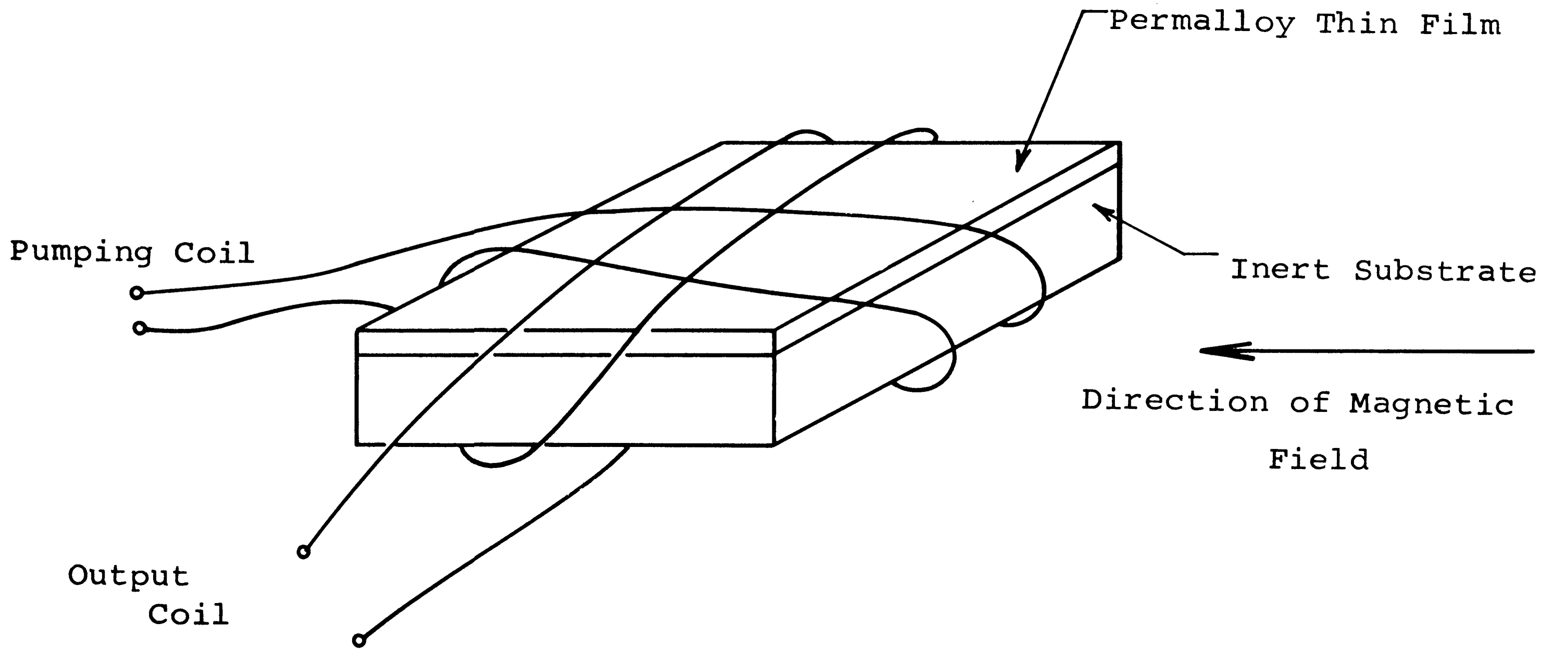
Another possibility considered for the solution to the detection problem was the use of strain gauges imbeded in the reinforcing rods of the highway. The presence of a vehicle would then register as a strain response in a specific lane. It was learned, however, that it would be impossible to detect which lane is actually being occupied by a vehicle. Also, the installation of these gauges in existing highways would be a difficult and expensive task. The incorporation of these sensors into new highways as they are being built could still be the ideal solution for the detection problem. This is, of course, assuming that some method could be devised to determine the lane in which a detected vehicle is moving.

The most practical solution to the detection problem appears to be a magnetometer, or flux sensor, which will be buried in the road in a small hole or slot, from which two pairs of wires will be run to the side of the road in a diamond-saw slit. The magnetometer being considered is an extremely sensitive thin film device, and could easily detect the presence of a car in any of the lanes from a position on the roadside, but the sensitivity will be adjusted so that it will respond only to the car directly above it. The presence of a car near the sensor is registered by the sensor because of the distortion of the earth's magnetic field in the vicinity of the car. This distortion is due to the large mass of iron in the car.

Lockheed Corporation Microsystems Division has developed the sensor shown in Figure 5, and is negotiating with several firms for its production. The cost of the unit is approximately $5. Only a very simple amplitude detector is needed at the output of the sensor, plus a source of ac voltage at the input, for operation.

These sensors, when installed in each lane with the necessary wiring running off to the side of the road, will constitute the detection points. The detectors will be sealed in epoxy and set in small, shallow holes cut in the pavement, one in each lane, spaced every five feet. There are two coils on each detector, one a pumping or drive coil and the other an output coil. The pumping coils of several sensors can be connected in parallel, with one side grounded, and driven from a common source. One side of the output coil can be grounded, so there will be two leads plus one lead for each detector coming off to the side of the highway. That is, for a three lane highway there will be a five conductor cable from each row of three detectors. The cables will be terminated in a metal channel which runs parallel to the highway near one edge. It would be desirable to pre-wire the rows of detectors, sealing the solder joints in the epoxy along with the detector, so that at installation it would be necessary only to make the three holes (for a three lane highway), cut the slot from one edge of the pavement across the two holes over to the third, and drop in the wiring harness containing the detectors, and seal.

In some applications of this magnetometer, a third coil is used to provide a means of neutralizing the "bias" of the



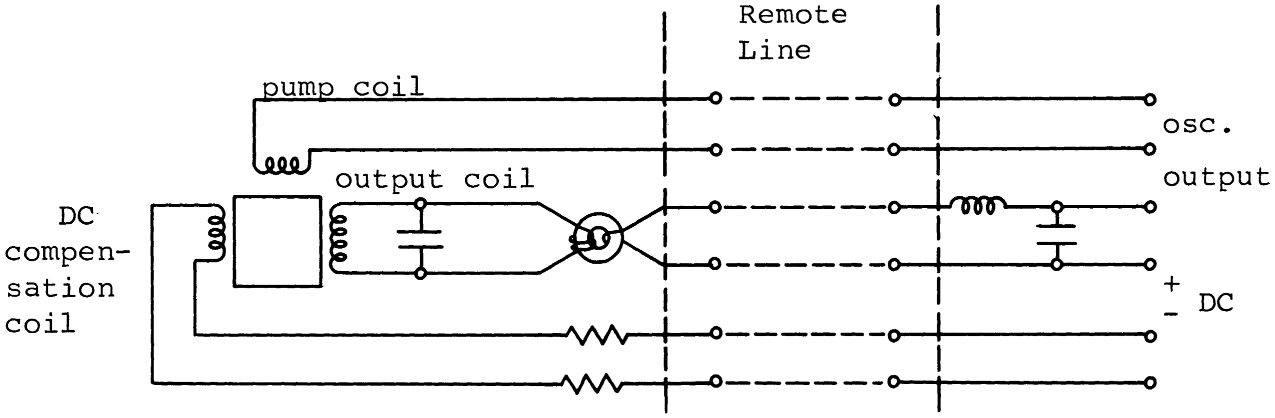
Thin Film Magnetometer

Figure 5

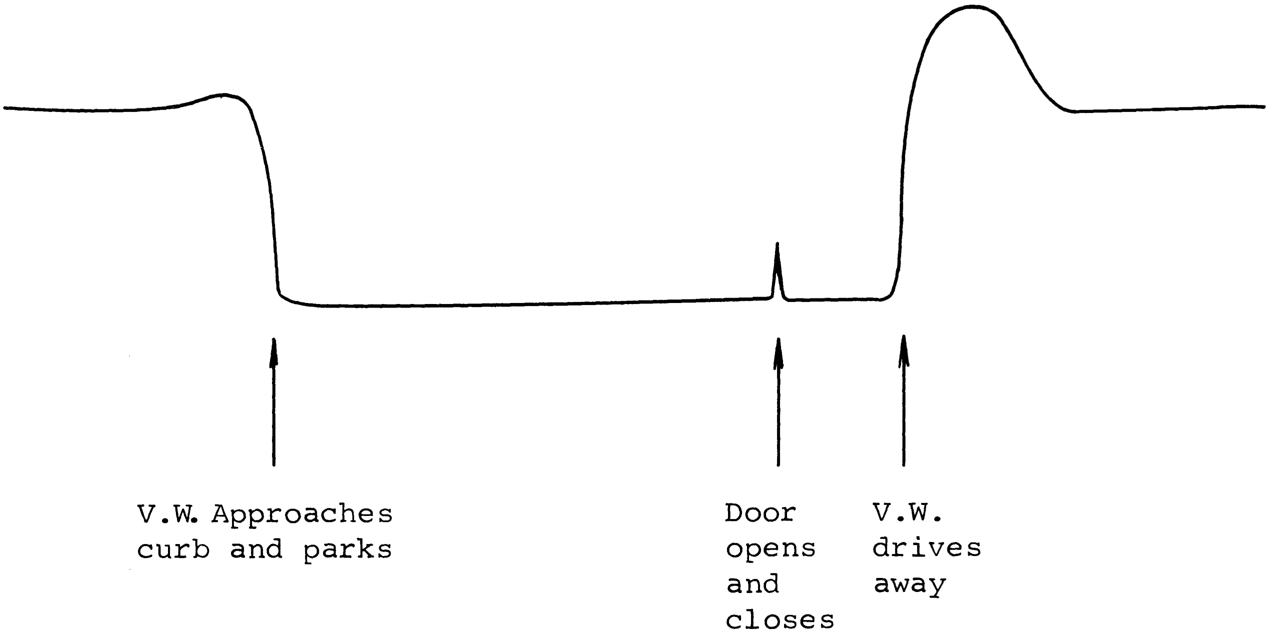
earth's magnetic field, which would allow operation in the most sensitive region of the magnetometer and set the output to zero in the absence of a vehicle. A small d.c. current would be passed through this third coil, in which case another wire would have to be run to each detector from roadside. It is expected that this third coil will not be needed, since the change in the magnetic field impinging upon the detector will be quite large in this case.

The output of the magnetometer is a bi-phase a.c. voltage, at an even harmonic of the pumping frequency. The pumping frequency may range from 15 kc to 10 mc, at a power input for a typical size sensor (1/2" x 9/16" x 1/16") of 100 milliwatts. The optimum size sensor and pumping frequency remain to be determined. Lockheed engineers used the device as a vehicle presence indicator using a pump frequency of 50 kc, and tuned the output to the second harmonic. By using a low frequency, the sensitivity is still high, and the detuning effect of varying capacitance due to varying lengths of output cable may be reduced. Lockheed engineers used a small step-down transformer embedded with the sensor to further reduce the effects of varying cable capacitance. It is expected by Lockheed engineering, however, that for this application a simple diode detector will be all that is necessary, eliminating the tuning problems.

The experimental setup as used by Lockheed engineers is shown in Figure 6 along with the output response of the system to a car. Although the system is more complicated than is expected will be necessary, even this system would not be pro-



Vehicle Presence Indicator



Recording of Volkswagon Approach
To Curb and Discharging Passenger.

Figure 6

hibitive in complexity or cost. The point is that this thin film sensor has been proven to be a successful vehicle presence detector.

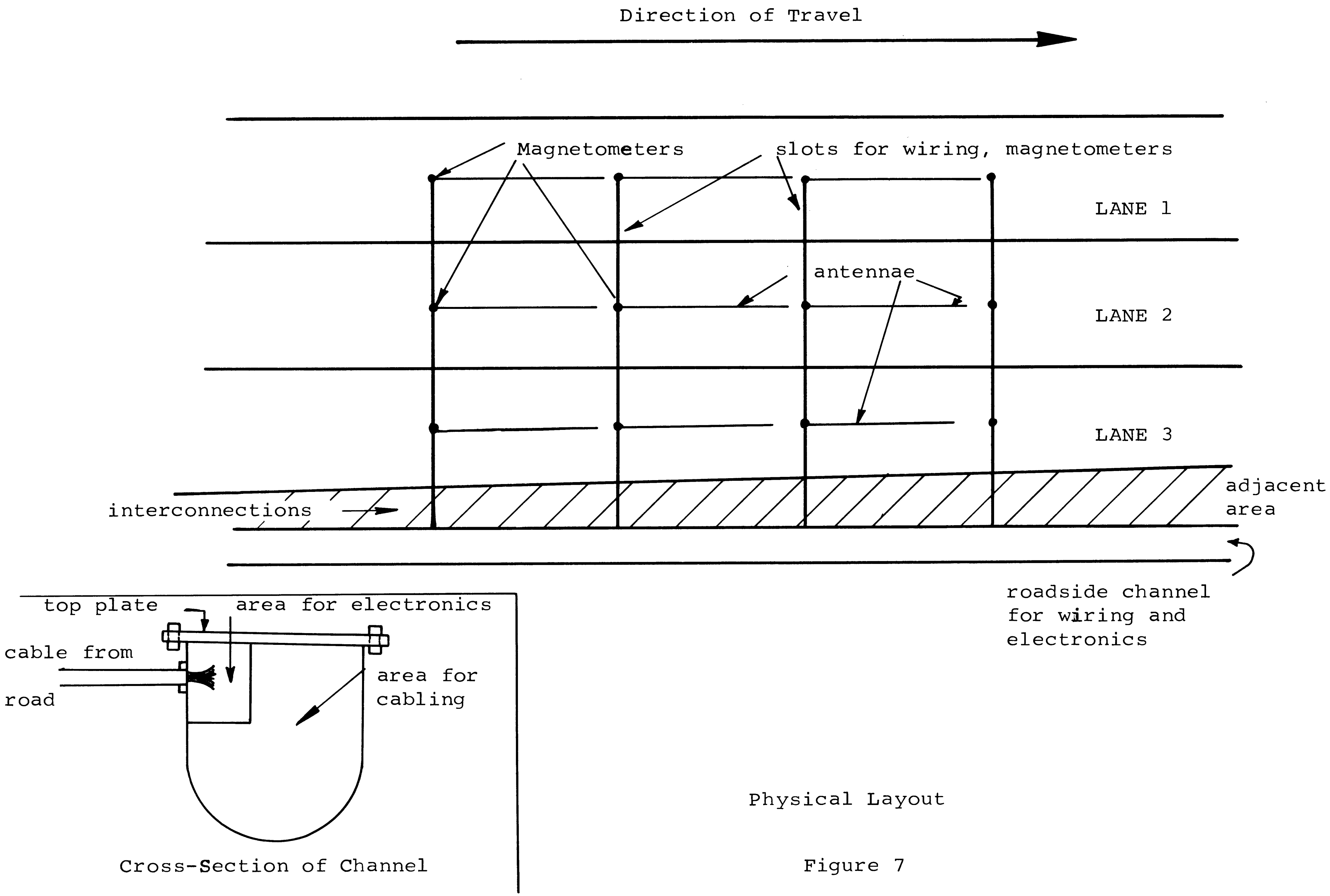
The detection system will thus consist of the thin film magnetometer connected by a short length of cable to a roadside termination, wherein a diode rectifier and filter will be installed. The output of the detection system will, therefore, be a d.c. voltage proportional to the magnetic flux impinging upon the sensor. How this voltage will be utilized is the subject of another section.

2. Physical Layout of Roadside Equipment

In order to facilitate understanding of the system, a brief and descriptive outline of the proposed physical layout along the highway is given, as shown in Figure 7.

There will be a small hole or slot cut in the center of each lane of the highway, with a narrow slot connecting the holes and the road edge. This latter slot may be 1/4" or 3/8" deep, through which cables for connection to the flux sensor, among other things to be described later, will be run. The cabling will be weatherproof, and will run buried beneath the road adjacent surface to a channel, where it will terminate.

The channel will be buried with its top surface flush with the ground surface, and could be located right next to the road edge if such a location is not used as an emergency or drive-off area in normal use. This channel will run parallel to the highway and will contain two pairs of wires for each detection point, plus some electronics. This wiring will be fed to a common computation location for approximately every three lane-miles of highway. There will be about 3000 pairs of wires at a point in



Cross-Section of Channel

Physical Layout

Figure 7

the channel near the computation location, and the channel will have to be about one square foot in cross section, to accomodate the wire plus electronics.

3. Information Transfer and Encoding

The output of the presence detector system, which is a d.c. voltage proportional to the flux at the detector, will be operated on by a triggering circuit, which will establish a fixed d.c. voltage at its output whenever the detector voltage rises above a predetermined level. A simple Schmitt trigger will serve this purpose. The triggering level will be fixed by selection of the trigger circuit and the number of turns in the output coil of the flux sensor so that the trigger will activate whenever a vehicle is within approximately one foot of the flux sensor. The output of the trigger will be connected to a pair of wires in the channel running to the computation location.

At the computation location there will then be a large number of pairs from all the detection points along some length of highway, perhaps three lanes wide and one mile in length. At those detection points where a vehicle is present, the corresponding pair of wires will register a specific voltage, such as 6 volts. At the rest of the wires, only low level random noise will be present.

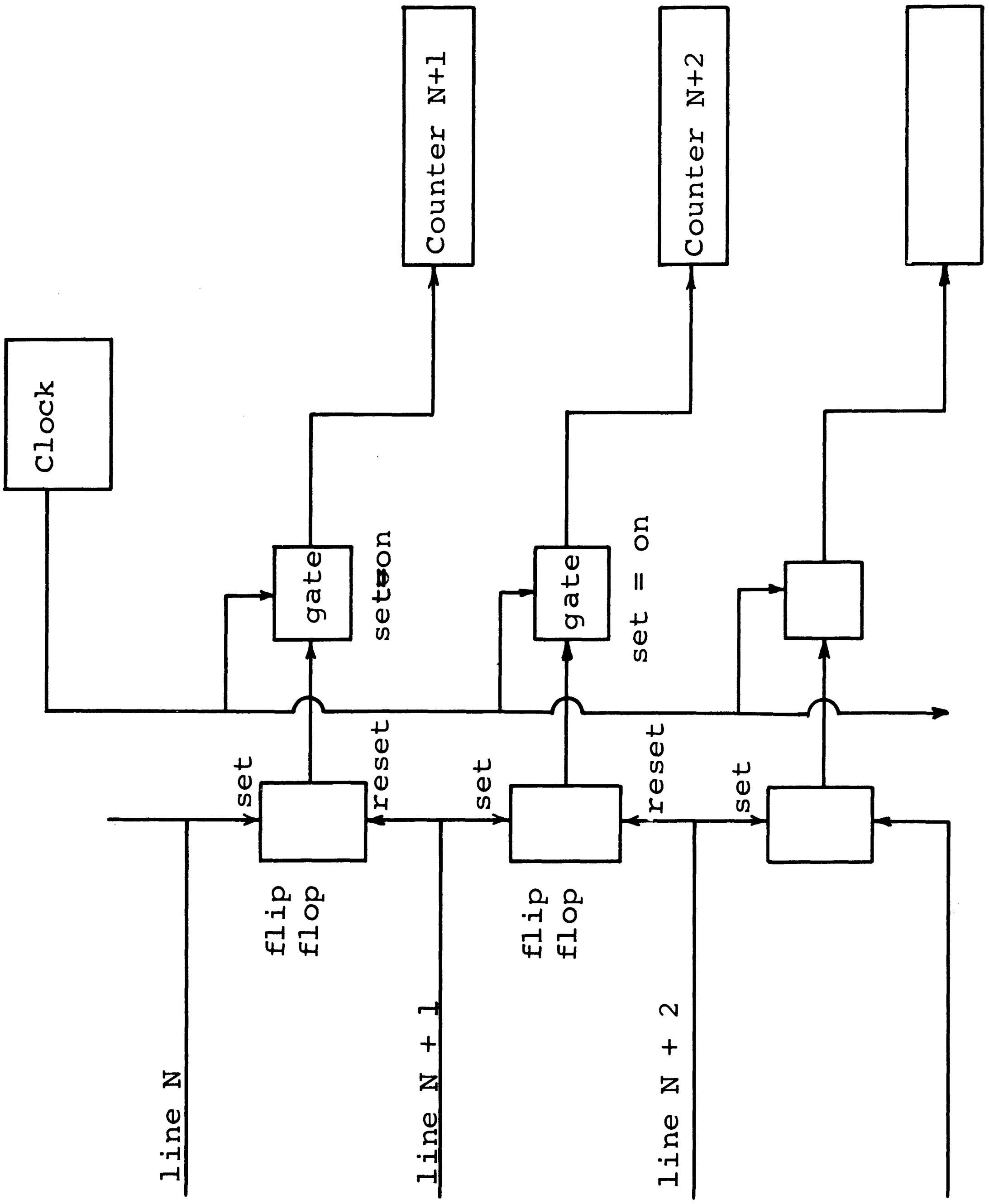
Along any given lane in the direction of travel the detection points can be labeled for explanatory purposes N, N + 1, N + 2, etc. Their corresponding pairs in the computation location would be identically numbered. Connected at the termination of each pair is a circuit which will perform the following function: When a car crosses the Nth detection point, a pulse generator will start to fill a binary counter associated with the N + 1st pair. When the same car crosses the N + 1st point, the N + 1st counter will cease to fill, and the N + 2nd counter will start to fill. There will then be stored in the N + 1st binary number which is inversely proportional to the velocity of the car which is now over the N + 1st detection point. Similarly, for each vehicle on the highway: there will be a number stored in the counter associated with the point it has last crossed which contains information about its average velocity over the last five feet of travel.

There are many gating circuits which will achieve the above task. A simpler and cheaper way to accomplish such a gating function could probably eventually be found, but an outline of a circuit that will work is shown.

It is now necessary to read the velocity and presence information in to the device which will perform computations. This will be done by "scanning" the highway, or looking at successive detection points in some sequential pattern. The highway can be scanned in many ways, but it is assumed here that it will be scanned lane by lane. The scanner will start with the first detection point in its control area and work down one lane opposite the direction of traffic flow until it reaches the end of its section, then return to the beginning and scan the next lane. The scanner will look at each successive detection point in a lane until the presence of a vehicle is registered. It will remain "observing" that point until the computer is ready to utilize the information it has ready, at which time the computer will read into its accumulator the detection point concerned and the information about the velocity of the vehicle at that point. The scanner will then move on down the lane, measuring the length of the vehicle in integral units of detector spacing (5 feet). This length will be stored in a separate register for occasional use by the computer. While the computations are proceeding, the scanner moves down the lane to find the next vehicle.

The above function is performed by the system shown in Figure 8, the heart of which is a matrix decoding tree. This is a device which allows the selection of one of a large number of inputs, the input selected corresponding to the number registered in a binary counter connected to the tree. There will be one "row tree" for each lane of highway, and it will be large, depending upon the length of highway being monitored, with perhaps 1000 inputs. There will be a small "column tree" for selecting which of the inputs of the "row tree" will be monitored. Thus, the two numbers in the two counters driving the trees will form a matrix indication of the point being monitored.

When the scanner comes to a vehicle, it will stop there. When the computer is ready for the information, it will read in the numbers M and N simultaneously, which will identify the point, and then read in T, which contains the velocity information. This is accomplished by sending the read pulse from the computer through the decoding tree to the counter associated with M, N and activating ten diode "and" gates associated with



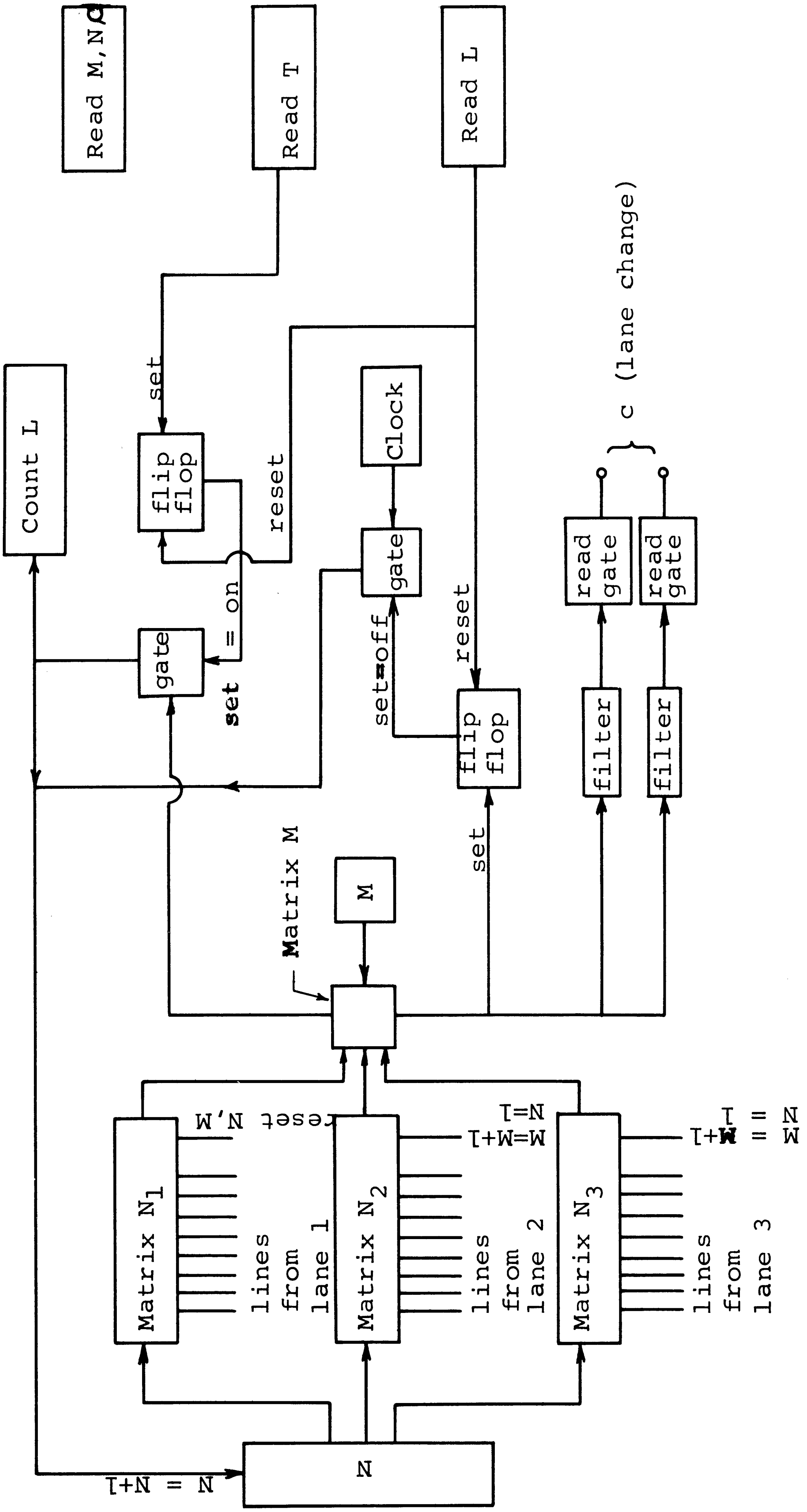
System for Encoding Velocity Information

Figure 8

the "T" counter, so that the binary number T is fed into ten digit lines common to all of the "T" counters. The M, Nth "T" counter is reset to zero in the process, ready for the next vehicle, and the scanner moves on.

At certain points along the highway there will be transmitting devices which will actuate a transmitter in those cars which are not in the correct lane to exit where they have indicated. The details of this device are described elsewhere. There will then be a string of receivers located after the actuation points, and they will pick up a signal from those cars whose lane position is to be changed, and relay this information along with presence and velocity information back to the computation location. This lane changing information will be in the form of one of two modulating frequencies, which will modulate the d.c. level produced by the trigger circuit. The level of modulation will be low, about 35 per cent, so that the voltage on the wires at the computation location can be used to actuate the gating device described earlier with a minimum of filtering, if any, necessary. The lane changing information will be extracted through the use of two band pass filters, connected at the output of the decoding trees. The outputs of the band pass filters will be rectified, filtered, and amplified to an appropriate d.c. level, which will then serve as a two bit binary number to be read into the computer. This lane changing information will be read in simultaneously with the velocity information, and together they will constitute a twelve bit word.

This is the extent of the information gathering and disseminating link. The detailed operation of the system can be



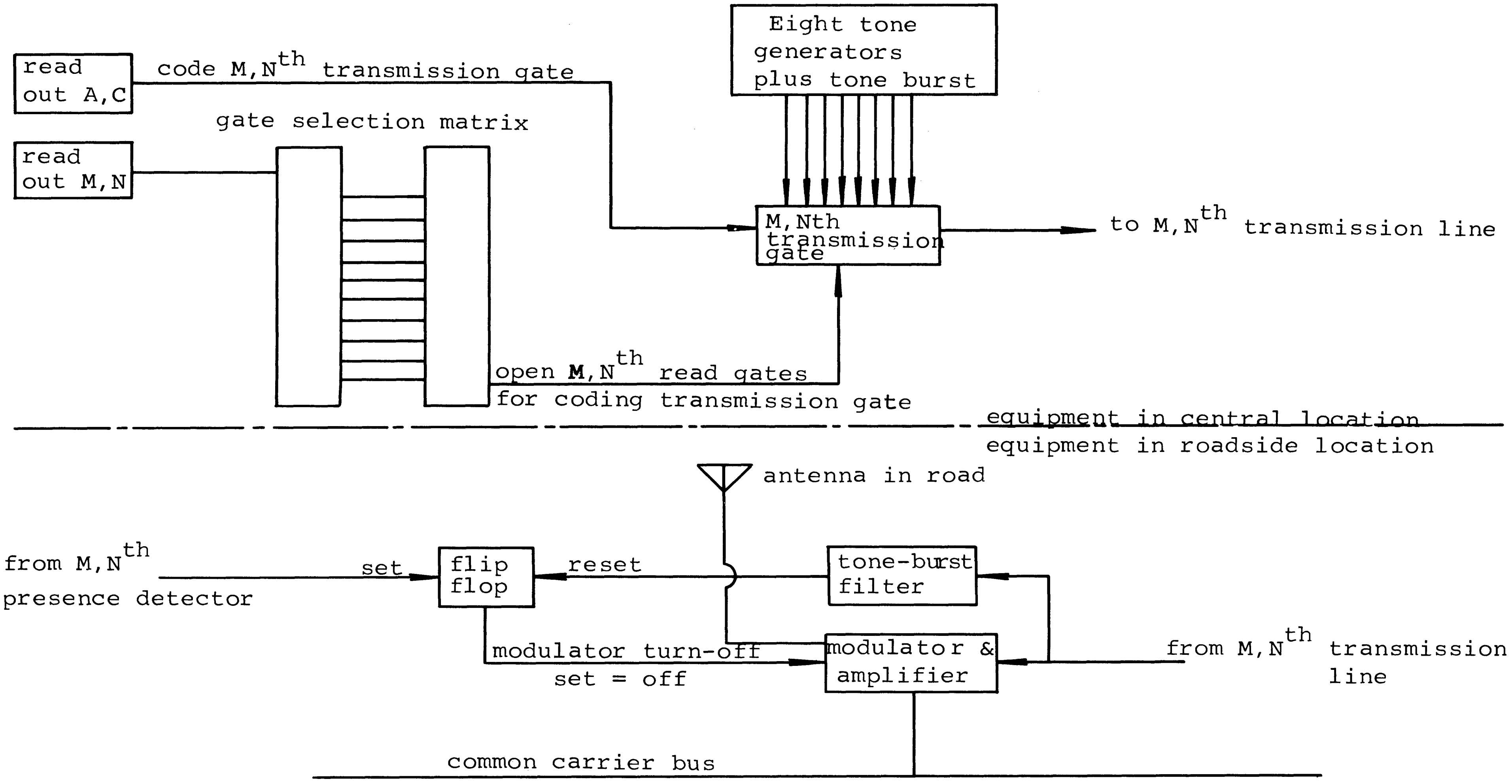
Communication Link Decoder

Figure 9

extracted from the block diagram more easily than it could from a verbal description. Most of the details are of relatively little significance, since in many cases specific functions can be accomplished in a number of ways, and the way shown is just one approach. It does show, however, the exact function of the system, and gives the details of how it can be accomplished.

B. Control Link

After the computer has read in the information about the car at the N^{th} detection point, the scanning system will move on down the lane to the next vehicle. When the computation has been completed, it is necessary to transmit the command signal back to the proper vehicle. This will be done through another decoding tree which operates in parallel with the one described in the communication section. See Figure 10. Since the computation time is but a few microseconds, the car will be in essentially the same position, over the N^{th} detector. The computer will then read out the matrix identification of the location of the car into the second decoding tree, and a gate connected to the corresponding pairs of wires will be activated. The command signal for the car will then be read out from the computer into this gate in the form of an eight bit word. This signal will so actuate the gate that the output of eight tone generators will be fed through the gate to the transmission line. There will be one tone generator for each bit in the eight bit word, and wherever a "one" is present in the command signal, the corresponding tone will be passed to the transmission line. Wherever a "zero" is present, the corresponding tone will not be



Command Link Encoding System

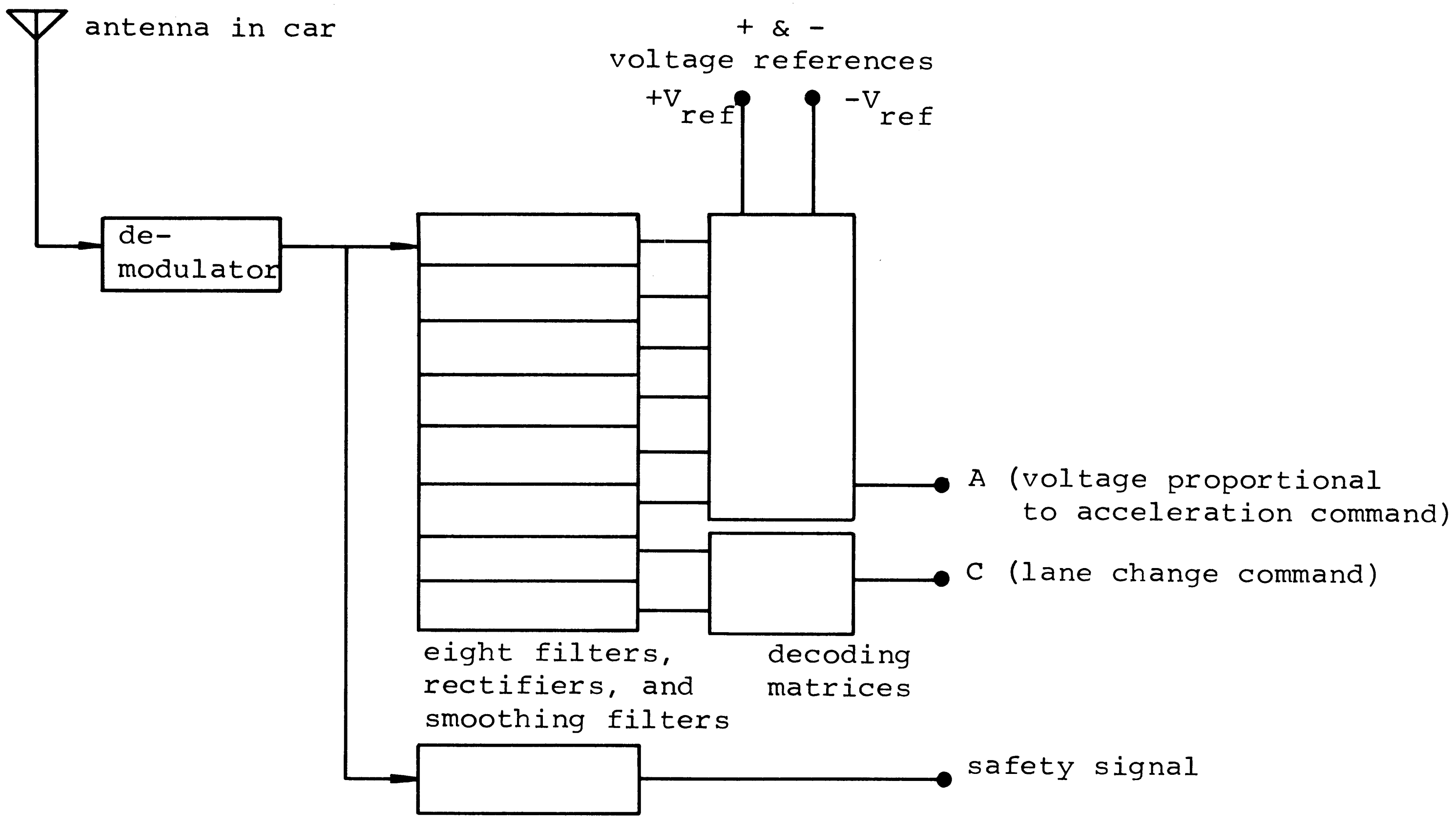
Figure 10

passed. Thus, the binary command signal is transferred to discrete frequencies and sent down the transmission line. The gate will remain in this last state until a new command signal for that particular location is given during some other computation cycle.

This combination of eight tones will then appear as a voltage across the isolating resistor at the N^{th} location. That voltage is then fed into a single stage of amplification and into a modulator. The modulator will modulate a low frequency carrier with the command tones. Starting from the position of the N^{th} detector this modulated carrier is fed to the antenna, or cable section, extending down the center of the lane in the direction of traffic flow. The car whose velocity was read in by the computer an instant earlier will be over this antenna, and by means of a short antenna mounted underneath the car parallel to the one in the road will pick up the command tones as indicated by Figure 11.

There will be no radiation of energy, since the antenna in the road will be very short compared to a wavelength of the carrier. The car will not receive a signal from more than one antenna at a time. Since the total distance of transmission will be at most a few feet, the ends of the road antenna will be separated accordingly. Since this carrier transmitted by the antennas in the road also serves as the steering signal for the steering mechanism to follow, the reception of the command signal of the car could actually be accomplished by demodulating the signal from one of the steering pickup coils.

As mentioned earlier, the command signal to any given point on the road remains the same until a new command is issued to that lo-



Decoding System in Each Vehicle

Figure 11

cation. Therefore, it is necessary to turn the modulator off as the car leaves the detection area. This is done with a bistable circuit that turns the modulator off as the car leaves, and turns the modulator back on when a new command is received, as indicated by the presence of a ninth tone transmitted for one fiftieth of a second as part of every signal.

The command signal itself consists of eight tones, five of which are decoded into an acceleration command, two of which are decoded into a lane change command. The eighth tone is a safety tone used as a check on the operation of the system. The decoding is accomplished through the use of eight filters and a diode decoding matrix. There are two zener diode voltage references in the car connected to the output of the decoding matrix, and depending upon the command signal, there will be a fraction of one of the two voltage references. If the two reference voltages were +10 volts and -10 volts, then the output would be one of thirty-one levels between +10 and -10 volts. These levels correspond to the command acceleration signal as calculated by the computer, and are used with a feedback loop from an accelerometer to actuate the brake and accelerator servomechanism, as described later in this report.

C. Economic Analysis of Communication and Control Link

Thin film detector	$5.00
Rectifier and Filter	0.30
Schmitt Trigger	1.00
Counter and Diode Gates	11.00
Bistable Circuit	1.00
	$18.30

x 1056 units/mile-lane -------------------------------- $19,000 (app)

Twenty 50-pair cable/mile-lane, average run = 1400'
@ $.79/foot = $28,000

Channel @ $ 2.50/foot = $13,000/mile

Scanner (Decoder & Logic), 2 per mile = $4,500

Economic Analysis (Cont'd)

For a total of six lanes (both directions):

Electronics		$ 114,000
Wiring		167,000
Channel		13,000
Scanners		4,500
Installation of wiring channel, detector and antennae		100,000
Total cost	App	$400,000

Chapter III

Computer Operation

A. Reasons for Adopting Computer Control

The basic assumption underlying the design of an automated superhighway system is that a computer is able to perform the logical operations and the decision-making of the driver, and perform them more reliably and more efficiently than any human being. In analyzing the driver's thought process it becomes apparent that his decision-making takes on a binary pattern--questions or comparisons with YES/No answers. As an example, let us follow through the thought pattern of a driver in the process of changing lanes assuming that the driver is asking himself a series of mental questions. Then the sequence of his questions would be similar to the following: Is there a car next to mine in the next lane? If NO, is there a car ahead of mine the next lane? If YES, is he traveling faster than I am? If YES, is there a car behind mine in the next lane? If YES, is he traveling faster than I am? If NO, then TURN into the next lane.

From this and other simple examples, it becomes apparent that a similar pattern of questions may be simulated by a series of logic units which perform comparative operations, or may be programmed into a digital computer which will give binary answers. As explained in the following section, the logic modules are able to perform the operations much more quickly, but a digitial computer is most desirable in the initial design. Even so, the speed and the accuracy with which the computer can perform such comparative operations far exceeds that of any human being. The accuracy of the driver's estimate of the position and speed of another car is subject to weather conditions, the alertness of the driver, and the driver's experience. On the other hand, by means of electronic devices the computer can have available in its storage, the numerical velocity and position within desired tolerances of every car under its control. With this accessible information, the computer can reach a decision much more rapidly and more reliably than the driver.

B. General Outline of System

1. Type of Computer

The basic function of the computer in this system is to scan the various inputs on a section of highway, perform the necessary calculations, and produce the desired output in the form of a command signal. These facts limit us somewhat as to the type of computer needed. It must be an operational computer since the outputs are command signals and not just information. It must be a high speed computer because it must scan an entire section of highway and get the necessary information back to the car before it has moved more than a few feet. To be precise, the computer must scan a section of highway, compute, and transmit, in about 1/100 seconds. The slower the computer, the less road it can control and still maintain this 1/100 second time.

Since this high speed is necessary and since most of the basic logic steps are simple comparisons, the use of solid state analog modules is the best way to perform the logic sequences. The computation time can be reduced tremendously by using this solid state analog hardware for most of the logic. The disadvantage here is that a change in the logic in a pre-set analog system involves rewiring the computer, whereas, it would simply require a new program for a digital computer.

The sequence of logic presented here is simply a way of performing the desired operations and is not necessarily the best way of doing it. For this reason, it would be wise to set up a small test strip of highway using a digital computer. In this way, the logic could be experimented with until the best form is found. When this "best form" is decided upon, it can be wired into a permanent analog system.

As stated before, the advantage of the analog system is its speed. A fast digital computer takes about 1.5 μ sec. (microseconds) to 3 μ sec. to carry out the basic comparisons. An analog circuit can do the same operation in the order of 10 nanoseconds (10^{-8} sec.) However, the digital computer would not be eliminated entirely. It would perform such operations as computing the velocity of each car and storing the velocity and position of each car in a memory storage, while the logic would be carried out by analog circuits. A relatively small digital computer such as the PDP-8, built by Digital Equipment Corporation, would be a good possibility for the digital part of this integrated system. It has a basic memory unit of 4096 twelve-bit words, which would be quite sufficient for our needs.

2. Cost Analysis

By using an integrated system the cost would be cut down considerably. The solid state logic modules can be mass produced for less than two dollars each. This is much less than the cost of the equivalent digital time. The speed of this system is such that about one basic unit a mile would be needed with a cost in the range of $100,000 to $200,000 per mile. A unit here would consist of a computer, such as the PDP-8, and the necessary analog modules to perform the logic sequences.

Cost Analysis

Digital Computer (PDP-8)	$20,000
Peripheral Equipment for Multiplication, Division, Interrupt Facility	30,000-40,000
Logic Modules, Integration of Modules with Digital Computer	40,000-100,000
Installation	10,000-30,000
Housing	10,000
Total Per Integrated Unit	$100,000-$200,000

3. Central Control

Central Control has two basic functions: (1) to monitor each individual computer on the highway to be sure it is functioning correctly and (2) to change and control the various parameters of the system, such as control velocity, spacing, etc.

This central control is not necessarily a computer. Physically, it could consist of a large panel of T.V. monitors, controls, and lights. The T.V. monitors would show a small portion of each computer's highway. These monitors would indicate road conditions so that the control velocity and spacing on each section can be set accordingly. There are also indicators on the board to signal a local power failure and to indicate the position of any stopped vehicle on the highway. In this way a fairly close central control or watch can be kept on the entire system. If there is an accident or a failure in the system, it is readily detected and can be coped with accordingly.

4. Housing

The physical housing of the individual computers is accomplished by means of a small brick or cement block house. It would be located within a few hundred feet of the highway and would have no windows. It should be made as secure as practical to discourage individuals with over-developed curiosities from investigating. It would have some type of heating (probably electric) and air conditioning in warm climates, to keep the temperature between 60° F and 80° F. These installations need not be elaborate and should cost about nine to ten thousand dollars apiece. The temperature and humidity for the small computers being considered is not too critical. So no elaborate weather-making equipment is necessary.

C. Computer Logic

1. Introduction

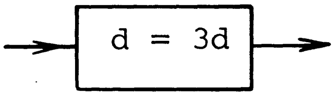
In this large system the computer acts very much like the driver, taking certain input data, processing this data through certain logistic steps, making a decision, and giving some kind of output.

The input of the computer consists of the velocity and position of each car and whether or not the car is signaling to turn. Actually, the velocity signal is inversely proportional to velocity and represents a time signal over a set distance. This time signal is used to simplify external electronics. The logic explained will be in terms of velocity rather than time simply for better understanding of the computer operations. The logic is the same in either case.

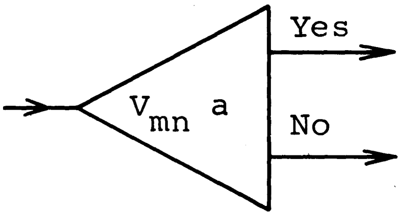
The output of the computer is an acceleration signal (positive, negative, or no change) and a change lane command (left, right, or no change). The process that the computer goes through to come out with an output from a given input is callled computer logic. It is this logic which will be explained now for several of the operations involved.

2. Spacing and Velocity

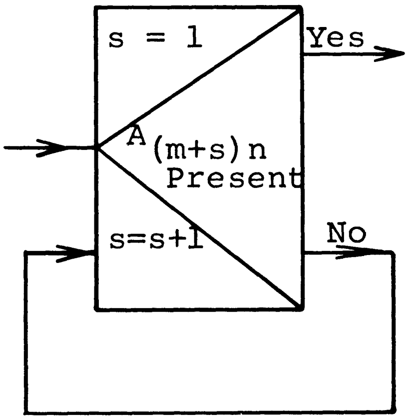
The first operation will be confined to one lane. It is the operation of speed and spacing control. The computer must maintain the proper velocity for each car as well as the correct spacing. This sequence of logic will also take care of slowing vehicles and moving of cars around dead objects on the highway if adjoining lanes permit. The flow diagrams, Figures 12 and 13 entitled "Velocity and Spacing Control", shows the step by step logic the computer goes through to complete the operation. This logic is for one lane and is completed one hundred times per second for each lane of traffic. The program is set up for a section of expressway three lanes wide with all three lanes flowing in one direction. Each five foot detection point in the highway



A rectangle denotes a statement or a command



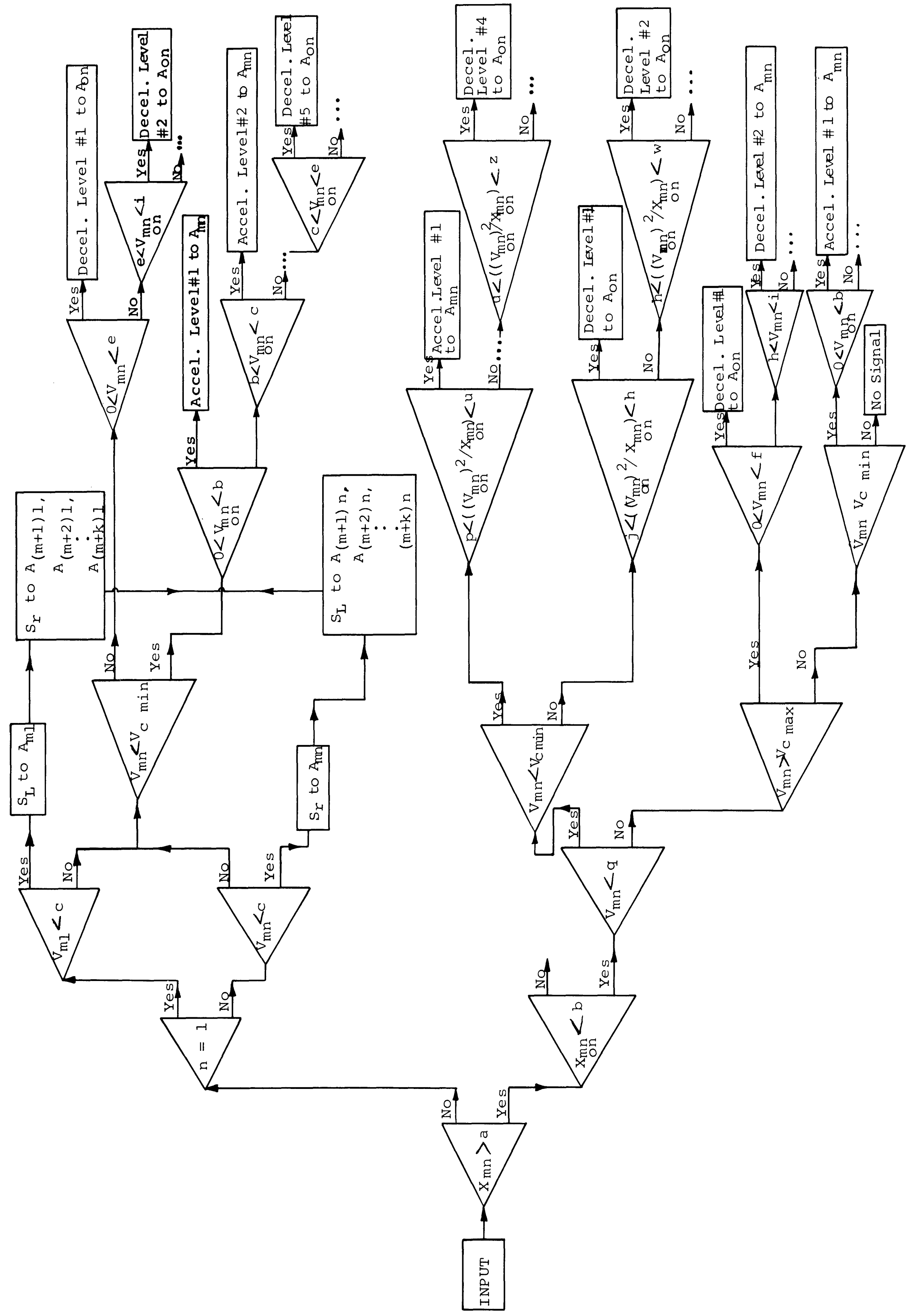
A triangle denotes a question



Such a combination of triangles is called an iteration box. It says: (1) Set s = 1. (2) Is $A_{(m+s)n}$ Present? (3) If Yes, proceed to the next step; if No, set s=s+1 (increase s by one) and ask the question again...

Key to Flow Chart Notation

Figure 12



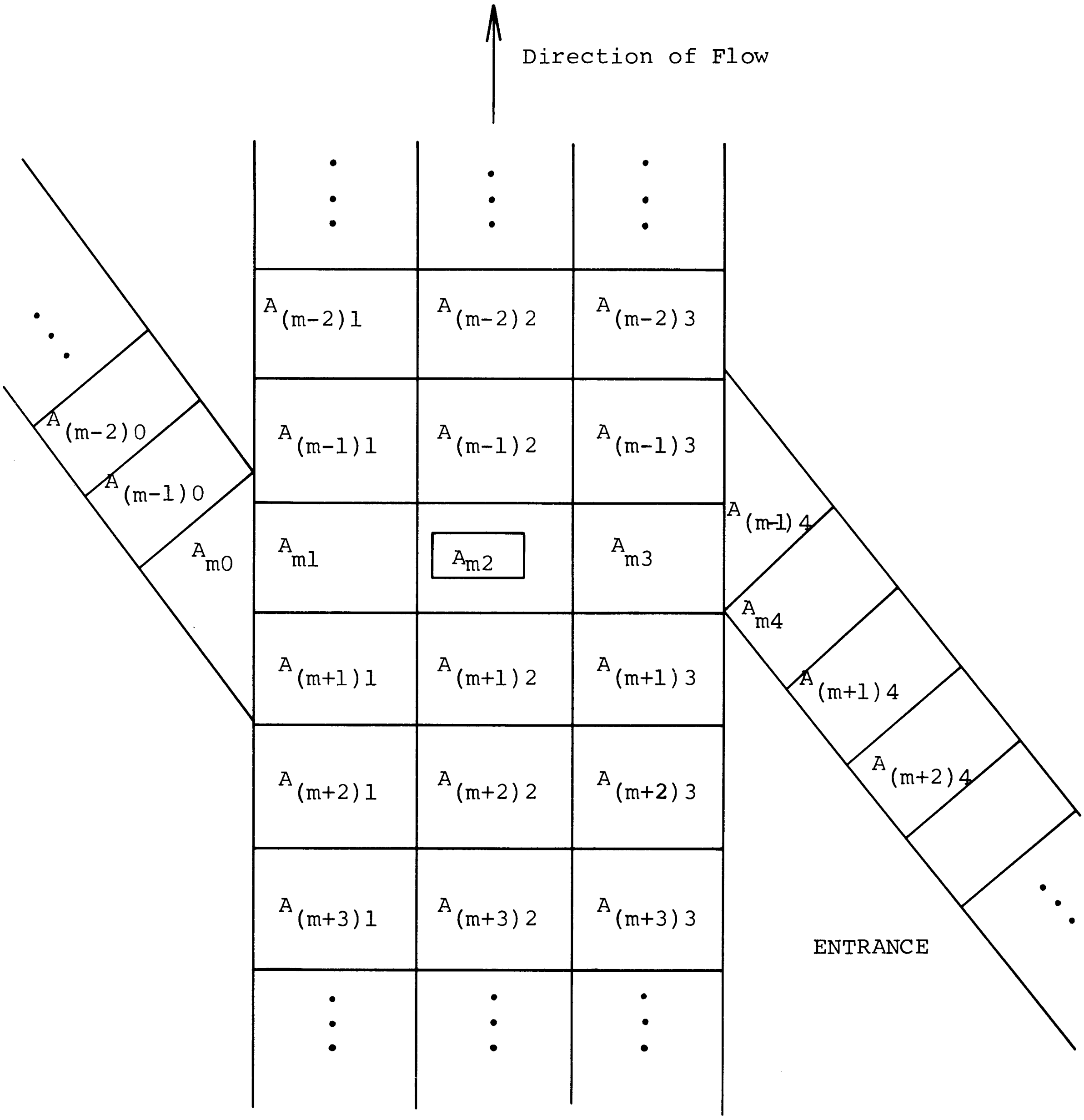
Flow Chart For Velocity and Spacing Control

Figure 13

is part of a matrix which is illustrated in Figure 14 labeled "Three-Lane Highway Detector Matrix".

This matrix has three columns and any number of rows depending on the length of the particular section of highway involved with each computer. A_{mn} represents the detector at position mn in the above matrix. V_{mn} represents the velocity of the car in position mn. Xmn_{on} represents the distance between cars m and o in lane (column) n. Vmn_{on} represents the relative velocity between cars m and o in lane n. Essentially, the computer compares the relative velocity and distances between cars to certain parameters and proceeds accordingly. For example, in the first step the computer asks whether Xmn_{on} is greater than some parameter "a" or not. If it is, it proceeds in the "YES" direction on the flow chart, if not, in the "NO" direction.

In words what the computer does is scan cars and goes through the following logic for each car. Given a car m, the computer compares the distance between car m and car o, the car directly behind car m, with a predetermined range. If car o is too close to car m and car m is going too slow, the computer speeds up car m. If car m is not going to slow, car o is slowed up. The computer also looks at the relative velocity between cars m and o and if car o is approaching car m too fast and car m is going too slow, car m is again speeded up, otherwise car o is slowed up. This same train of logic is carried out for car m and car p, the second car back, and so on to the fifth car back. At this point, the computer



Three-Lane Highway Detector Matrix

Figure 14

moves from car m as the lead car to car o and compares car o to the five cars following it, etc.

There is a division of this program which signals a slowing car to the right if it is in the center or right hand lane, or off the next left exit if it is in the left lane. This division of the program also signals the cars behind a slowing or stopped car into another lane, depending on which lane the slowing car is in. This prevents one car from blocking an entire lane of traffic.

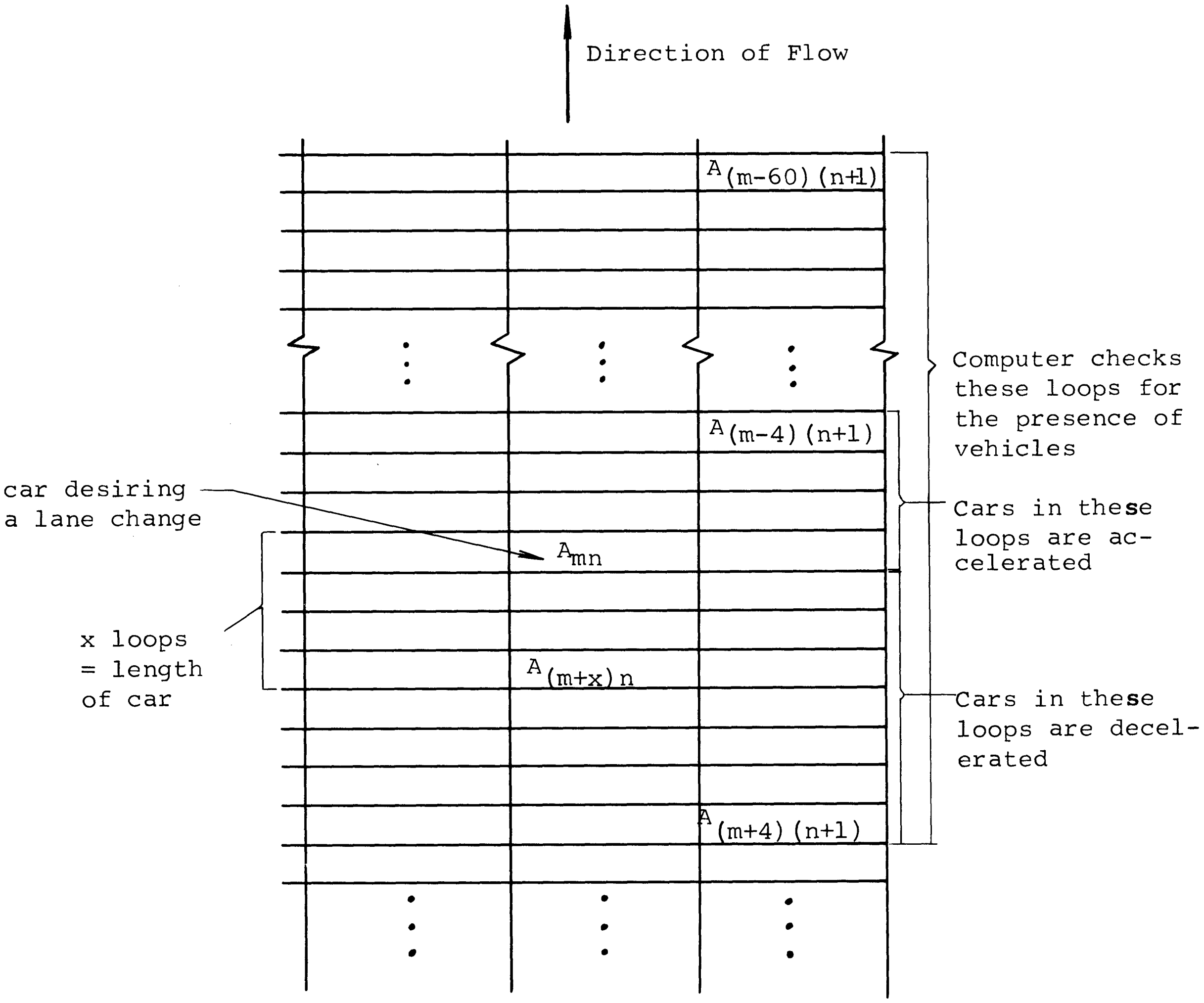
The speed of each car is maintained between $V_{c\ min}$ and $V_{c\ max}$. These are parameters of the system which can be changed from central control.

If the logic of this program is followed carefully it is noted, for a perfectly flat rod with no wind, that a group of cars tends toward the minimum speed $V_{c\ min}$, and also grows in size. In the limit, we end up with one large group which makes it difficult for an uncontrolled vehicle to change lanes. It should be noted that this poses a problem only for the uncontrolled vehicle, which will eventually be eliminated from the system. However, upon closer observation, we find that even slight grades found in the city are enough to break up any large groups tending to form. As the cars go up a slight grade, the computer accelerates the cars to keep them above $V_{c\ min}$. Then, as the cars proceed down the other side of the grade, their velocity reaches $V_{c\ max}$ very quickly due to the added throttle opening needed on the up-grade. Now following through the program for a group of cars at $V_{c\ max}$, it is found that they tend to disperse, alleviating the problem of bunching.

3. Lane Changing and Exiting

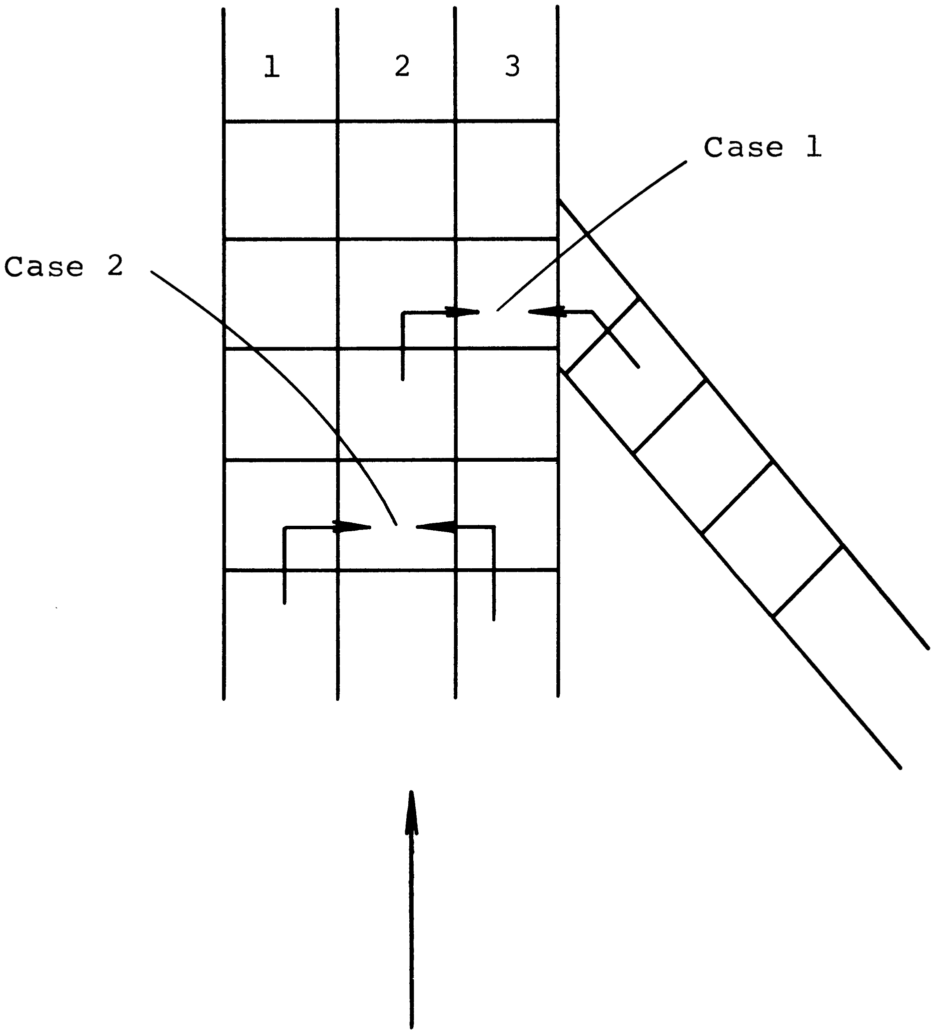
In order to facilitate the flow of traffic by maintaining predetermined relative densities among the three lanes, and in order to eliminate the human error involved in expressway driving, it is felt that the computer should maintain control of all lane-changing, entering, and exiting of vehicles. In the proposed system, there are essentially three initiators of a lane change signal: (1) A driver desiring to exit, indicates the exit number on the control in his car. This exit signal is filtered to the computer along with the direction of the exit (Right/Left) when the vehicle is within a specific distance of the exit. (2) The density of each lane under computer control is calculated and compared to a desired density. A decision is made by the computer as to the number and direction of cars to be moved from one lane to another, and commands are sent to the specified cars to turn on their lane changing signals which are then relayed back to the computer. Since such a signal is not as urgent as an exiting signal, it is felt that the short delay inherent in this method is not a significant disadvantage; and by this means, the vehicle's turn signal could be activated so as to make drivers of uncontrolled cars aware of the imminent movement. (3) An object is detected in the road ahead and cars in that lane are given a lane changing signal when space is available for them in the adjacent lanes.

With the assumption of a given signal to change lanes, flow charts, Figures 15, 16, 17, of computer logic were drawn up



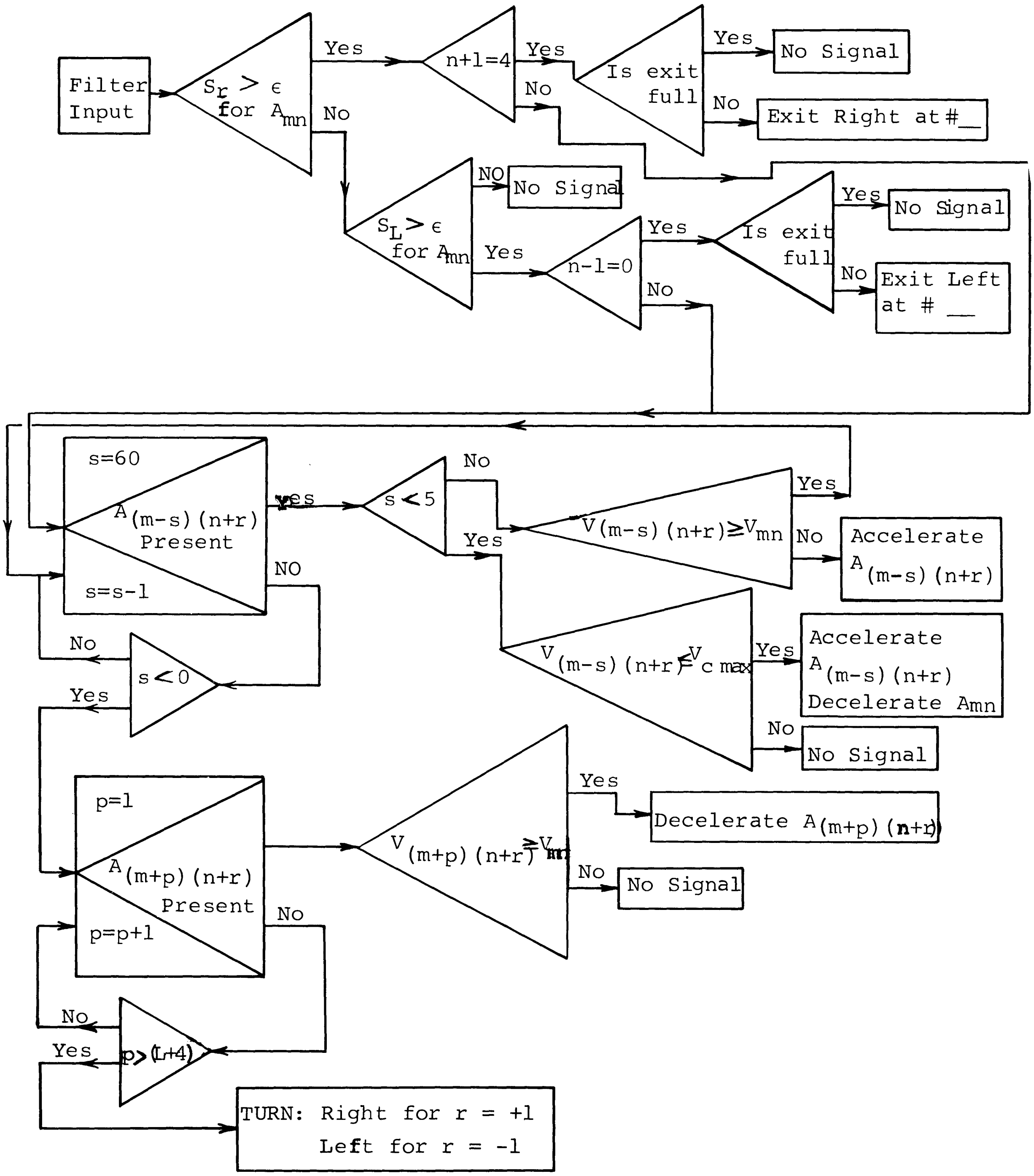
Lane Changing - Notational Diagram

Figure 15



Command Conflicts

Figure 16



Flow Chart for Lane-Changing and Exiting

Figure 17

to simulate a driver's reasoning process. The following explanation of the computer logic will be given for a RIGHT TURN SIGNAL (S_r), where S_r is greater than the noise level ϵ -- the LEFT TURN problem is dealt with in a similar manner. When S_r is received from a lane adjacent to the exit ramp, the car is simply given the instruction to follow the next antenna to the right up the exit ramp, if the ramp is not "full". When S_r is received from either the left or center lanes, the remainder of the program is completed, the car is moved over one lane, and the program is repeated until the vehicle is in the correct lane to exit.

When the computer receives the signal S_r, it also receives the position of the front of the vehicle (A_{mn}), the position of the rear of the vehicle ($A_{(x+L)n}$), and the velocity of the vehicle (V_{mn}). The computer then checks s = sixty dectectors (300 feet) ahead in the adjacent right lane for the presence of vehicle $A_{(m-60)(n+1)}$. This distance is chosen in order to insure that there are no stopped vehicles in the desired lane. If presence is detected, if s is greater than 5, and if the velocity of $A_{(m-60)(n+1)}$ is less than the original car's velocity (V_{mn}), car $A_{(m-60)(n+1)}$ is accelerated. If this velocity condition is not met, then no acceleration signal is needed, since vehicle $A_{(m-60)(n+1)}$ already has a velocity that is greater than or equal to V_{mn}. If no car is present at detector $A_{(m-60)(n+1)}$, the computer checks the remaining detectors in a direction back towards the original car, and accelerates any vehicles in lane (n+1) which are more than four detectors ahead of the original car. When the presence of a second car is detected within four detectors of the front of the original vehicle, and when the velocity of the second car $V_{(m-s)(n+1)}$ $V_{c\ max}$, the second car is accelerated and the original car in position A_{mn} is decelerated, the net effect being that the second car will pull forward to make room for the original car behind it.

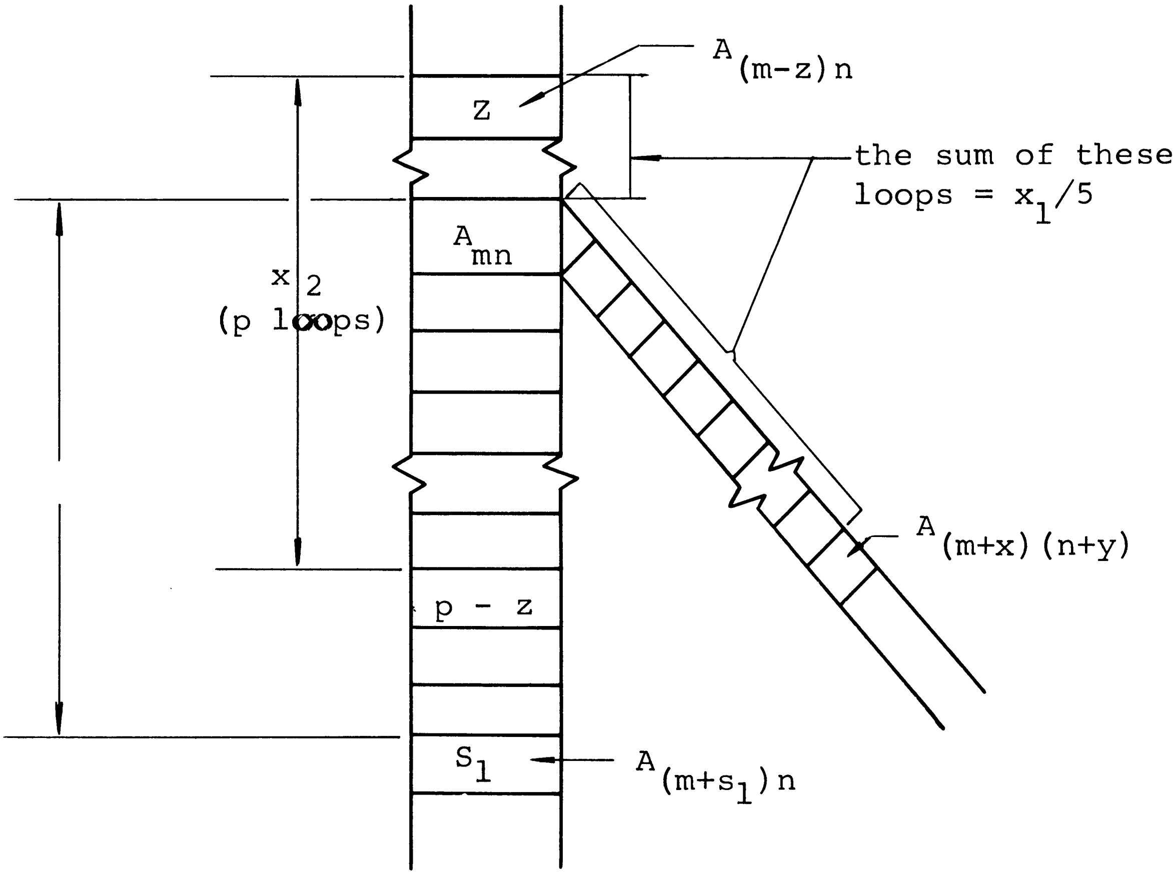
When the above process has been completed, the computer continues to check for the presence of vehicles in the adjacent lane whose "front ends" are anywhere in the range between detector (m+1) and detector (m+L+4), that is, vehicles beside, or within four detectors beyond the rear of the original car, where L = the length of the original car measured in detector sections. If vehicles are detected in this range, and their velocities are greater than or equal to the original car's velocity, these cars are decelerated to widen the gap and make room for the original car. When no cars are detected in the adjacent lane within the above range four detectors in front of, beside, and four detectors beyond the original car - a gap has been produced and the original car in position A_{mn} is signaled to TURN RIGHT. This is the basic lane-changing program adaptable to exiting and density control.

At some random time t, it may happen that two cars from non-adjacent lanes may both desire to turn into a free space in the lane between them. If all entrances come from the righthand side, there are only two cases to consider: (1) that of an entering vehicle and a vehicle in lane 2 desiring to move into lane 3, (2) that of a vehicle in lane 1 and another in lane 3 desiring to move into lane 2. Since the probability of this happening is very small and since there are only two cases to consider, the right-hand vehicle will be given preference to turn left first (in both cases) in order to make room for entering cars in the right lane.

4. Entering the Superhighway

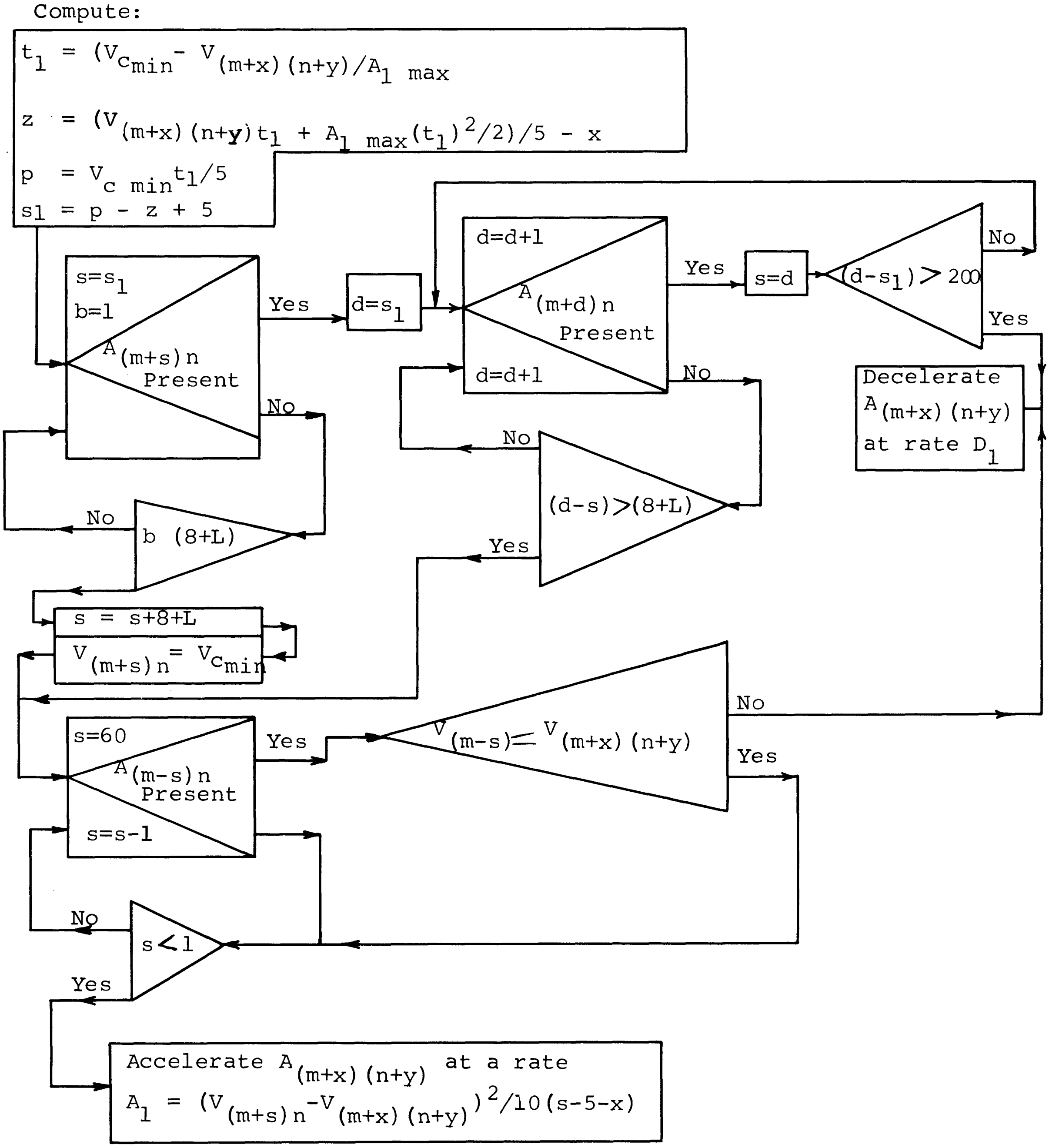
From first considerations, it appears that the entering operations may be governed by the same computer program as the lane changing operations. However, the program for changing lanes is based on the assumption that most of the time, cars will be traveling at nearly the same velocity, and high acceleration rates will be impossible, due to the other traffic on the roadway. In the lane changing situation, it is much more practical to "make" a gap; whereas in the entering situation, it is more practical to "find" a gap and accelerate the car on the open ramp at the desired rate.

In order to find such a gap in the traffic, it becomes necessary to define a maximum acceleration level ($A_{1\ max}$) which every car could reach. (This would eventually entail a safety check on all cars to insure that every vehicle - including any trucks - could match this acceleration level.) Then given this $A_{1\ max}$, the computer would calculate the theoretical time (t_1) that it would take the entering car to accelerate up to the minimum lane velocity ($V_{c\ min}$), and calculate the distance (x_1) that the entering car would travel in time t_1 according to the notation in figures 18 and 19. Designating the position at the bottom of the ramp in the traffic lane as A_{mn}, the position of the entering car after time t_1 would be detector (m-z), where $z = ((x_1$ ft./5 ft. per detector section) - x detectors), and x = the number of detector sections to be traveled on the entrance ramp - see diagram. Now suppose that the computer also calculates the



Entrance Program Diagram - Loop Notation

Figure 18



Flow Chart For Entering the Superhighway

Figure 19

distance travled in the traffic lane by a minimum velocity car which will also be in position (m-z) at time t_1; then the computer can calculate the position of this imaginary car at time $t = 0$ when the entering car is first detected.

Since it has been assumed that the entering car is accelerating at a maximum rate, and since it can not possibly reach a position ahead of the imaginary car, the position of this imaginary car will be the closest place for the computer to begin searching for a gap in which to fit the entering car. The computer will then be looking for a space which is (L + 8) detector sections long, four in front of the car, four in back of the car, and L detector sections along the length of the car. The computer scans for a gap of the correct size, back to 200 detector sections behind the imaginary car. If no gap is found in this range, the entering car is decelerated at a rate D_1 so as not to enter the traffic lane and collide with slow-velocity vehicles. If no cars are found in this range, or if there are cars present in this range but a gap is found between them, the computer scans 60 detectors ahead of the gap to insure that the velocities of all cars are greater than the velocity of the entering car. If this condition is not met, the entering car is again decelerated at rate D_1; if the above condition _is_ met, the entering car is accelerated at a rate A_1 as derived below.

Computation of the Acceleration Signal A_1 for a Car on the Entrance Ramp

Since part of the entering car's acceleration will take place in the traffic lane, it would be desirable for this car to reach the speed V_2 before car #2 hits it. Therefore, we want the distance (z_1) traveled in the traffic lane by the entering car (while accelerating) to be greater than or equal to 20 feet plus the distance (z_2) past the entrance ramp which the highway car would travel during the same accelerating period.

Then, $(x_1/5 - x) \quad (x_2/5 - s + 5)$ .....(1)

For calculation purposes, set these two quantities equal.

We know that, $t = (V_2 - V_1)/ A_1$

$$x_1 = V_1 t + A_1 t^2/2$$

$$x_2 = V_2 t$$

where V_2 = the velocity of the car behind the gap, or = $V_{c\ min}$ if there are no cars in the 200 detector range

V_1 = the velocity of the entering car

t = actual time it will take the entering car to reach the velocity V_2

Substituting the expressions for t, x_1, and x_2 into equation (1) and solving for A_1,

$$(V_1 t + A_1 t^2)/5 - x = V_2 t/5 - s + 5$$

$$(V_1 - V_2)(V_2 - V_1)/A_1 + A_1/2(V_2 - V_1)/A_1)^2 = 5(x - s + 5)$$

$$-2(V_2 - V_1)^2 + (V_2 - V_1)^2 = 2A_1 5(x - s + 5)$$

Then, $A_1 = (V_2 - V_1)^2/10(s - 5 - x)$

By means of this acceleration value, the acceleration of an entering vehicle may be revised as often as is deemed necessary while the car moves down the ramp.

Computations of the Deceleration Signal D_1 for a Car on the Entrance Ramp:

If t_d = the time it takes to stop a car on the ramp before it moves into the lane, then $t_d = (0 - V_1)/D_1$.

The stopping distance $= 5x = V_1 t_d + D_1(t_d)^2/2$.

Substituting t_d into the stopping distance equation,

$$5x = V_1(-V_1/D_1)^2 + D_1(V_1/D_1)^2/2$$
$$= V_1^2/2D_1$$

Add, $D_1 = -V_1^2/10x$

It should be noted that the cars on the entrance ramp will also be accelerated or decelerated by the Spacing and Velocity Control Program, just as if they were in a traffic lane.

Definitions and Notation for Entering Description

Subscript 1 refers to the car on the entrance ramp.

Subscript 2 refers to the car behind the gap which is moving along with the traffic.

$V_{c\ min}$ = the minimum control velocity of lane n.

$A_{1\ max}$ = the maximum possible acceleration of the "slowest" car in the system.

t_1 = the minimum time it would take car #1 to get up to velocity $V_{c\ min}$ by accelerating at a level $A_{1\ max} = (V_{c\ min} - V_1)/A_{1\ max}$

V_1 = the instanteous velocity of car #1

V_2 = the instanteous velocity of car #2

x = the number of detectors on the entrance ramp indicating the position of car #1

x_1 = the distance car #2 would travel in time $t_1 = V_1 t_1 + A_{1\ max} (t_1)^2/2 = 5(x + z)$

x_2 = the distance car #2 would travel in time $t_1 = V_{c\ min}\ t_1$

z = the position at which car #1 would reach velocity $V_{c\ min} = x_1/5 - x = (V_1 t_1 + A_{1\ max} (t_1)^2/2/5 - x$ (must be rounded off)

p = the number of detectors car #2 would pass over in time $t_1 = x_2/5 = V_{c\ min}\ t_1/5$ (must be rounded off)

t = the actual acceleration period of car #1

s, s_1 = iteration variables (integers) which denote the number of the first detector section occupied by car #2 = p-z+5

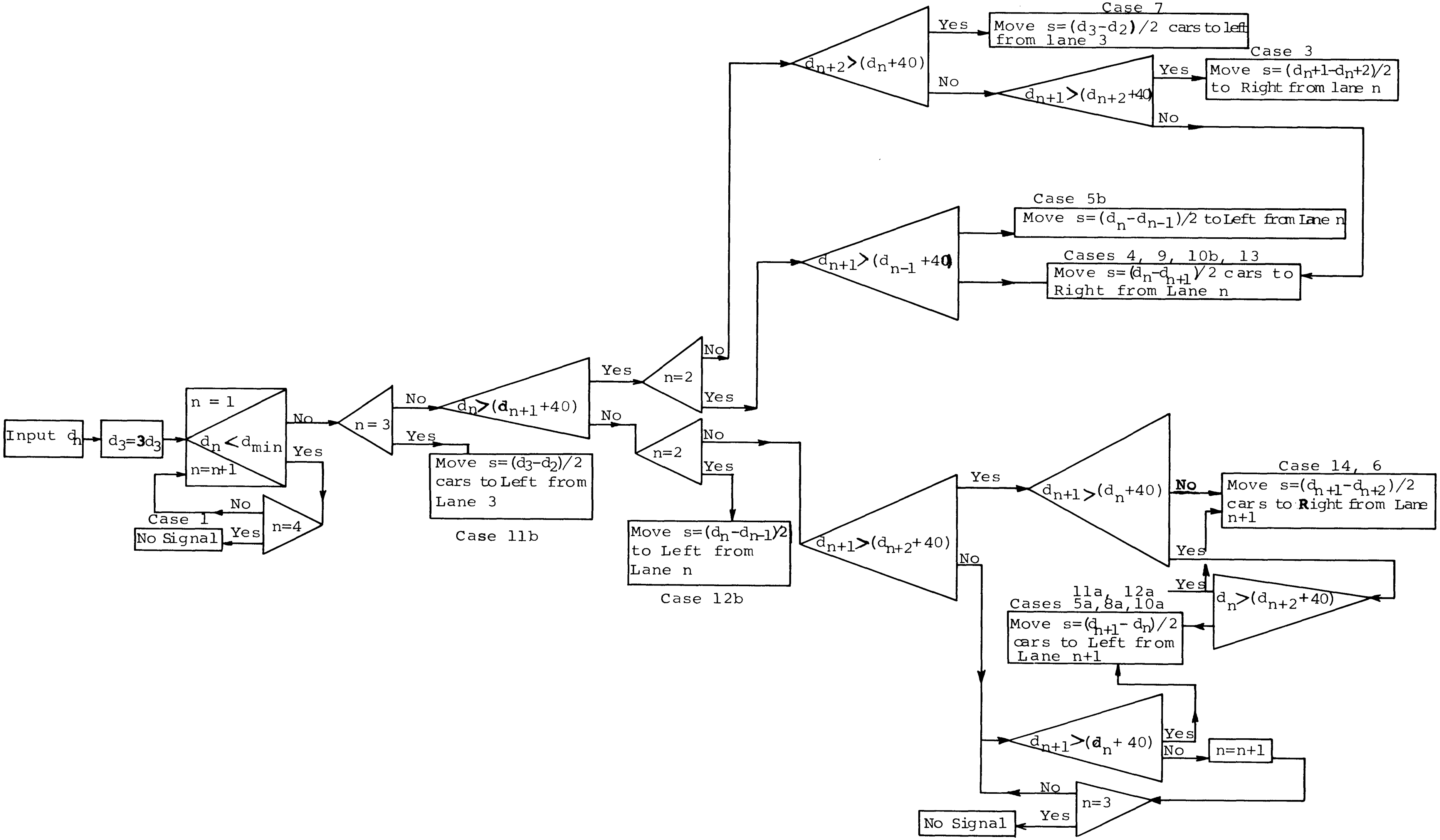
b = a counting integer to determine the length of any gap

D_1 = the deceleration rate for cars on the entrance ramp, which can not be "fit" into a gap in the traffic lane.
$= - V_1^{\,2}/10x$

Note: t_1, x_1, x_2, $V_{c\ min}$, and $A_{1\ max}$ are used only to estimate the spot in the traffic lane to start looking for gaps. The acceleration signal A_1 is calculated on actual velocities, times, and positions.

5. Density Distribution

In order to maximize the efficiency of the existing highway systems and to facilitate entering and exiting from the right-hand lane in particular, a computer program as shown in Figure 20 has been devised to distribute the vehicles among the three lanes according to specified relative densities. To



Flow Chart for Density Distribution

Figure 20

obtain the information for such a program, the computer must count the activated detectors in each lane as it scans a particular section of the highway. Then d_n = (the density of lane n) = the number of activated detectors in lane n. Let d_{min} equal a minimum density so that when d_n is less than d_{min} for all three lanes, the highway is sufficiently "empty" so as not to merit a specified distribution of vehicles across lanes. When d_n is above the minimum value for any lane, vehicles will be moved from one lane to the next if the densities between any two lanes differ by more than five cars (twenty activated detectors) in the stretch of roadway under computer control. In all cases, the value of d_3 which represents the density of the right-hand lane, will be three times the actual density in order to make room for entering vehicles and to account for uncontrolled vehicles which can not be distributed by the computer. In addition, vehicles giving exit signals for some reason, other than density distribution, will be moved only in the direction of their signals, otherwise will be left in their present lanes by the density operation.

In order to devise a system which would function for all cases, each case had to be considered separately. The following is a list of all the combinations of density distribution for a three-lane highway.

Cases: (1) $d_1 \approx d_2 \approx d_3 < d_{min}$

(2) $d_1 \approx d_2 \approx d_3 > d_{min}$

(3) - (8) Three different densities; max, med, min.

Cases:

Lane	3	4	5	6	7	8
1	max	max	min	med	med	min
2	med	min	max	max	min	med
3	min	med	med	min	max	max

(9) - (14) Two different densities; max, min.

Cases:

Lane	9	10	11	12	13	14
1	max	min	min	min	max	max
2	min	max	min	max	min	max
3	min	min	max	max	max	min

Rather than explain the entire program in detail, let us consider only case (5) as an example where d_1 = min, d_2 = max, d_3 = med value, and d_1 d_{min}. Program: d_1 is greater than d_{min} and is sufficiently less than d_2 to warrant a change; however, d_2 is larger than d_3 but a change from d_2 to d_3 would probably result in d_3 = max, so the computer instructs that "s" cars be moved to the left from lane 2 where $s = (d_2 - d_1)/2$ activated detectors to be transferred from lane 1 to lane 2, times (1/4-detectors per vehicle on the average), or $s = (d_2 - d_1)/8$ vehicles. Then every $(d_2/4s)^{th}$ vehicle in lane 2 would be moved unless it had a prior lane changing signal. This equalization of lanes 1 and 2 could result in case (11) which instructs that "s" cars be moved to the left lane 3, where $s = (d_3 - d_2)/8$. Then every $(d_3/4s)^{th}$ vehicle in lane 3 would be moved unless it had a prior lane-change signal. The equalization of d_3 and d_2 would result in case (12) which again moved cars from lane 2 to lane 1, and so on until the differences between the densities are less than five cars or twenty detectors. Similar considerations are made for all other cases.

6. Future Goals

In the analysis and design of the computer control for an automated superhighway system, we have (in general) taken the point of view that the computer operations must be adapted to the existing highways. In some cases, however, this adaptation leads to undo complications in the computer logic. Such a problem is confronted when considering entrance and exit ramps. If the computer programs a car to accelerate on an entrance ramp in order to fit into a moving gap in the traffic lane, the increased speed of the car may be too great when compared with the curvature of the ramp, and centrifugal force may cause the car to leave the roadway. In this case, rather than modify each computer program for each of the different ramp configurations in its domain, it may be easier and less costly to modify the ramsp either by banking each ramp to accomodate excessive speeds or by rebuilding the ramps with long straight-a-ways leading to the traffic lanes.

It is also necessary to place the subject of reliability in the category of future goals. It is felt that the 100th of a second time check on each vehicle will be sufficient to operate the system safely; however, the optimum time will have to be a function of detector and computer limitations. In addition, the reliability of the computer system should be checked by completing a mathematical study of the possible wave patterns caused by the computer. As a final reliability check, it is proposed that a dummy variable (consisting of a dummy position and velocity) be fed into each computer unit at pre-determined intervals and the output be checked against expected output to insure against malfunctions in the roadside system.

Chapter IV

Braking and Acceleration Control

A. Introduction

A study of the urban problem of the automated highway has led to the conclusion that the controlled vehicle must incorporate a measurement of acceleration in its feedback loop. Present day speed controllers for automobiles use velocity as the only parameter in the loop. This method is acceptable in the case of the intercity highways since the distance between cars is large (300 ft). However, in the case of the urban expressway the spacing will be of the order of 35 feet (two car lenghs) between vehicles. Here it becomes manditory to accurately control the acceleration of the vehicles during any period of sustained acceleration or braking. For example, if an emergency condition on the highway requires that a lane of cars be stopped rapidly, they would all have to maintain approximately the same deceleration rate to avoid serious accidents. A braking level can not accurately be specified in an automobile by reference to hydraulic pressure or brake pedal position. Acceleration likewise is not a function of throttle position alone. In both cases there are other parameters with considerable influence. Loading of thecar affects acceleration and deceleration, wear on the brakes and even brake drum temperature affect deceleration. When these factors are considered it can be seen that a braking level can only be specified by reference to the acceleration of the vehicle. If the car's braking level were not referenced it can be seen that in the case of the emergency stop they would all have different decelerations. By the time this is detected using the formula $(V_1 - V_2)^2/(d_1 - d_2)$ it may be too late to take corrective measures. Even if additional braking is available in the trailing vehicle, the relative velocity would be too large to avoid a collision. With these things in mind it was decided that the automated vehicle must be controlled entirely by acceleration and deceleration commands. Consequently, an accurate means of sensing acceleration in the car is needed. The proposed system which follows shows the results of the investigation. Acceleration is measured in the vehicle and a feedback loop referenced to an external command maintains this parameter.

It should be pointed out that the external command signal to the vehicle is determined in the computer by consideration of the relative velocity and spacing and that there is no measurement of vehicle acceleration made by the external detection system. In the case of a line of cars stopping together, they would be given the same deceleration command. The feedback loop in the car should be able to maintain this deceleration with a small margin of error, not exceeding 10 per cent. Small errors such as this can be tolerated since the external command will be altered for any vehicle which deviates from the spacing and relative velocity requirements. However, the computer could not correct major deviations which would be present if acceleration were not controlled in the vehicle.

B. Speed and Acceleration Sensing Devices

1. Introduction

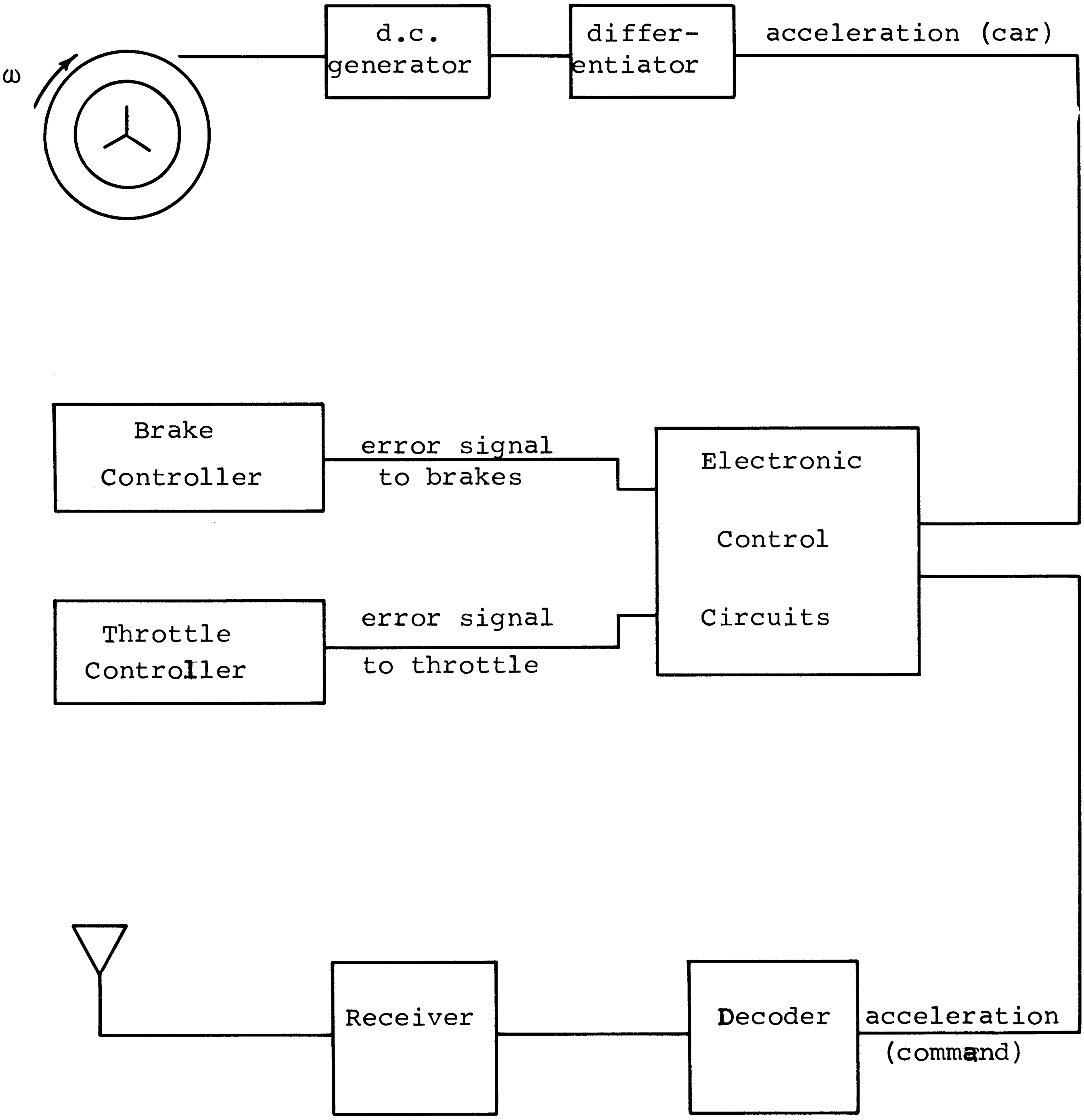
There were three methods investigated for measuring the acceleration of the automated vehicle. The proposed system which appears in Figure 21 uses a precision d.c. generator driven from the speedometer cable. A differentiator circuit is coupled to the generator to give a reading for acceleration. This method was found to be the most practical from the standpoint of cost. Also it will later be seen that this accelerometer is the only one that will provide effective anti-skid protection-a feature which is necessary on any automated vehicle. The other two devices investigated were the buried magnet speedometer and the mass-balance accelerometer.

2. Buried Magnets for Speed Sensing

The method of determining speed by the distance between pulses from magnets buried in the road had the advantage of being reasonably accurate for speeds of the range 30 to 80 miles per hour. A simple differentiator circuit could be placed on the output of the speed measurement, giving a reading for acceleration. However, this method of speed and acceleration measurement has a lack of range which prohibits its use below 30 miles per hour. Although larger magnets could be used to expand the speed range the system would still be too limited.

3. Mass-Balance Accelerometers

Commerically available accelerometers which utilize



Complete Control System for the

Automated Vehicle

Figure 21

a spring supported mass were investigated. They have the advantage of giving an electrical signal output which could be fed into a differential amplifier for control. These devices can measure accelerations with good accuracy (I.02G on a I1.0G scale) and have extremely fast response. However, there are two major drawbacks to this method of detection:

1. The present cost is prohibitive. A suitable model for use cost $330. Although a considerable increase in production of a specified model might reduce the price, it would still probably not be economically acceptable.
2. There is no fixed reference on which to mount the accelerometer so as to detect the actual acceleration relative to the road's surface. The accelerometer's reading would vary with the automobile's loading.

For the above reasons the mass-balance accelerometers were eliminated from the system.

4. D. C. Generator Plus Differentiator Circuit

a. Proposed System

A small precision d.c. generator could be used to measure speed accurately and a differentiator could then convert the velocity reading into an acceleration reading. A mechanical linkage with the speedometer cable could be used to drive a small precision d.c. generator which has a voltage output proportional to rotational speed. This voltage could then be run through a simple differentiator circuit shown in Figure 22.

b. Accuracy

This system provides sufficient accuracy for it purpose. An acceleration reading with as much as 10 per cent error could be tolerated, however, this accelerometer should be able to work within a range of ± 3 per cent. Since the speed and the distance of all cars on the road would be continuously monitored by the computer, such errors would not lead to any difficulties.

If the differentiator introduces no error, then the reading for acceleration will have the same inaccuracy as the reading for velocity. This is shown below:

V_T = true velocity of vehicle

e = percentage error in velocity reading

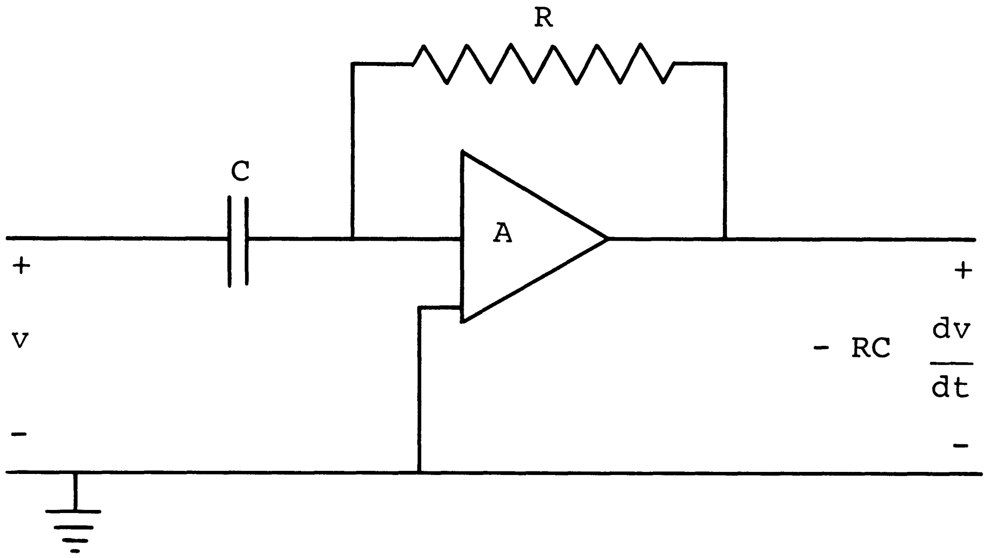
v_D = velocity reading of the d.c. generator

$$v_D = v_T(1 + e)$$

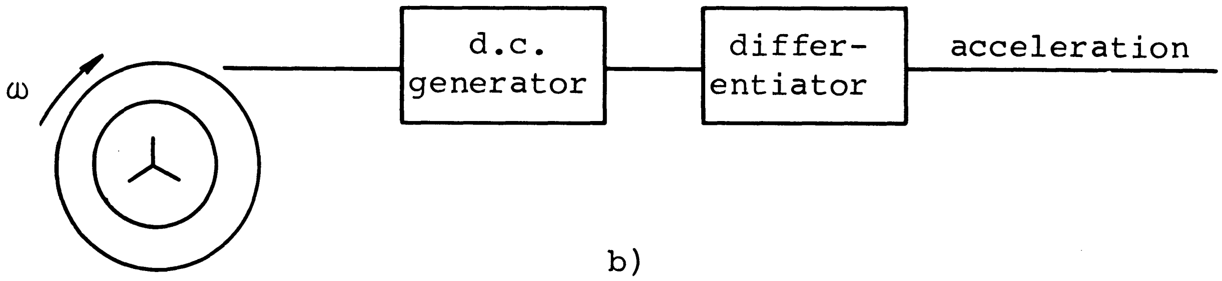
$$a_t = \text{true acceleration} = \frac{dv_T}{dt}$$

$$a_D = \text{acceleration reading} = \frac{dv_D}{dt}$$

$$a_D = \frac{dv_D}{dt} = \frac{d}{dt}\,(v_T(1 + e))$$



a)



b)

a) Simple differentiator circuit

b) Accelerometer for the Automated Vehicle

Figure 22

$$a_D = (1 + e) \frac{dv_T}{dt}$$

$$a_D = (1 + e) aT$$

The per cent error in the acceleration reading will be the same as the per cent error in the velocity reading if the differentiator is accurate.

One particularly important aspect of this type of accelerometer range. The acceleration and speed can be determined accurately in a range of 3 or 4 to 80 miles per hour.

c. Costs

The cost for this accelerometer (not including an external calibration circuit shown below) will be about $30.

Cable and gear attached existing speedometer	4
D. C. Generator	10
Differentiator Circuit	6
Installation and Packaging	10
	$30

5. External Calibration of the Proposed Accelerometer

Increased accuracy could be obtained if the accelerometers were calibrated by a signal obtained externally. Allowances for variations in tires wear, air pressure in the tires and circuit parameter changes could be compensated in this manner.

A method of calibrating the accelerometer involves comparison of the velocity voltage to a known voltage reference obtained externally. The velocity will calibrated in this case rather than the acceleration since an accurate velocity reading should assure an accurate acceleration reading.

Certain calibration areas would be set up every few miles along the highway. The external signal will be derived from the same value of velocity used by the computer. This velocity is transmitted to the car just as the acceleration reading and is received by the receiver on the car. A d.c. signal corresponding to the car's velocity is compared to the velocity reading in the car derived from the precision d.c. generator. A direct couple differential amplifier will be used, for this comparison, its output will regulate a small positioning motor which positions a reostat. The reostat will calibrate the velocity voltage to its true value.

The cost of this calibration circuit would probably be considerably more than the accelerometer alone. The added equipment could also cause reliability problems. Therefore, the calibrating circuit is not recommended as a part of the proposed system.

C. Brake Actuator and Throttle Positioner

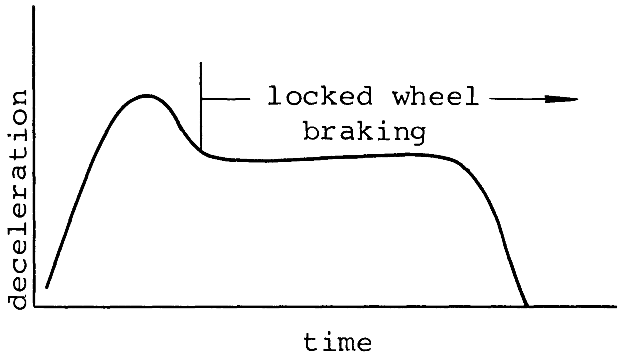
1. Braking System

The automatic braking system of the controlled vehicle must be readily adaptable to conventional cars now on the highways. The proposed system can be installed on any passenger car with hydraulic brakes, regardless of whether they are power brakes or the conventional non-power variety.

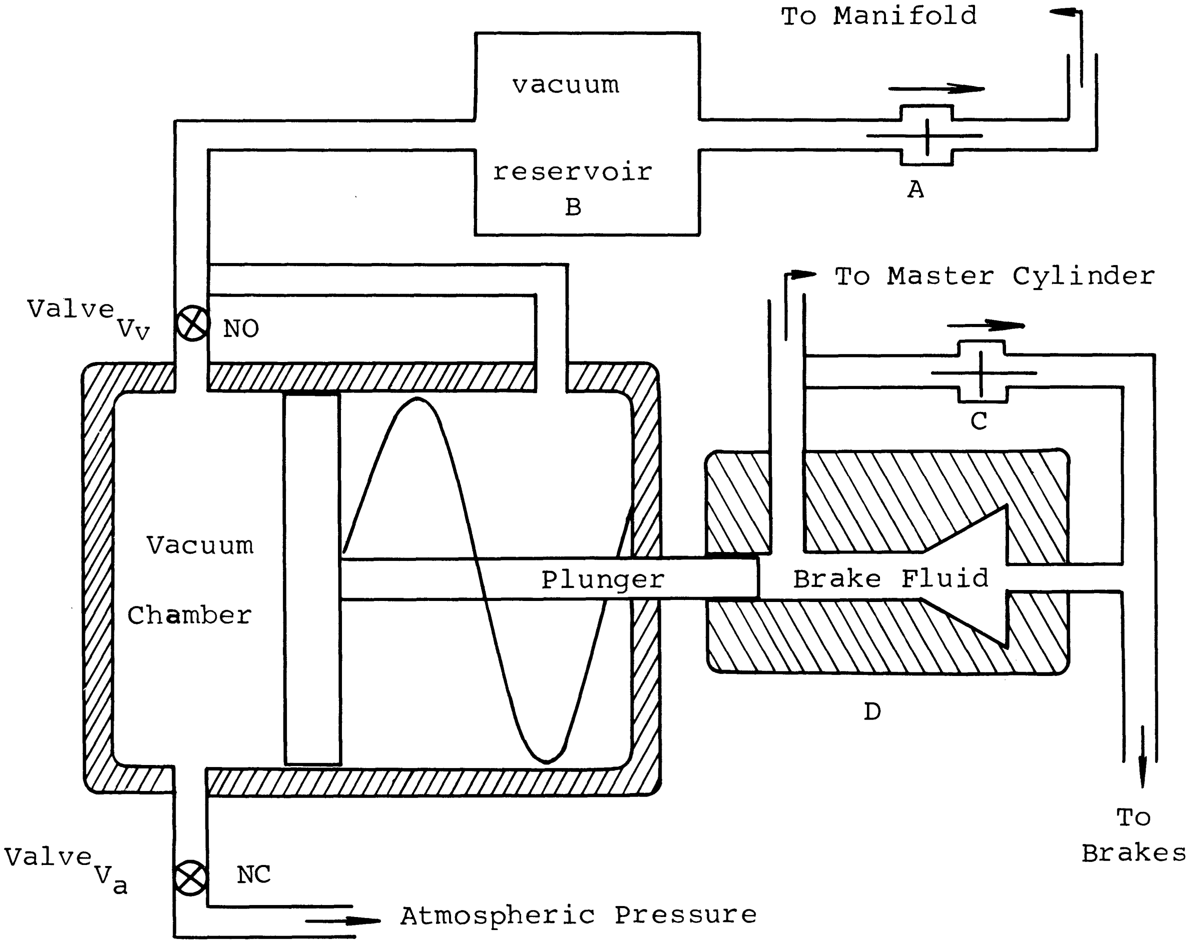
2. Proposed System

It is proposed that a vacuum device be installed to control braking. The proposed system shown in Figure 23 is similar to that used as a power assist on conventional power braking system. When it is desired to increase the braking level an electrical signal will open the valve V_A which admits air at an atmospheric pressure into the pneumatic cylinder. This pushes the plunger into the hydraulic fluid and consequently increases the braking level. The car should now be decelerating at a greater rate. When deceleration reaches the desired level (as compared to the command signal from the transmitter in the road) the valve V_A will be closed. The hydraulic fluid pressure should be maintained until a signal is received to open one of the two valves. If it is desired to crease the braking level, a signal will be sent to open valve V_V, which will evacuate the left hand side of the cylinder and as a result lower the hydraulic pressure. It is important to note that when the car is not receiving a deceleration command that the valve V_V should be opened, allowing the pressure on both sides of the piston to equalize. Otherwise, changes in the vacuum pressure could cause the brakes to operate at an undesirable time.

The vacuum required to operate this device is obtained



a)



b)

Diagram

a) Deceleration vs. Time graph for an automobile braking from 50 miles per hour.

b) Braking Controller for the automated vehicle

Figure 23

from the manifold of the engine. Check valve A prevents gas from the manifold from entering the reservoir tank B and helps maintain a relatively constant vacuum. The vacuum reservoir tank is needed so that a vacuum will be available to operate the brakes even if the engine should stall under severe braking. Installation involves placing the assembly D in the hydraulic line between the master cylinder and the brakes. Check valve C allows the driver to override the automatic braking system with the conventional brakes. In 1967 models will all be equipped with independent hydraulic systems for the front and rear wheels. This will involve two master cylinders and will complicate the proposed system somewhat, however, this presents no major problem.

3. Anti-Skid Protection

Any braking control system must prevent skidding as a result of a locked wheel condition during braking. Skidding can occur during emergency braking or during relatively moderate braking on wet pavements and can result in serious accidents. For this reason some fromof feedback must be used to detect and correct any skidding condition.

Anti-skid devices for automobiles have been developed and are presently being marketed. They measure angular deceleration of the wheels and release the brakes when an impending skid condition is sensed. For example, if the angular deceleration of the wheels indicated a deceleration of the wheels indicated a deceleration of the car of 1G, the wheels would start to lock, and the brakes should be released. It is important to note that anti-skid devices not only prevent loss of steering control but also can often bring the car to a stop in a shorter distance than if the driver had had complete control of the car himself. The graph below shows the deceleration of a car before and after a locked wheel condition. The maximum deceleration occurs before the wheels lock. If the brakes could be held at this level, the shortest stopping distance would be accomplished. This is one of the advantages of the anti-skid device.

Inspection of the proposed system shows that anti-skid protection is an inherent part of the design. A locked wheel condition will be sensed by the accelerometer as an abnormally high deceleration and consequently the brakes will immediately be released. This requires a fast response time on the part of the feedback system. However, existing anti-skid devices have demonstrated that such parameters are reasonable.

As an example of how the braking system on the automated car will provide anti-skid protection consider the following example. Imagine a car travelling on wet pavement, capable of maintaining a deceleration of only 5 ft/sec^2 without skidding. If this car were to receive a deceleration command of 10 ft/sec^2 the brakes would be applied until an impending skid, indicated a deceleration of greater than 10 ft/sec^2. At this point the brakes would be released and reapplied in a pumping manner until the car stopped. The minimum stopping distance would be accomplished and control would be maintained at all times.

4. Cost of Braking System

The cost below are only for the equipment shown in the diagram. The installation would be relatively simple.

Equipment	$35
Installation	20
	$55

5. Throttle Positioners

Two methods were considered for positioning the throttle on the automatic vehicle, one is an electronic positioner, the other pneumatic. Both are commercially available and are presently being used in speed control mechanisms. The electronic positioner was chosen for use on the automated vehicle. The control system in the car is electrical, therefore, an electrical signal from the controller can be used directly by the positioner, whereas in the case of the pneumatic positioner the electrical signal would have to be converted into pneumatic form to operate the controller.

The electronic positioner for the throttle is a simple on-off reversible d.c. motor attached to the carburetor. When the car receives a command to accelerate the d.c. motor will be turned on and will rotate until the desired value of acceleration is attained. The self locking gears will maintain this throttle position until the motor receives another signal. This type of positioner has already been implemented by the Perfect Circle Corporation as part of a speed controller. Consequently, further analysis will not be undertaken here.

However, one more thing should be pointed out. It may appear that rejecting the pneumatic positioner here is contradictory since it was previously specified in the case of the braking system. A pneumatic system was necessary for braking because of the large force that must be transmitted. No electrical devices acceptable to our system could supply such a force. But the force restriction is not important in the case of the throttle positioner.

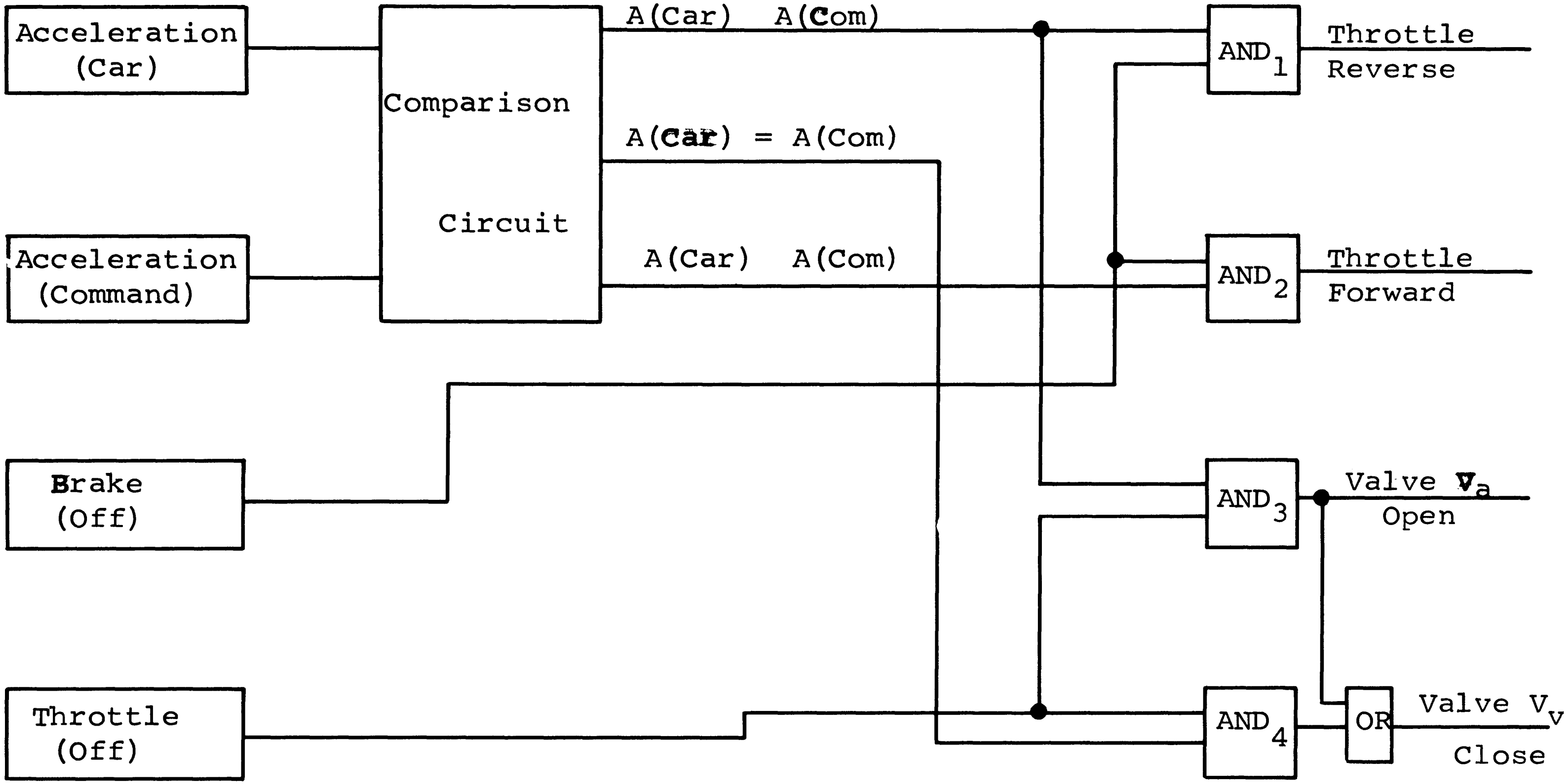
6. Costs of Throttle Positioner

The cost of the reversible d.c. motor is estimated to be $20 installation included.

D. Electronic Control System

1. Introduction

A flow diagram of the electronic control system of the automated vehicle is in Figure 24. The external command signal will be received and decoded as previously explained. The system will compare the command signal to the actual acceleration and take corrective measures. The comparison circuit includes a d.c. differential amp-



Electronic Control System for

Acceleration and Deceleration

Figure 24

lifier and some simple logic circuits. The output signals for the throttle and brake positioners will have to be amplified before they can be used.

2. Explanation of the Flow Diagram

The command signal and the actual acceleration will be compared in the comparison circuit which will yield one of three possible outputs. The blocks labeled Throttle (OFF) and Brake (OFF) are two important parts of the control system. Whenever the throttle is in its zero position a voltage will be indicated at Throttle (OFF). This voltage will be derived from a switch on the carburetor. The same type of scheme is employed on the brake positioner.

Figure 25 shows the output of the electronic control system necessary to accomplish the required acceleration or deceleration. Note that the valve V_a is normally closed and the valve V_V is normally opened.

As an example of the operation of the electronic control system consider a car maintaining a constant speed (case 10). When the car receives a deceleration command the comparison circuit will give an output showing that the acceleration of the car is greater than the acceleration desired. Since the brake is off, AND_1 will be activated, and the throttle positioner will be reversed (case 2). If the throttle reaches its lowest point without accomplishing the desired command the Throttle (OFF) switch will be activated. At this time AND_3 will be activated. The air valve will open and the vacuum valve

	Reverse R	Forward F	Valve V_aNC	Valve V_vNO
1. Increase Acceleration	-	x	-	-
2. Decrease Acceleration	x	-	-	-
3. Increase Braking	-	-	x	x
4. Decrease Braking	-	-	-	-
5. Increase Engine Braking	x	-	-	-
6. Decrease Engine Braking	-	x	-	-
7. Maintain Acceleration	-	-	-	-
8. Maintain Braking	-	-	-	x
9. Maintain Engine Braking	-	-	-	-
10. Maintain Speed	-	-	-	-

Outputs of the Electronic

Control System

Figure 25

will close (case 3). This will increase the brake fluid pressure until the desired deceleration is obtained. At this time AND_3 will no longer be activated, but AND_4 will now be putting out a signal. This will hold the vacuum valve V_V closed (case 8) so that the brake fluid pressure will be maintained. This pressure will be held as long as the deceleration of the vehicle matches the desired value.

The response of the throttle and brake positioners will have to be fast enough to insure safety and yet not create an uncomfortable ride or result in an unstable system. This system should be able to improve on the relatively slow reaction time of the driver.

3. Costs

The costs of the electronic control system should be about $60. This does not include the throttle and brake positioners, the accelerometer or the receiver and decoder.

Chapter V

Exiting

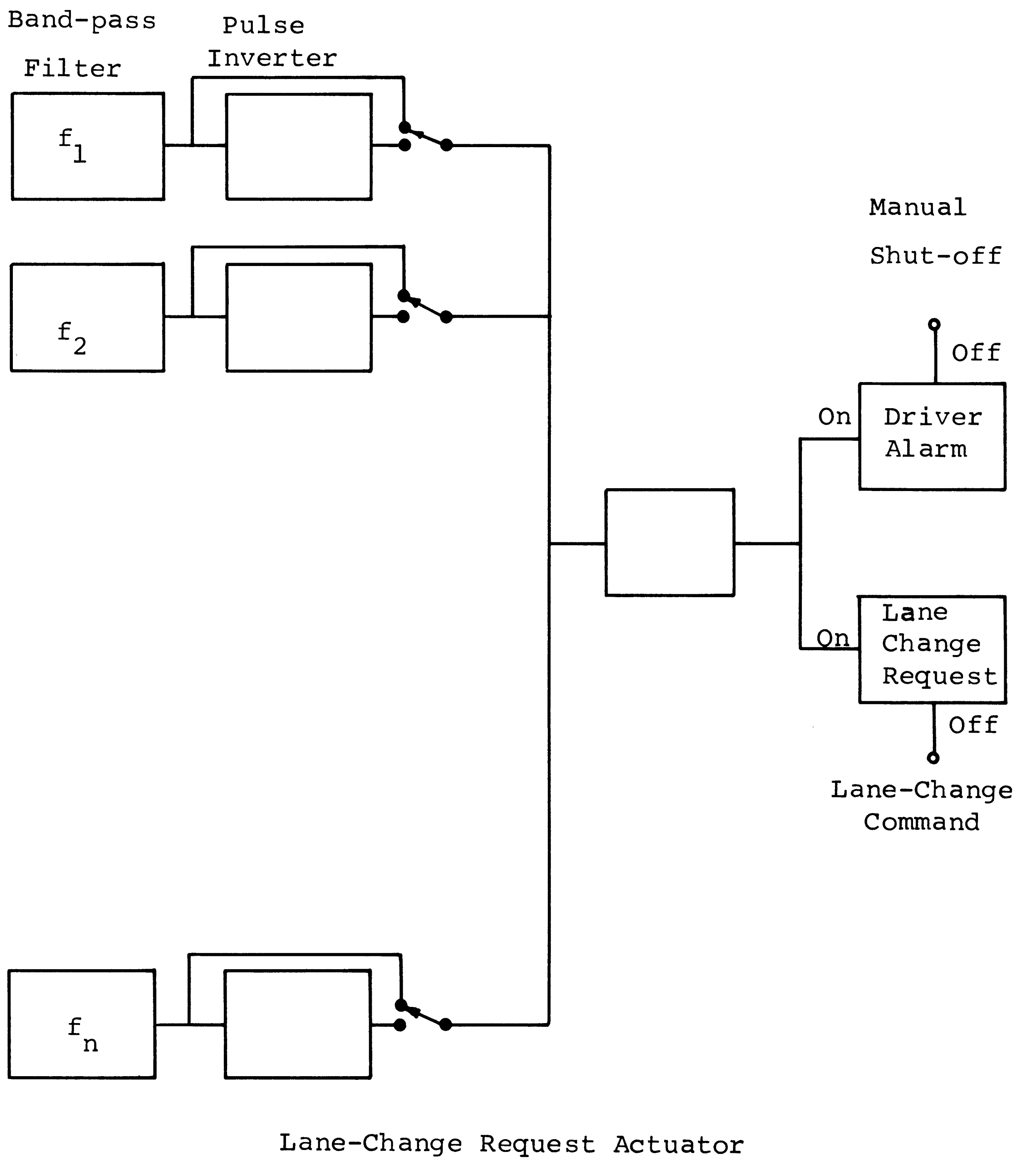
In order that his vehicle be taken off the expressway at the desired exit, the driver will set a number corresponding to that exit by pushing a series of numbered buttons on an exit control panel located below the dashboard. This control panel need not be complex - a series of toggle switches would be sufficient. This system of exit "requesting" presupposes the driver's knowledge of the exits and exit numbers that he will be concerned with. With the extensive number of exit signs found well ahead of a particular exit on today's expressway, it seems that it would be a relatively simple task to number the exits as they appear on these signs. In this way the driver would have ample time to set the desired exit number on the control panel before he was within, say, one-half mile of the exit ramp. It would also be a relatively simple matter to include a "next exit" switch on the control panel in the case that the driver missed reading the desired exit number or in case he wanted to leave the expressway earlier than first intended.

It was first decided that there would be no differentiation between a lane change and an exit from the expressway. An exit would be considered as a lane change to the right from the right lane, or to the left from the left lane. This would simplify the equipment needed, and would also simplify the programming of the control.

The entire sequence of changing lanes can be divided into two segments, the request from the car to the control to change lanes, and the command from the control to the car to begin moving to the next lane.

The request would be a signal, triggered either manually or a system such as will be described later. This signal will continue until the car receives the command to change lanes, at which time it will automatically cease. In order to move more than one lane at a time, it will be necessary to begin the sequence again. When the car is in the right lane and intends to exit on the right (or is in left lane for a left exit) a request for a lane change to the right is sent and at the proper time, the car will move to the right to pick up the guiding cable in the exit ramp. The car will be brought to a stop at the head of the ramp at which time the driver will have to take control of the car and proceed. In the event of an exit without a stop at the end, such as a merging lane, the driver could be allowed to take control of the car while it is moving with proper precautions taken to avoid the risk of an uncontrolled car moving on the highway.

For automatic operation of the request, a receiver in the car would receive a coded signal from the road each time it neared an exit. If this corresponded to the code which was programmed into the receiver, the lane changing request would be sent from the car. This code is programmed by the switch setting operation of the driver and functions as follows: The inverters are inserted after the filters of the frequencies corresponding to the 1's in the code for the desired exit. (See Figure 26). In this way, when the unit receives the signal which indicates the desired exit, all the in-



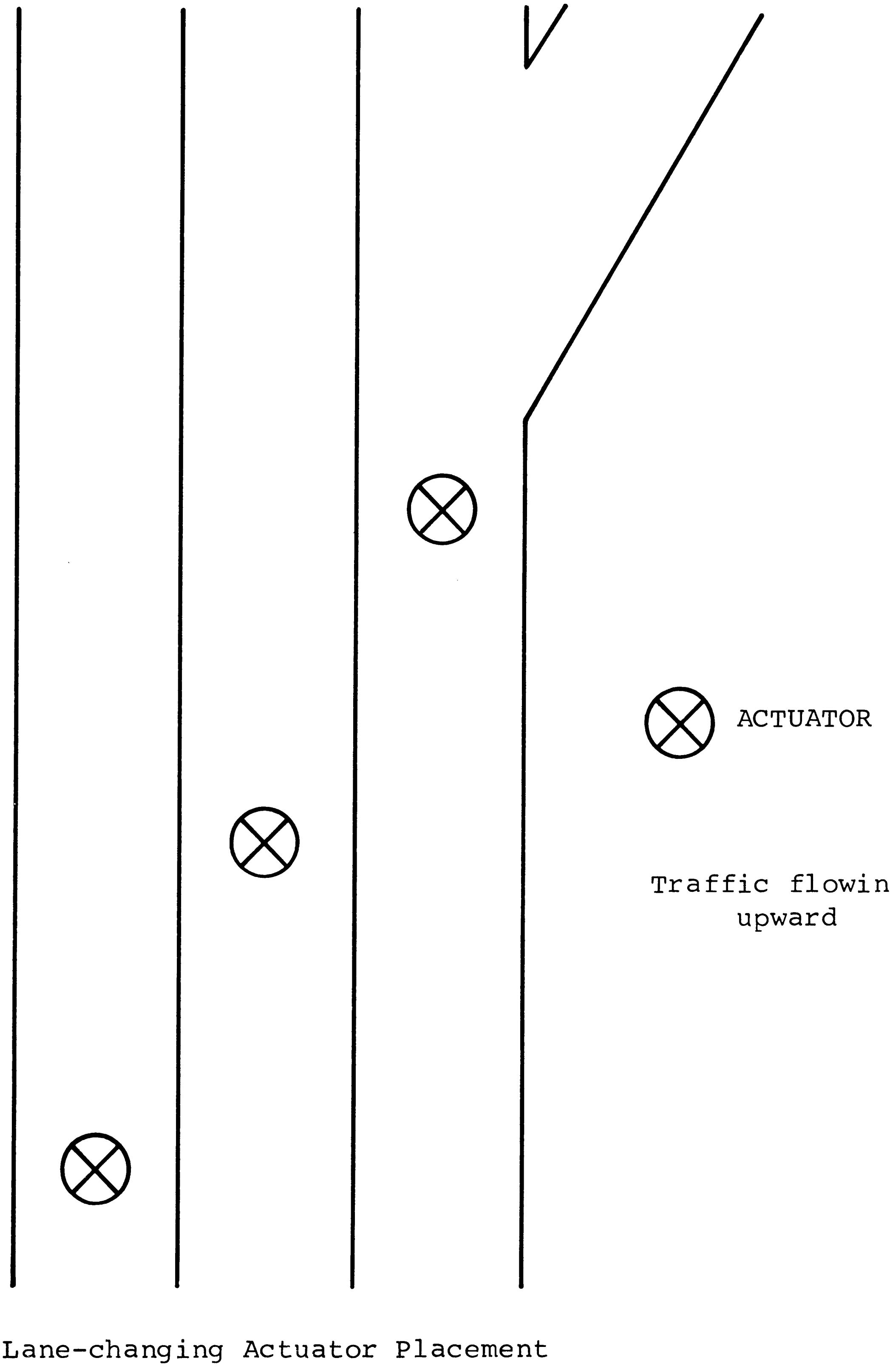
Lane-Change Request Actuator

Figure 26

puts to the NOR circuit will be zero; and at all other times, there will be at least one input to the NOR circuit of value other than zero, so that there will be no output. When the desired exit is approached, the input to the unit will be such that the output of the NOR circuit will trigger the lane change request. This will continue until the car actually is commanded to change lanes, at which time, the request will cease. This sequence of changing lanes will continue until the car is off the expressway and onto the ramp and this will have to begin about one-half mile before the exit to insure that the car will be able to be in the right lane in time to exit as indicated in Figure 27.

Incorporated in the unit would have to be an alarm to warn the driver that he would soon exit and he would be again in control of his car. The command would be another signal received by the car which would through the normal control channel override the normal steering control, causing the car to drift in the desired direction, for a short time, then returning the car to the normal steering control. The car would now be controlled by the cable in the new lane. This would best be accomplished by continuous control from the highway computer, but it would also be possible to perform this move by introducing a fixed error signal for a fixed time, then letting the steering control bring the car to the exact position desired.

The cost of this system to the driver, including installation, is estimated at $50.



Traffic flowing upward

Lane-changing Actuator Placement

Figure 27

Chapter VI

Economic Analysis

For a six lane highway:

2 computers		$300,000/mile
Communication and control links		$400,000/mile
	Total	$700,000/mile

Vehicle Equipment

Accelerometer	$ 30
Braking Servo	55
Accelerator Servo	20
Electronic Control System	60
Steering System	150
Receiver, filters, lane-changing equipment and housing	100
	$ 415

Chapter VII

Safety, Override, Reliability and Phasing-In

A. Safety, Override, and Reliability

One of the most important considerations in the development of this system is that of safety and reliability. Obviously, without the existence of a working model of the system, extensive reliability studies are impossible to perform. All that can be done at this stage of the system's development is the presentation of a few general suggestions.

Any failure of the central computer would be catastrophic. Since most of the cost of the system lies in the communication and control link, it would be relatively inexpensive to provide one or more back-up logic circuits for each one found in the computer. Mention has already been made to self-testing phase of computer operation. Testing signals could be sent through the logic circuits at specified intervals time or at certain points in the computer program. If a circuit were found to be faulty, it would be immediately replaced by a back-up circuit. Notification of this replacement would then be relayed to central control.

On the highway, any failure of one of the detection units of antennae, or any failure in the communication or control link corresponding to those units, would have almost no effect on vehicle control. Even a vehicle moving at as low a velocity as 10 miles per hour requires only 1/3 second to cross the 5 foot control zone of each individual unit. It does not seem likely that vehicle control will be lost in such a short period of time. If deemed necessary, the vehicle spacing under the condition of stopped traffic could be set at, say, 10 feet so that if the unit over which a vehicle was standing was non-operational, that vehicle would drift at idle speed until it came under the control of the next unit and was stopped. In any case, periodic checks on the condition of these units could easily be made and corrective maintenance would be provided where indicated.

Reliability studies of on-vehicle equipment would have to be postponed until actual models are built. High quality circuit components or redundant systems, could be included in critical electrical circuits.

Vehicle emergencies such as flat tires, running out of gas, and internal mechanical failures could be detected by the computer through the vehicles subsequent erratic behavior, i.e., the failure of that vehicle to respond to command signals within a preset time span. Immediately after the detection of erratic behavior, the computer could begin moving the vehicle to the outside of inside lane, and if possible, actually move it off the highway.

Non-metallic objects such as cinder block or wood beams are often found scattered on the highway. These objects would be undetected and, in some cases, collision with them may be inevitable. The exclusion of trucks, the major cause of this littering from controlled lanes, however, would reduce the number of these occurrences considerably. Also, unless the object were very large, the loss of velocity due to impact would not be great enough so as to involve a trailing vehicle. In the case that a vehicle is brought to a complete halt by collision with one of these obstacles, the lane behind the vehicle could be cleared into adjacent lanes and emergency action for the handling of the disabled vehicle would be initated by central control.

Direct manual override of the controlled vehicle does not seem to be indicated in any case. No provision, therefore, is made for this and, since manual override would just interfere with the control of the vehicle eventual provision for the removal of any possibility of manual override is recommended. This may require severence of the braking, throttle, and steering linkages, or the like.

B. Phasing-In Procedure

The system in its final form would be phased in over a period of time. It is hoped that, by doing this, the transition involved in the equipping of the vehicles intending to be driven on the automatically controlled system will be facilitated. By phasing in one section and/or lane at a time, the public can more easily adjust to the demands of the controlled system.

It is recommended that the system be phased in one lane at a time beginning with the left, or inner lane. At this time a person desiring to drive as a controlled vehicle in the inside lane will enter the expressway in the usual manner, cross over to the controlled lane, and turn on his on-vehicle equipment. The computer will then take command of the vehicle until the exit, whose number is coded on the lane-changing request circuit is neared, at which time the driver will resume control of the vehicle and pull out of the controlled lane. There is the possibility,however, especially in heavy traffic, that the velocity difference between those vehicles in the controlled lane and those in the adjacent lanes becomes too great for the controlled vehicle to leave the controlled lane. In view of this possibility, there have been several suggestions:

1. That the speed setting of the controlled lane be kept nearly the same as that of the adjacent lane. This seems to defeat the purpose of the controlled lane. Even in this case, however, the vehicle spacing could be less in the controlled lane, thus at least partially improving that lane's efficiency.
2. That zones in the adjacent lane be marked off as forbidden to uncontrolled vehicles when approaching an exit. This has the obvious disadvantage of "bottle necking" traffic, even though it does provide for transition back to the uncontrolled lanes.
3. That in this early part of the phasing-in process, the controlled lane not be operated during periods of

> traffic, but only be employed where there exists sufficient opportunity for a controlled vehicle to safely pull out of the controlled lane. It would be at the discretion of central control as to when the controlled lane would be operating.

It is this third suggestion that is recommended. It seems to be the only way in which the phasing-in process could be accomplished without actual interference with the existing system.

After the above is accomplished and after equipment is installed in all lanes and ramps, the computer could begin taking command of controlled vehicles at the top of an entrance ramp and move it to the inner lane while treating uncontrolled vehicles as obstacles. As more vehicles have the necessary equipment installed, the center lane could be operated as a controlled lane. Eventually all lanes would be used as control lanes.

During the phasing-in process uncontrolled vehicles would have to be excluded from those lanes operating as controlled lanes. One uncontrolled vehicle moving at a slow speed in a control lane could destroy the efficiency of that lane. Provision could be made for an uncontrolled vehicle to pass through a controlled lane (for example, when exiting left) but this would require a complex system of lights and is not recommended unless it is an absolute necessity.

Eventually the system would exclude all but controlled vehicles. Here problems of consumer acceptability reach maximum intensity, and extensive studies made before hand would do much in the way of providing answers to this problem. If the highway system is to function at maximum efficiency, however, this restriction must be imposed. Also, as mentioned earlier, the system as seen now does not appear to be flexible enough to allow for large trucks and standard transmission automobiles. This, again, is only a problem of maximum system tolerance and does not seem to be insurmountable.