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AUTOMATIC LONGITUDINAL CONTROL OF RAMP VEHICLES — THEORY AND EXPERIMENT

DISSERTATION

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

By

Teymour Eliassi-Rad, B.S., M.S.

The Ohio State University
1971

Approved by

Robert E. Fenton
Adviser
Department of Electrical Engineering
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who cheerfully endured the many problems of transient existence during the completion of this research.
VITA

August 24, 1939 ................... Born - Mazendran, Iran

1963 ................................ B.S., Tehran Institute of Technology, Iran

1963 - 1964 ....................... Instructor, Tehran Technical School, Narmak, Iran

1967 ................................ M.S., Michigan State University, East Lansing, Michigan, U.S.A.

1967   . ...  Teaching Assistant, Department of Electrical Engineering, Michigan State University, East Lansing, Michigan

1967 ................................ Design Engineer, Michigan Department of Highways, Lansing, Michigan

1967 - 1971 ...................... Research Associate, Department of Electrical Engineering, The Ohio State University, Columbus, Ohio

PUBLICATION


FIELDS OF STUDY

Major Field: Electrical Engineering

Studies in Network Synthesis: Professor W. C. Davis

Studies in Electromagnetic Fields: Professor J. H. Richmond

Studies in Physics: Professor W. H. Shaffer

Studies in Mathematics: Professor H. D. Colson
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A. Introduction

Since the turn of the century, there has been a tremendous increase in the number, speed, and length of trips of road vehicles in this country. This increase has reached a point where the Nation's roadway network has become increasingly inadequate to cope with users' demands, and extremely congested roads, together with an alarmingly high rate of traffic accidents and fatalities have resulted. Thus, over the decade of the sixties, there was a 44% increase in the number of registered vehicles and a 49% increase in the motor-vehicle travel, compared to the year 1960. During the same period, however, the total road mileage increased by only 4.6% and the Nation's population increased some 12.5%. Further, the National Safety Council has reported that from 1960 to 1969, there were increases of 48% in highway fatalities and 88% in the economic costs of highway accidents per the figures listed in Table I.

There is a growing realization among transportation experts that, if these present trends continue, the demand will soon exceed the capacity of the roadway network system. Unfortunately, it is predicted that the current traffic condition will probably be worse in the future as it has been estimated that from 1960 to 1980, the urban population of the United States is expected to increase some 50%, while the land de-
TABLE 1
COMPARISON OF VEHICLE FACTORS FOR 1960 AND 1969

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<th>Year</th>
<th>Motor Vehicle Registration</th>
<th>Motor Vehicle Travel (Million Vehicle-Mile)</th>
<th>Total Rural and Municipal Mileage in the U.S.</th>
<th>Motor Vehicle Accidents</th>
<th>Total Cost in Million</th>
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<td>1960</td>
<td>74,475,000</td>
<td>718,845</td>
<td>3,545,693</td>
<td>38,137</td>
<td>$6,500.</td>
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<tr>
<td>1969</td>
<td>107,391,000</td>
<td>1,070,575</td>
<td>3,710,299</td>
<td>56,400</td>
<td>$12,200.</td>
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voted to urban uses will double; there will probably be an 80% increase in urban car ownership, and urban motor vehicle travel will more than double. It is not difficult to foresee that, unless some radical improvements and changes are initiated, there will soon be a chaotic situation in our urban streets which will greatly curtail the Nation's mobility and progress. Correspondingly, one would expect this same situation to subsequently prevail on inter-city highways.

These universally recognized potential transportation problems have led many researchers to propose new transportation system concepts, for it is obvious that the future demands cannot be met by simply building more roadways or by adding lanes to the existing ones. In most urban areas, expansion of street width is quite impractical, and when such extension is possible, the cost of land and road construction is generally prohibitive.

High-speed trains for inter-city transportation, high speed ground transportation (HSGT), Dial-A-Bus for suburban-to-downtown and
around-town travel,\textsuperscript{7} and The Network Cab\textsuperscript{8} for intra-city travel are among many of the partial solutions suggested for ameliorating our future transportation problems. It is quite probable that either these or their combination with other modes of transportation will provide a partial solution; however, any successful transportation system in this country will have to include a role for the individual, privately owned vehicle. This follows both from the role such vehicles have played in the Nation's development, the average citizen's unwillingness to give up his personal vehicle and almost certain congressional inability to legislate substantial restrictions on either the ownership or use of same. Further, consider that the balance between public and private transportation mainly reflects the balance between centralization and dispersion of urban activities. The success of a mass transit is generally contingent on centralization of travel, while private automobiles best serve trips that are dispersed in space and time. Thus the preference of many people for low-density suburban living has resulted in a sizable increase in the mileage traveled by private automobiles. For example, in 1969 such travel accounted for 86 per cent of all inter-city passenger miles. All this indicates that a majority of people enjoy the mobility, privacy, and freedom offered by private automobiles, and they will not be satisfied with only inter-city or intra-city public transportation. Dial-A-Bus, The Network Cab, and other similar captive modes of transportation have the advantage of being able to serve the people who do not either own or drive or have access to a private automobile, but they do not offer the mobility and flexibility of an individually-owned transportation unit.

In light of these considerations, one satisfactory partial
solution would be the automation of individual vehicles. Initial studies indicate that an automatic transportation system, in addition to retention of individual automobiles, would considerably increase roadway capacity and would reduce both congestion and the number of traffic accidents. Modern electronic technology can offer safe solutions to the problems raised by the inability of the average human operator to always cope with sensing, decision-making, and reaction problems. Reliable microcircuits and minicomputers, in an automatic transportation system, would relieve a driver of his duties, thereby removing the cause of the great majority of traffic accidents. Since a computer would not drink, doze, or be affected by emotional problems, its effective use as a vehicle controller should increase safety, reduce travel time, and lastly, make an automated ground transportation system a promising prospect as a viable future transportation modality.

Several automated ground transportation concepts have been proposed by a number of researchers. Some of these concepts apply to urban area transportation, and some others to inter-city limited-access highways. However, it appears that many of the latter concepts could also be applied to automation of urban traffic. The general concern of this study is with one facet of such a system -- the complete automation of inter-city highway operations. This is hereafter referred to as the automatic highway.

B. The Automatic Highway

1. System Operation

One general concept of automated highway operation would be as
follows: A driver, wishing to use the system, would manually drive his vehicle into an inspection station on an entrance ramp where his vehicle would go through a quick static and/or dynamic checkout (see Fig. 1). If it passed the checkout, the vehicle would advance to the control station, where the driver would select his destination by activating the appropriate control (possibly by pushing a selector switch mounted on the dashboard). At this time, an automatic control system would take control and as soon as an acceptable gap were detected in the mainstream traffic, the ramp vehicle would be automatically merged. However, if the vehicle failed the checkout, or if the merge were not successful, it would not be allowed to enter the main highway. The rejected vehicle would be directed to a service plaza for repair or it would return to the control station for a new merge attempt. Once in the main highway, the vehicle would be longitudinally and directionally controlled, and if no unforeseen circumstances occurred, then in due course, it would arrive at the preselected exit location, where control would be returned to the driver. If a vehicle were to become disabled, the driver would regain the control of his vehicle and manually guide it to the nearest exit point. If the vehicle were not controllable, the use of that lane would be lost until the disabled vehicle could be moved off the highway.

The system concept proposed by the Highway Research Group at The Ohio State University is based on such a concept and it is envisioned that only limited-access highways would be automated. Further, the system would employ a dual-mode vehicle which would be manually controlled on conventional streets and would become fully automated, possibly without driver intervention (except in emergencies) on automated highways. It is
Fig. 1—The schematic representation of entering and exiting an automatic highway system.
also proposed that the system would be gradually introduced and be compatible with existing traffic facilities at all stages. The evolutionary nature of the system can be justified by the fact that, millions of vehicles and millions of miles of highways cannot be immediately automated; for the resulting technological, psychological, and economic problems would be enormous. Therefore, one could expect to see an orderly step-by-step progression from existing highways to the automated ones of the future. In order to maintain a compatibility through the entire period of evolution, it would be necessary to improve the performance of the driver in the interim and possibly use separate lanes for automated vehicles.

Driver aiding might comprise one early step toward a fully automated system. Improper driving and faulty decision-making by a human operator are the causes of a majority of traffic accidents, for in many cases, a driver does not always have the information necessary to properly control his vehicle. In order to improve his information gathering and decision-making capability, several driver-aid systems have been studied. One such aid is the Driver Aid, Information and Routing (DAIR) system which aids the driver via audio signing, code and voice emergency communication, and route guidance. A conceptually similar system, is the Experimental Route Guidance System (ERGS) which would guide the driver through a highway network in minimal time. This system is a dynamic adaptive route control which would adjust its choice of route in accordance with existing traffic conditions in the network.

Several experiments have been conducted on the use of a driver aid in steady-state car following. For example, Bierley investigated
the use of a galvanometer display mounted on the hood of a following car, which provided a driver with continuous visual headway and relative-velocity information. Gantzer and Rockwell\textsuperscript{23} mounted a matrix of four lights on the dashboard of the following car to provide the driver with headway and relative-velocity information. This display was designed so that, if headway was smaller than a minimum prescribed value or the relative velocity was negative, two red lights would come on, and if the headway were too large or the relative velocity was positive, both green lights would come on. Fenton's kinesthetic-tactile display has also been extensively studied in car-following situations by researchers at The Ohio State University.\textsuperscript{24-26} This servo-controlled driver-aid device provides an operator with instantaneous headway and relative-velocity information with respect to the nearest lead vehicle, and has resulted in improved car-following performance.

A second stage of a gradual advancement toward a fully automated system might involve the introduction of various control subsystems for partial automatic control of a highway network. Several of these control subsystems are discussed below.

2. Control Subsystems

A major objective of highway automation is associated with the development of a physically realizable and practical system for the simultaneous control of thousands of individual transportation units so as to obtain a significantly higher vehicle flow per lane than can be safely achieved with nonautomated vehicles. To accomplish this, any conceivable type of control must at least include the following essential subsystems:
a) Automatic Longitudinal Control
b) Automatic Lateral (Steering) Control
c) Automatic Interchange Control.

In addition to these, one must also develop effective means of network control (which includes effective routing and scheduling procedures), obstacle detection, and the handling of various emergency situations.

Two distinct types of controllers are presently under investigation for all automated highway concepts -- asynchronous control and synchronous control. The former is based upon the state of a controlled (following) vehicle -- i.e., a car-following controller.27-29 The second general type of control, synchronous control, is analogous to a "conveyor belt" in that the vehicles are all moved at the same constant speed and maintain fixed positions with respect to each other -- at least in steady-state flow.30,31

One approach to a car-following longitudinal controller was suggested by Cosgriff, et al.32 who proposed a multimode controller that would control a following car with respect to the nearest lead car. Different modes (lead-car overtaking, steady-state car following, and emergency braking) of operation of a modified form of this controller were studied by Bender, et al.33 and Bender and Fenton29,34,35 under both theoretical and full-scale conditions. Their findings have indicated that a car-following multimode longitudinal controller is practical, but there exists a danger of instability within a platoon of vehicles, i.e., the disturbance in the trajectory of the lead car might be magnified and propagated to the following car. Other types of car-following control
laws have been theoretically analysed by other investigators as a continuous or discrete optimal control problem. Their proposed performance criterion for headway and speed regulation is minimization of the sum of appropriately weighted squared errors in positions, velocities, and accelerations of a string of vehicles. A major difficulty with their approach is the inaccessibility of their derived control force, which is only indirectly controllable and their insistence on a quadratic cost function as being appropriate to the problem.

The second general type of longitudinal control, synchronous longitudinal control, has been studied by a number of researchers. Weiss has investigated such control for a capsule/transportation system in which the vehicles would follow a null point along the guideway. Others have proposed systems in which the vehicles occupy hypothetical "cells" and follow identical, deterministic position-time histories between two points in highway network. 

Two types of electromagnetic guidance schemes have been extensively studied for vehicle lateral control — active control systems and passive control systems. The first of these involves the use of an active reference system on the road — such as a current-carrying cable buried in the center of the controlled lane. The alternating current in the cable produces a magnetic field, which induces a voltage in tuned pick-up coils mounted on either side of a vehicle centerline. The difference between the voltages in the two coils specifies the location of the vehicle relative to the lane centerline and actuates a steering control unit. A conceptually similar system has been extensively
tested at The Ohio State University. Here, two wires separated by eight feet were employed and a signal coil was used for sensing the lateral guidance signal. The major advantage of this system is that the variation of the horizontal field component is approximately linear over most of the eight-foot range when no magnetic material is in the vicinity of the field. In contrast, under the same condition, a single-wire system yields a horizontal field component which is no wider than the spacing of the two sensing coils on the front of the vehicle. However, the presence of magnetic materials, such as steel-reinforcing rods in the pavement, distorts the reference field causing steering errors with the distortion being worse in the two-wire case as compared to the one-wire system.

Several approaches to automatic lateral control using a passive reference system has also been suggested. One such system employs a painted stripe in the center of the lane. The control system tracks the stripe via photocells mounted under the car. In spite of the simplicity and relative ease of implementing such systems, variations in ambient lighting and inclement weather would probably make them impractical for all-year, all-weather operation.

Consider next the automatic control of freeway interchanges. Thus far, virtually no effort has been expended on such control; however, several methods of driver aiding such as semi-automated merging control have been designed and tested. Since automatic ramp vehicle control is the subject of this study, the freeway interchange control system will be reviewed in greater detail in the following section.
C. Automatic Interchange Control

1. Introduction

Many vehicle interactions occur and a driver must frequently make important decisions upon entering a highway interchange. His selection of a particular merging or diverging strategy can greatly affect the traffic flow in the merge area, and often elsewhere. Since most of the malfunctions at highway switching points are a result of driver misjudgments, automatic interchange control would be imperative for successful automatic highway operation.

The control of entering into and exiting from mainstream traffic appears to be similar in nature, with the notable difference being that the former would require much tighter control. For, in a merging operation, one frequently must have a merging vehicle intercepting a gap at some carefully specified spatial and temporal "location" in a high-speed, high-volume traffic stream. In a diverging maneuver -- such as exiting from a mainstream of traffic -- much greater time, space, and velocity deviations would be generally tolerable.

The merging of on-ramp vehicles can greatly affect the efficiency and safety of traffic movement on the freeway. As the highway-traffic volume increases, the number of merging gaps in the mainline traffic decreases and the driver must enter the mainstream traffic under difficult conditions. In many cases, the driver does not have the necessary information about the size of the gap or the time of its arrival at the merge point. If such information were available to a driver, it is still doubtful that he could control his vehicle as effectively as an automatic control system because of his relatively slow reaction time.
To date, a fully automated on-ramp vehicle merging control has not been developed and tested. However, several ramp vehicle driver-aiding systems have been tested, and a considerable amount of theoretical work has been done in this area as is discussed next.

2. Operational Techniques of Ramp Control

2.1 Ramp Metering

The first large-scale efforts to control the entrance ramps to freeways involved various forms of ramp metering which is a method of limiting the input to a freeway so that the demand for a section of same will not exceed its capacity. Prototype manual and automatic ramp metering control devices have been installed in Detroit, Chicago, and Houston and similar projects have been initiated in Los Angeles, Seattle, Dallas, and elsewhere.

There are two different methods of ramp metering -- ramp closure and dynamic ramp metering. The ramp-closure approach involves the closing of some entrance ramps during peak traffic hours, and it can be regarded as a special case of dynamic ramp metering with a zero-metering rate at some ramps. It, of course, results in a reduction of freeway input and some redistribution of local traffic. This method of ramp control has been used with some success at John C. Lodge freeway in Detroit.

This type of ramp control has a serious disadvantage -- the inconvenience to drivers who normally use a ramp which is closed. For this reason, the sign "ramp closed," and even physical barriers, have been violated frequently. Thus, it would appear desirable to provide these drivers with convenient alternate routes.
Dynamic ramp metering is the most advanced and the most used form of ramp metering. There are two methods of such metering -- the demand-capacity approach and the gap-acceptance approach. The first of these will be discussed here, and the latter will be deferred to the following section.

The metering rate on a demand-capacity metering system is determined by either a fixed metering approach or a variable metering one. The former is employed when the ramp and freeway demand is relatively predictable from time-to-time. The necessary information is obtained in an origin-and-destination survey, and the traffic signals on the ramp are set so that a fixed number of ramp vehicles would be allowed to enter the mainstream traffic per unit time. This type of control is based on historical data, and it is not responsive to instantaneous traffic flow conditions on the freeways; that is, it does not make any provision for anomalous events such as a traffic accident, the loss of freeway lane, adverse weather, etc.

A demand-capacity ramp control with a variable metering rate involves the use of the instantaneous upstream volume of a freeway to adjust the downstream capacity; thus, the traffic signals on the ramp would be set according to the difference between the upstream demand and downstream capacity.

A demand-capacity metering system with a fixed metering rate has been experimentally evaluated by researchers at the Texas Transportation Institute on the Gulf freeway in Houston. They have reported that considerable reduction in both traffic congestion and total travel time at peak periods were obtained. However, this scheme is quite insensitive
to changes in demand once a fixed metering rate has been set.

The variable metering rate approach used on Chicago's Congress and Eisenhower expressways is based on lane occupancy -- namely upon one-minute samples of the occupancy of the middle (of three) traffic lanes. Ramp control was initiated as soon as the middle-lane occupancy equalled 15% and the ramp was closed when lane occupancy reached 25% (apparently no justification was given for either this scheme of setting metering rate, selection of middle lane as reference, or the figures 15% and 25%). This approach to ramp metering has resulted in a considerable improvement in traffic flow and a substantial reduction in total travel time, a reduction of accidents in the controlled area by 14.4%; however, the number of traffic bottlenecks remained unchanged.

A common deficiency of the discussed schemes is the lack of assistance given to the drivers in performing the merging maneuver. The recognition of this deficiency has led to the development of driver-aiding merge control, which in addition to relieving freeway congestion, would aid the driver in entering his vehicle into the mainstream traffic. Hopefully, this should minimize the chance of an accident in the merge area and hence reduce the possibility of loss of a freeway lane, which would, of course, temporarily reduce the capacity of the highway.

2.2 Driver-Aided Merge Control

The first experimental driver-aided merge control was evaluated by Texas Transportation Institute on the Telephone Road inbound entrance ramp of the Gulf freeway in Houston. Their merging control system, called gap-acceptance ramp control, is essentially a dynamic ramp meter-
ing technique, which apart from controlling the input to a highway, also aids the driver in performing the merging maneuver. Under this merging control system an ultrasonic detector mounted in a side-fire position about 950 feet upstream of the merge area would detect gaps on the right-hand freeway lane and transfer this information to a roadside computer. The control computer would compare the size of a detected gap with a critical gap* and if an acceptable gap (a gap larger than critical gap) were available, its time of arrival at the merge point would be predicted. The control system calculates an acceleration trajectory for the ramp vehicle based on its acceleration capability, length of the ramp, and the time of arrival of the detected gap at the merge point. The ramp vehicle would be released to follow this trajectory when the acceptable gap reached a point (the decision point) at which the travel time of the gap to the merge zone is the same as the time of arrival of the ramp vehicle from the control station to the merge zone.

Full-scale test results of this control on Gulf freeway in Houston, has verified the superiority of this system over the demand-capacity metering system, and it has been concluded that this type of ramp control is the only available ramp metering system that microscopically aids a ramp driver in the merging maneuver. However, as a control system it has a serious drawback, the ramp vehicle is released on the premise that it would intercept the oncoming gap at the correct time, but once the vehicle is released there is no further control over

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*A critical gap is being defined as one which is accepted and rejected by equal number of drivers.
the states of either the gap or the ramp vehicle. For example, if due to adverse environmental conditions the ramp vehicle were incapable of traveling on a predetermined trajectory or if a gap closure were to occur prior to the arrival of the gap at the merge point, the driver would have no knowledge of such changes, and thus a smooth merge might be difficult.

The present most advanced form of driver-aided merging has been studied by Raytheon Company. Their system is conceptually similar to that discussed above; however, an attempt is also made to achieve dynamic control over the ramp vehicle. In contrast to all other ramp metering controls, this system is somewhat responsive to the changes in the state of the ramp vehicle and the progress of the gap during the merging maneuver. Detectors on the ramp and on the right-most lane of a freeway -- some 1700 feet upstream from the merge area -- would communicate the state of the ramp vehicle and the progress of the detected gap to a roadside control computer. This information is then analyzed and presented to the driver of a merging vehicle. Two approaches were examined for presenting this information. In the first of these, the driver must track a sequential series of display lights (a "pacer" display) along the ramp. The lights would turn on in sequence as the gap progresses, and the driver would simply follow the moving lights to the merge area. This system is only responsive to the progress of a gap, but not to its size, and thus the biggest disadvantage of this scheme is the tacit assumption that the size of a detected gap would remain virtually constant from the detection point to the merge point, even though the lead care and the following car might be traveling at different velocities; as a result,
the pacer display does not make any provision for unforeseen circumstances such as a gap closure. A second type of display is a band of light, called a "green band" display which is proportional to the speed of the gap and moves forward with a speed proportional to the speed of the gap. In this scheme, the driver would continuously position his vehicle in line with the lighted portion of a long series of translucent panels until he merges onto the freeway.

The closed-loop nature of this ramp vehicle merging control system makes it adaptive to changes in the states of the gap, environment, and the ramp vehicle; however, it suffers from some deficiencies. The system uses a ramp driver with his relatively slow perception and reaction times as its transfer element, and it totally leaves the task of merging maneuver to the driver who must manually adjust his acceleration so as to keep pace with the moving lights. Further, since no mathematical model of the vehicle's dynamics is presented, an accurate measure of system performance regarding travel time, safety, and passenger comfort cannot be established.

Despite the deficiencies of the approaches discussed, all of these methods to ramp vehicle control are important steps in a gradual process toward a fully-automated ramp vehicle merging control system.

2.3 Automatic Merge Control

There are two primary aspects to the automatic control of merging -- the macroscopic or system level of control which deals with merging strategies and overall system performance, and the microscopic level which deals with control of individual vehicles during a
merging maneuver. Some efforts have been expended on the former, notably Godfrey, who considered six different merging strategies for a synchronous merge of two traffic streams. Breeding defined a number of merging strategies and evaluated each by comparing the average queue length on the minor stream and vehicle densities and service periods on the major stream. Athans treated the problem of merging two streams of traffic as an optimal control problem. His study is essentially an extension of Levine and Athans' optimal controller for position and velocity control of a stream of vehicles.

Aside from studies such as these, there exists a well-developed literature in closely related areas. The most relevant are those dealing with delays, queues, and gap distributions at intersections. The delay of a vehicle in merging and crossing maneuvers has been investigated by Little, and Weiss and Maradudin have used renewal theory to formulate the conditional probability distribution of waiting time that a vehicle must endure to cross or merge with a major-stream traffic when the entering vehicle is at a standstill. Oliver has investigated the distribution of gap sizes and the distribution of spacing between vehicles and gaps. Jewell and Evans, et al. have analyzed the problem of entering vehicles from a minor stream to a low or medium-density traffic stream. Merging into a high-density traffic has been discussed by Jewell, Oliver and Bisbee, and Haught, et al. Jewell examines the disturbance caused by forced merge, Oliver and Bisbee have studied the queues that build up in a minor-stream traffic waiting to cross or merge with a stream, and Haught, et al. were particularly concerned with various aspects of high-speed merges. Mine and Mimura introduced a proba-
bility density function for the delay of a merging vehicle by assuming an acceleration lane of infinite length, while Blumenfield and Weis\textsuperscript{71} studied this situation with a finite length acceleration lane.

There is presently almost no literature available on the microscopic aspects of automated merging. The single available study was done by Asghar and Fenton\textsuperscript{72} whose approach is conceptually similar to that suggested by Texas Transportation Institute.\textsuperscript{54} The former noted that environmental effects could have a large and undesired effect on a merging maneuver unless such effects were properly accounted for. As an example, in one set of tests they examined the behavior of a merging vehicle in two situations — no wind and 25 mph headwind — with all other experimental conditions the same. In the first situation (no wind), the vehicle reached its desired terminal velocity of 100 f/s in 21.75 sec., while it required 30 sec. to reach this speed in the second case (25 mph headwind). This performance variation was due to the open-loop nature of the vehicle control in these tests, and therefore, it was concluded that if a reliable automated merging system were desired, it must be a closed-loop system so that tight control over the state of the on-ramp vehicle would be available at all times during a merging maneuver. This effectively means that an automated merging control, in its ultimate form, will have to be flexible so as to make provision for a close control of acceleration-time history of the ramp vehicle.

It was also noted in this study that, based on some preferred modes for insertion of ramp vehicle into the mainstream traffic, a smooth and safe merge is more probably if the ramp vehicle entered the traffic stream with a zero or a positive acceleration.
D. Summary and Preview

The state of automated transporation technology has been briefly discussed in this chapter. Some of the inadequacies of the current roadway network system have been noted and it was established that in order to improve both the level of service and the safety of the Nation's ground transportation system, some solutions to existing and projected future problems must be found. The research directed toward one promising partial solution — highway automation — has been reviewed. One aspect of such automation which is the subject of this dissertation — automatic interchange control — has been discussed in some detail and the need for further study in this area has been emphasized.

The concern of the present work is the automatic longitudinal control of on-ramp vehicles merging into an automatically controlled freeway traffic stream. As previously noted, there have been studies of ramp-vehicle control through driver aiding and semi-automatic merges; however, the literature dealing with fully automated merging is very sparse and only several theoretical approaches have been discussed. Here, a combination of analytical methods, computer simulation, and full-scale testing are used to predict, examine, and verify the performance of an automatic merging control system under various environmental and vehicular conditions.

In Chapter 2 an ideal merge is defined, various system constraints are specified, and system measures of effectiveness for practical operation are defined. A mathematical model of the system is developed, and its response in the presence of external disturbance
forces is analyzed

The results of an extensive computer simulation, which incorporates a variety of environmental effects and disturbance inputs, on merging vehicle performance is presented in Chapter 3. The data obtained here were used to design the practical merging control system presented in Chapter 4. Here, the relevant experimental procedures are discussed and the results of full-scale road testing of the merging vehicle are analyzed and compared with the analytical and simulation results of Chapter 2 and 3, respectively.

This study concludes with Chapter 5 which contains a discussion of the conclusions derived from this study together with recommendations for further study.
CHAPTER II
AUTOMATIC MERGING CONTROL

A. Introduction

The need for tight control over the acceleration-time-history of a ramp vehicle has been discussed in Chapter I. In this chapter, an ideal merge is first defined in order to both gain insight into the merging process, and obtain a reference against which the performance of a physical system in a realistic environment can be compared. Various practical constraints associated with a merging situation are enumerated and the dynamic limitations of a controlled merging vehicle are defined.

A mathematical model of a merging vehicle which includes the effects of external forces such as wind gusts and road grades is developed, and a number of vehicle control algorithms are presented, analyzed and compared. One especially promising algorithm, which involves an updating of a reference signal \( n \) times during a merging maneuver, is discussed in detail. Furthermore, a feasible scheme for specifying \( n \) -- which physically corresponds to the number of "checkpoints" -- is discussed.

B. Ideal Merge

In order to define an ideal merge, consider the ramp geometries shown in Fig. 2. These consist of a single mainstream lane and a single-
In an automatic merging situation, a gap, suitable for merging would be detected at Detection point \( D_1 \), and subsequently a ramp vehicle would be released for merging into this gap. The latter would be under complete computer control during the merging maneuver per the block diagram shown in Fig. 3. Note that the input to this vehicle from a control computer is determined by the information the latter receives from the states of the freeway traffic, the ramp vehicle, the environment, and other vehicles on the ramp.

In an idealized situation, "perfect" information would be instantaneously available to the control computer at all times; that is, there would be no time lag involved in either collecting noise-free data or communicating it to the computer. Further the computer would have zero computational time and instantaneous communication would always exist between it and the ramp vehicle. Thus, the state of the ramp ve-
The vehicle would be continuously checked, and it would always be subject to any required change. The vehicle would respond with a zero time lag to a command input and would perfectly follow any trajectory specified by the computer; i.e., no deviations would be present due to such effects as wind gusts, road grades, etc. The velocity-versus-time and distance-versus-time relations would thus also be as specified and the merging vehicle would meet the detected gap with the desired spatial-time relationship.

The acceleration-time trajectory specified by the control computer must meet several requirements:

1. It must be physically realizable;
2. All acceleration and jerk values must be below the threshold of human discomfort;
3. It should be selected, subject to require-
ments (1) and (2) so that the required on-ramp length is not excessive; and

(4) No error should exist in either the longitudinal or the lateral state of the merging vehicle as it enters the mainstream.

It is clear that a large number of functions satisfying these requirements could be selected even in an ideal situation; i.e., in the context described here, there is no unique optimum trajectory.

C. General System Performance Needs

In practice, one would not expect an ideal merge for a variety of reasons. These would include measurement errors in the detection of a gap in the mainstream traffic, finite communication and computation times with respect to the controlling computer, finite lags and nonlinear dynamics associated with the vehicle, and imperfections in the detection of environmental effects and their subsequent effects. Therefore, it would be impractical to use a pre-programmed merging maneuver without provision for modification during system operation. Thus, an automatic merging system must be sufficiently flexible to compensate for a wide variety of undesired effects and still maintain certain standards of safety, passenger comfort and convenience, and reliability.

Two qualitative descriptors which have been used to discuss the performance of nonautomated merging systems are "quality of service" and "economy of service." Since these descriptors are also applicable to an automated merging system, they are discussed in detail. The first of these is generally described in terms of safety, comfort, convenience
and merging system capacity (throughput), while the second is obviously related to system costs.

Consider the matter of safety. It is certainly probable that no system could be made absolutely fail-safe; however, a good measure of safety could be assured by incorporating safety "checks" into the operation of the system. One vital such check would involve frequent monitoring of the mainstream traffic so that the merging maneuver could be aborted when necessary; i.e., when an unsafe situation developed in the mainstream traffic. Secondly, the state of all ramp vehicles must be monitored to prevent an unsafe situation from developing on the on-ramp.

Passenger comfort in a normal merging situation is primarily dependent on the magnitude of jerk and its frequency of occurrence, and thus any discontinuities in vehicle acceleration might cause passenger discomfort. This can obviously be overcome by a proper selection of an acceleration-versus-time trajectory for merging.

The matter of convenience is largely dependent on the capacity, efficiency, and reliability of the overall automatic highway system. One related factor is the waiting time required before entrance can be gained to the system. This is obviously a systems-level problem which is related to both overall network control and the level of system usage — factors which are not considered here. However, there are aspects of local control which relate to user convenience which must be considered. For example, a merging control system must be highly reliable in both accurately predicting gap arrival under normal conditions and in detecting abnormal situations so that the number of aborted merges can be held to some necessary minimum. One approach is illus-
Fig. 4—A scheme for rerouting the aborted on-ramp vehicle.
trated in Fig. 4 where an aborted vehicle could be either returned to the control station for another merge attempt (perhaps with some priority), or directed to a downstream ramp via a frontage road.

The throughput of a merging system is largely dependent on the number of acceptable mainstream gaps; for example, if gaps were not forced, then one might have to wait a long time for a "natural" gap to appear. Therefore, the resulting fewer acceptable gaps would mean a small throughput. The economy of service depends on the initial and operating cost of the system which would include the cost of system breakdowns and repair. The former cost depends largely on the merging schemes, the length of the ramp, the amount of hardware required, etc.

D. Vehicle Control Functions

1. General Considerations

Any acceleration-versus-time function selected for vehicle merging must meet the four criteria listed in Section B of this chapter. Consider the acceleration function $a(t)$ shown in Fig. 5.

![Graph showing $\alpha(t)$ over time](image)

Fig. 5--An acceleration-versus-time trajectory of a merging vehicle.
The corresponding vehicle velocity \( v(t) \) and its displacement \( x(t) \) from its starting point on the ramp are

\[
v(t) = \int_0^t a(t) \, dt \]

\[
x(t) = \int_0^t v(t) \, dt.
\]

At the time of arrival \( (T_m) \) of the gap at the merge point, one must have

\[
v(T_m) = V_m
\]

\[
x(T_m) = D
\]

where

\[
V_m = \text{the desired ramp-vehicle velocity at the merge point}
\]

\[
D = \text{the ramp length from the control station to the merge point.}
\]

Any selected acceleration function must be both easy and inexpensive to implement. This would increase not only the safety and reliability of the system, but it would also affect the amount of required hardware, and thereby system cost.

In light of these and previously discussed considerations, several feasible acceleration functions are next discussed.

2. Feasible Acceleration Functions for Ramp-Vehicle Control

Consider first a proposed control scheme which would be used in conjunction with any of several feasible acceleration functions. When a suitable gap were sensed by \( D_1 \) (see Fig. 6) and its speed measured by \( D_1 \) and \( D_2 \), a ramp vehicle would be released and required to follow a specified acceleration-versus-time trace (trajectory 1 in Fig. 7). This trajectory would be determined by knowing the speed of
Fig. 6—A ramp configuration with hypothetical checkpoints.

Fig. 7—Acceleration-versus-time profiles.
the gap, its arrival time at the merge point, and the length of the ramp.

Ideally, the vehicle would follow this trajectory and be properly inserted into the gap. However, if a vehicle were subject to some external disturbances or if noise were contaminating some measured quantity, then the vehicle would follow a different path (trajectory 2 in Fig. 7). The resulting deviation would be detected when the ramp vehicle arrives at a checkpoint (see Fig. 6) and a modified acceleration function would be selected (trajectory 3 in Fig. 7). (The desired number and location of the detectors and the checkpoints on both freeway and ramp are discussed later). This third trajectory would be selected so that, if it were followed, the merging vehicle would be properly inserted into the oncoming gap. This process would continue with the state of the merging vehicle being checked n times and corrected as necessary.

Now consider some possible acceleration-versus-time trajectories that might be satisfactory in an automatic merging situation. It seems clear, of course, that such functions must meet the qualitative standards previously discussed, and also other requirements pertaining to vehicle controllability.

Consider a function which has been widely used by researchers at the Texas Transportation Institute. It is the exponential acceleration-versus-time trajectory shown in Fig. 8. Qualitatively, this seems a good choice for it can be easily constructed, instrumented, and implemented. In addition, since it doesn't contain any inherent discontinuities, it shouldn't result in passenger discomfort. One of the biggest disadvantages of this control function is that unless \( t \) is large (see
The value of the acceleration decreases very sharply, and hence it takes the vehicle a long time to reach high speeds. For example, with a time constant ($\tau$) of 10 seconds and an initial acceleration of 10 ft/sec$^2$, the vehicle reaches a speed of 89.2 ft/sec in 22.5 seconds while it takes the same vehicle 7.65 more seconds to attain a speed of 95 ft/sec. This could be overcome by increasing $\tau$, but unfortunately this would also increase the final acceleration of the vehicle at the merge point which is quite undesirable in terms of passenger comfort and safety considerations.

A second, and especially simple choice of vehicle control function, is shown in Fig. 9. In theory, a vehicle would be accelerated at a constant rate $a_i$ until it were inserted into the traffic stream at time $T_m$; however, in practice, its state would be checked, say at time $t_i$, and its acceleration changed to $a_{i+1}$ to account for any errors in the vehicle's state.

Simplicity, ease of instrumentation, and reconstruction of constant acceleration at the checkpoints make this function a very good
candidate for a ramp-vehicle control function. However, a disadvantage is its inability to fully realize the acceleration capability of the ramp vehicle. As a result, it would require an excessive ramp length and merging vehicle travel time. For example, assuming that a vehicle can continuously provide a constant acceleration of $0.1g$ (3.22 ft/sec$^2$) within a velocity range of 0-100 ft/sec, a ramp vehicle would require approximately 31 seconds and a ramp length of 1553 ft in order to reach a merge velocity of 100 ft/sec.

The third vehicle control function considered, is the decaying-staircase acceleration-versus-time trajectory shown in Fig. 10. When a suitable gap were detected, a set of initial values for each step of the constant acceleration with their time durations would be calculated and the ramp vehicle would be commanded to follow this trajectory. If a vehicle were to deviate from its ideal path, at a control point, say $t_j$, another set of these constant accelerations would be calculated so that if the vehicle were to follow the new trajectory, it would be properly merged into the through traffic.
Fig. 10--Acceleration-versus-time trajectory.

The primary disadvantage of this profile is its complexity. The calculation of constant acceleration levels with their time durations would require an excessive amount of logic circuitry. This could partially be overcome by assuming an equal period \( \Delta t \) for the duration of each acceleration level and also reducing the number of acceleration step changes available at each control point. This would reduce the flexibility of this function since it cannot make use of full acceleration capability of the car. In addition, if one were to maintain a reasonable level of passenger comfort, then step changes \( \Delta a \) must be kept small; i.e., the number of acceleration levels must be increased. This in turn would increase the number of parameters and therefore, the computational complexity of the function.

The last vehicle control function to be discussed here, is the linear acceleration-versus-time trajectory shown in Fig. 11. This function is essentially a limiting case of the staircase acceleration profile as \( \Delta a \) approaches zero and the number of acceleration levels \( n \) becomes very large. The operation of this control function is much the
same as the previous one. In an actual merging situation, if a vehicle were to deviate from its desired trajectory, the resulting error would be detected at a checkpoint and a modified trajectory would be constructed.

In the study of the feasible acceleration profiles for ramp-vehicle merging, it was noted that there could literally be many other functions which could satisfy the basic system requirements and perhaps, even could offer some improvements. Some of these functions which were the most likely candidates included the sum of two or more exponentials, polynomials, and combinations of these with each other or with some other functions. However, the initial studies on the latter acceleration profiles have indicated that most of these functions possess some or all of the functional properties of those already discussed above. In some cases, however, some improvements could be obtained at the expense of increased operational complexities. For example, the sum of
two exponentials had an advantage over a single exponential function in that it could to a large extent prevent the rapid decrease in the vehicle acceleration function, but this could only be done at the expense of added parameters of the new acceleration function. Therefore, the selection of the acceleration profiles considered above, were largely for reasons of mathematical expediency, the relative simplicity and ease of implementation, and potential operational effectiveness. Thus, while these functions could quite adequately be used as merging-vehicle control functions, they are by no means claimed to be the only choices or the best possible ones.

3. Comparison of Vehicle Control Functions

Of the four acceleration functions considered, two have serious drawbacks. Because of the dynamic limitations of the vehicle at higher speeds, the value of the "constant" acceleration must be small, but this prevents the utilization of full acceleration capability of the vehicle at lower speeds. As a result, an excessive ramp length and a large $T_m$ would be required. The staircase acceleration function has a quite different disadvantage in that its relative complexity would almost certainly lead to decreased reliability and increased cost — at least with respect to the other suggested functions. Further, if large step changes were required, it would tend to result in passenger discomfort. This could, of course, be easily overcome by increasing $n$ but unfortunately this would also increase the complexity of the control algorithm.

The other two acceleration functions, initially appear to sat-
isfy all the basic requirements for a merging system. Their simplicity, ease of implementation, flexibility, and greater adaptability would certainly make them good candidates for detailed consideration. These functions, together with their corresponding velocity and distance trajectories are shown in Fig. 12. If it were assumed that the initial acceleration were $10 \text{ ft/sec}^2$ in both cases, a vehicle, initially at rest and controlled in accordance with the linear function, would travel 1333 ft in 20 seconds in order to merge with zero acceleration into mainstream traffic traveling at 100 ft/sec (see Fig. 12). In contrast, a vehicle controlled in accordance with the exponential function, would travel the same distance in 22.5 seconds, and only reach a speed of 89.2 ft/sec and an acceleration of $1 \text{ ft/sec}^2$.

A continuation of such a comparison leads one to choose the linear function as the preferred one of these two; hence, it is next examined in considerable detail.

4. A Mathematical Development of the "Linear" Acceleration Function

The mathematical relationships between the acceleration and the resulting velocity and distance-versus-time of the linear control function (see Fig. 12) are easily derived and are listed below

$$a(t) = a_i - \frac{a_i - a_f}{T_m} t, \quad 0 \leq t \leq T_m$$ (1)

$$v(t) = v_0 + \int_0^t a(t) dt = v_0 + a_i t - \frac{a_i - a_f}{2T_m} t^2, \quad 0 \leq t \leq T_m$$ (2)
Fig. 12—Comparison of two acceleration-versus-time functions for a merging vehicle.
\begin{align*}
\chi(t) &= \int_0^t v(t)\, dt = v_o \, t + \frac{1}{2} \, a_i \, t^2 - \frac{a_i - a_f}{6 \, T_m} \, t^3, \quad 0 \leq t \leq T_m
\end{align*}

where

\begin{itemize}
    \item \(a_i\) = initial acceleration calculated at the starting point in ft/sec\(^2\)
    \item \(a_f\) = final acceleration calculated at the starting point in ft/sec\(^2\)
    \item \(v_o\) = initial velocity of the ramp vehicle at the control station (see Fig. 2).
\end{itemize}

If the vehicle were following its prescribed path, then these equations would define the merging maneuver. However, if the vehicle were to deviate from its path, then it would be necessary to select a new acceleration trajectory. Thus, assume that a vehicle were to be merged using trajectory 1 as shown in Fig. 13. If the vehicle state were perturbed from its desired state, as defined by this trajectory and the associated \(v(t)\) and \(x(t)\) curves, its state (trajectory 2 in Fig. 13) would differ from the desired one. At a checkpoint, encountered at \(t = t_1\), the error in \(v(t)\), and \(x(t)\) would be used to select another acceleration function (trajectory 3 in Fig. 13), so that in the absence of any disturbance forces the vehicle errors would be corrected and it would be properly merged into the highway. This process would be repeated at each checkpoint until the vehicle arrived at the last checkpoint. Here the state of the ramp vehicle would be examined for the last time and, if a safe merge were probable, it would be allowed to move into the mainstream traffic; otherwise the merging operation would be aborted. A logic flow
Fig. 13—Acceleration, velocity, and distance-versus-time trajectories of a merging vehicle.
The generation of modified acceleration trajectories at the checkpoints, including the point where a merge initiates (control station on Fig. 2), is very simple. A measurement of velocity \( v_j \), displacement \( x_j \), and elapsed travel time \( t_j \) of the ramp vehicle at this point would enable one to calculate the desired control trajectory. For example, at the j-th checkpoint (see Fig. 13) where \( t = t_j \), the general mathematical relationships between the acceleration, velocity, and distance-versus-time of the ramp vehicle for the remaining portion of the ramp (still to be traveled) are given by

\[
a(t) = a_i - \frac{a_i - a_f}{T_m - t_j} (t - t_j), \quad t_j \leq t \leq T_m
\]

\[
v(t) = v_j + a_i(t - t_j) - \frac{a_i - a_f}{2(T_m - t_j)} (t - t_j)^2, \quad t_j \leq t \leq T_m
\]

\[
a(t) = a_j + v_j(t - t_j) + \frac{1}{2} a_i(t - t_j)^2 - \frac{a_i - a_f}{6(T_m - t_j)} (t - t_j)^3, \quad t_j \leq t \leq T_m
\]

Note that these equations will reduce to equations (1) - (3) if one lets \( t_j = 0 \) and \( x_j = 0 \) -- i.e., the starting condition for the merging operation.

If a successful merge is to be expected, then at time \( t = T_m \), equations (4) - (6) must satisfy the following requirements,

\[
a(T_m) = a_f \quad \text{(7)}
\]

\[
v(T_m) = v_m \quad \text{(8)}
\]

\[
x(T_m) = D \quad \text{(9)}
\]
Fig. 14—Simplified vehicle control logic diagram.
Applying the endpoint condition of equations (8) and (9) into equation (5) and (6) respectively yields

\[ V_m - V_j = \frac{a_i + a_f}{2} (T_m - t_j) \quad , \quad 0 \leq t_j \leq T_m \] (10)

\[ D - \alpha_j = V_j (T_m - t_j) + \frac{2a_i + a_f}{6} (T_m - t_j)^2 \quad , \quad 0 \leq t_j \leq T_m \] (11)

Solving equations (10) and (11) simultaneously will give the two parameters required to specify the modified trajectory at \( t = t_j \)

\[ a_i = \frac{6(D - \alpha_j) - 2(V_m + 2V_j)(T_m - t_j)}{(T_m - t_j)^2} \quad , \quad 0 \leq t_j \leq T_m \] (12)

\[ a_f = \frac{2(V_m - V_j)}{T_m - t_j} - a_i = \frac{2(V_m + V_j)(T_m - t_j) - 6(D - \alpha_j)}{(T_m - t_j)^2} \quad , \quad 0 \leq t_j \leq T_m \] (13)

These values of \( a_i \) and \( a_f \) would be different from the actual acceleration of the ramp vehicle at some or all the checkpoints only if the vehicle were not following the desired path; otherwise, they would lie on the previously determined acceleration trajectory. It should be noted that \( a_f \) could be positive, zero, or negative depending on the merging strategy and the automatic longitudinal control law after the insertion of a merging vehicle into the mainstream traffic. Thus, using the multimode longitudinal controller developed at The Ohio State University, Asghar and Fenton have established a preferred state of merging states upon the premise that a ramp vehicle should not cause any signifi-
cantly disturbance in the mainstream traffic. They specified that the ramp vehicle should be inserted into the freeway with a non-negative acceleration; i.e., its velocity should not exceed the mainstream speed. Throughout this study, this constraint is used as a design criteria; however, if unpredicted circumstances occur after a merge has been initiated, a limiting negative final acceleration of up to $-1 \text{ ft/sec}^2$ would be tolerated.

E. A Linear Mathematical Model for a Merging Vehicle

It is a difficult task to develop a general vehicle model which takes into account the nonlinearities in the engine, drivetrain, and vehicle-roadway interface. Of course, such a model could be used to accurately describe vehicle performance; however, to this author's knowledge, such a comprehensive model has not yet been developed. In practice, some relatively simple models have been used to adequately describe the performance of an automobile — at least to the extent that road-test data approximated results predicted from the models. Therefore, derivation of an exact model of vehicle dynamics does not seem essential for the task of interest here.

Consider the model of vehicle longitudinal dynamics shown in Fig. 15, where

\[ r = \text{ throttle valve position} \]
\[ F_e = \text{ effective force applied to the vehicle by drivetrain} \]
\[ F_d = \text{ external disturbance force, such as wind gusts, roadway grades, and random environmental perturbations.} \]
\[ F_r = \text{vehicle resistive force, such as still-air drag force, rolling resistance, and chassis friction.} \]
\[ m = \text{loaded mass of the vehicle (mass of the vehicle and passengers and/or goods)} \]
\[ p = \frac{d}{dt} \]

The dynamics of carburetor, engine, and drivetrain are nonlinear in nature; however, within the acceleration capability of the car, it is convenient to assume that the engine responds essentially instantaneously to acceleration pedal position and also that the response is linear. Therefore, the engine and drivetrain are approximated by a pure gain \( K_e \).

Furthermore, the effect of nonlinear drag due to still air can be substantially reduced by introduction of internal velocity feedback through a gain of \( \delta \) (see Fig. 16). In such a case, it is convenient to linearize this force via
$$F_r \approx K_r \nu$$

The resulting vehicle longitudinal dynamics are depicted in Fig. 16.

![Block diagram of modified vehicle longitudinal dynamics.](image)

Fig. 16—Block diagram of modified vehicle longitudinal dynamics.

where

- $R$ = the reference throttle position.

From Fig. 16

$$F_e + F_d = m \rho \nu + F_r = m \rho \nu + K_r \nu$$

and, after some simplification

$$\nu = \frac{K}{T \rho + 1} \left( \frac{F_e + F_d}{K_e} \right)$$  \hspace{1cm} (14)

where

- $K = K_e / K_r$ = vehicle gain constant  \hspace{1cm} (15)
- $T = m / K_r$ = vehicle time constant  \hspace{1cm} (16)
Writing the transfer function between \( v \) and \( R \) under the assumption that \( F_d = 0 \),

\[
\frac{v}{R} = \frac{K_c}{T_c p + 1} \tag{17}
\]

which hereafter will be referred to as the compensated vehicle dynamics. Here

\[
K_c = K/(1 + \delta K) = \text{compensated vehicle gain constant} \tag{18}
\]

\[
T_c = T/(1 + \delta K) = \text{compensated vehicle time constant} \tag{19}
\]

Note that the velocity feedback loop (5) has reduced the vehicle gain and time constant by \( 1/(1 + \delta K) \).

It is desirable to insert a compensator in series with the compensated dynamics so as to cancel out the pole at \(-1/T_c\) and replace it with one at the origin. Further, since vehicle acceleration is to be controlled during the merging maneuver, it is appropriate to provide a measure of \( a(t) \) so that it can be compared against a reference input. The resulting block diagram is shown in Fig. 17, where

\[
a_v = \text{a reference voltage proportional to the command acceleration}
\]

\[
K_g, K_a, K_b, \text{ and } K_o = \text{gain constants.}
\]

From Fig. 17, the response of the system for \( F_d = 0 \) is

\[
\nu = \frac{K_g K_a K_c}{\rho} \left( \frac{K_b}{K_a} \frac{p+1}{T_c p + 1} \right) \frac{1}{1 + K_a K_b K_c} \left( \frac{K_b}{K_a} \frac{p+1}{T_c p + 1} \right) a_v \tag{20}
\]
The cancellation of the pole at $-1/T_c$ requires

$$\frac{K_b}{K_a} = T_c$$

Therefore, equation (20) reduces to

$$v = \frac{K_b K_a K_c}{1 + K_a K_b K_c} \left( \frac{a_v}{p} \right)$$

A corresponding block-diagram representation is shown in Fig. 18.
If a transfer function of the form

\[
\frac{v}{\dot{a}_n} = \frac{l}{p}
\]

were required, then

\[
\frac{K_g K_a K_c}{1 + K_c K_a K_c} = l
\]

Solving equations (21) and (24) simultaneously gives

\[
K_a = \frac{l}{K_c (K_g - K_o)} = \frac{l + \delta K}{k (K_g - K_o)}
\]

\[
K_b = \frac{\tau}{k (K_g - K_o)}
\]

Next, consider the nature of the external disturbance forces and their effects on the merging controller. From Fig. 17, the response of the system due to \( F_d \) is given by
\[ \nu_d = \frac{K_2}{T_d \rho + l} \frac{F_d}{K_e} \]  \hspace{1cm} (27)

where

\[ \nu_d \]  = velocity deviation due to a disturbance force

\[ K_2 = \frac{K}{(1 + \delta K + K_0 K_a K)} \]

\[ T_d = \frac{(T + K_0 K_a K)/(1 + \delta K + K_0 K_a K)} \]

Using equations (15) and (16), one can write

\[ \frac{F_d}{k_e} = \frac{F_d}{m} \frac{m}{K_r} \frac{K_r}{K_e} = \frac{T}{K} \frac{F_d}{m} \]  \hspace{1cm} (30)

Therefore, Eqn. (24) reduces to

\[ \nu_d = \frac{K_d}{T_d \rho + l} A_d \]  \hspace{1cm} (31)

where

\[ K_d = \frac{TK_2}{K} = \frac{T}{(1 + \delta K + K_0 K_a K)} \]  \hspace{1cm} (32)

\[ A_d = \frac{F_d}{m} \]  \hspace{1cm} (33)

On substituting Eqns. (25) and (26) into (29) and (30) one obtains

\[ K_d = \frac{T_c}{K_2} (K_g - K_o) \]  \hspace{1cm} (34)

and

\[ T_d = T_c \]  \hspace{1cm} (35)
The overall system response is the superposition of the responses given in Eqns. (23) and (31)

\[ V = v + v_d = \left( \frac{a v}{p} + \frac{K_d A_d}{T_d p + 1} \right) \]  

(36)

Assuming a constant acceleration \( A_d \) due to an external disturbance force, the resulting velocity and displacement errors can be derived by using Eqn. (31)

\[ v_d(t) = K_d A_d \left( 1 - e^{-\frac{t}{T_d}} \right) \]  

(37)

and

\[ d_d(t) = \int_0^t v_d(t) dt = K_d A_d t - K_d A_d T_d \left( 1 - e^{-\frac{t}{T_d}} \right) \]  

(38)

where

\( x_d = \) displacement error due to perturbation forces.

Consider next the effects due to typical disturbance forces such as roadway grades and wind gusts. These forces are commonly applied to any moving highway vehicle and the resulting effects can frequently be predicted and compensated in advance. Thus, first consider the effect of a roadway grade (\( \alpha \)) on vehicle performance. From Fig. 19, the component of the force opposing vehicle thrust is

\[ F_g = mg \sin \alpha \]

For small \( \alpha \)

\[ \sin \alpha \approx \tan \alpha \approx \alpha \]
Then,

\[ F_G = mg \alpha \]  \hspace{1cm} (39)

where

\[ F_G = \text{retarding force due to grade in lbs} \]
\[ g = \text{acceleration constant, (32.2 ft/sec}^2\text{)}. \]

Fig. 19—The effect of grades on the vehicle.

Next consider the effect of a wind force on the system. The terms wind resistance and air resistance are interchangeably used by many researchers; however, there appears to be a definite distinction between the two. Air resistance corresponds to the case whenever the air is at rest and the vehicle is in motion, while wind resistance corresponds to a force generated by moving air, for example, a wind gust. Air resistance is considered to affect the dynamics of the vehicle and thus, it should not be considered as an external disturbance. The effect of the wind forces on the vehicle can be described by the following equation.\textsuperscript{73,74}

\[ F_w = C_d A \nu_w^2 \]  \hspace{1cm} (40)
where

\[ F_d = \text{wind resistive force in lbs} \]
\[ c_d = \text{an experimentally obtained drag coefficient} \]
\[ A = \text{projected frontal surface area of the vehicle in ft}^2 \]
\[ v_w = \text{speed of wind in mph}. \]

A typical value of \( c_d \) for conventional sedans is given as .0017; however, experimental results show that streamlining of the vehicle could reduce this empirical constant to .0008.\(^{75} \)

Therefore, if one assumes a frontal vehicle area of 25 ft\(^2 \), then a vehicle would require 36 lbs additional tractive force to overcome a 44 fps head wind and maintain its given steady-state velocity.

In practice, there are also other factors which can cause errors in the state of a merging vehicle. These include measurement errors pertaining to the detected gap, mainstream speed, and the state of the ramp vehicle. Unpredicted environmental effects, such as a slippery spot on the ramp and inaccurate state information from other ramp vehicles are some other sources of errors which would also adversely affect the performance of a merging control system.

**F. Detection and Checkpoint Requirements**

Consider the on-ramp configuration shown in Fig. 20. In an idealized situation, "perfect" information regarding the instantaneous state of the mainstream traffic would always be available to the logic device which controlled the on-ramp vehicles. In practice, one could approach this ideal by blanketing the freeway with sensing and informa-
tion transmitting units, which would probably result in both an expensive and relatively complex system. In practice, it would be desirable to use only as many units as would be compatible with economy, system efficiency and system safety. Similar comments can be made regarding the information available to the control station concerning the state of the on-ramp vehicles; however, in practice, it would appear sufficient to specify the minimum number of sensing units required to provide both satisfactory performance and fail-safe operation.

In this context, the absolute minimum number of required mainstream sensing units would be four located as depicted in Fig. 20. Two of these, $D_1$ and $D_2$, would be used to both detect the arrival of an acceptable gap and to check the speed of the mainstream traffic. Signals from $D_1$ and $D_2$ would be sent to the control station where the projected gap arrival time at the merge point would be calculated. The output of
the sensor $D_3$, which would be located just before the merge point, would be used to make a final gap check and $D_4$ would be used in conjunction with $D_3$ to both check the mainstream speed and to insure that the vehicle, which defined the start of the gap, had properly cleared the merging point before the on-ramp vehicle entered the traffic stream.

The locations of $D_1$, $D_2$, $D_3$, and $D_4$ must be carefully specified. For example, if a ramp vehicle were to require 20 seconds to reach $V_m = 100$ ft/sec, then $D_1$ and $D_2$ should be located at least 2000 ft upstream from the merging point. $D_4$ should be located approximately at a distance corresponding to the minimum permitted time headway downstream from this point and $D_3$ should be located the same distance upstream.

It should be noted that the information available to the control station from these four sensors would not completely specify the behavior of all vehicles between $D_1$ and $D_4$, and, in this sense, any system operating on the derived information would not be absolutely fail-safe. However, as is subsequently shown, the size of the gap between detectors $D_1$ and $D_4$ would tend to remain virtually unchanged, and thus no hazardous situation would normally be expected. Even in case of emergencies on the freeway, the system would be operationally safe, for detectors $D_3$ and $D_4$ would not issue a go-ahead signal for a ramp vehicle insertion unless an acceptable size gap were available at the merging time. This information-collection system and the corresponding decision-making logic would probably be satisfactory for control of merging into relatively low-density traffic streams and inadequate for very high ones.

The requirements for a more complete information-colllecting system can be visualized by considering the following: Assume the maxi-
The response of this system to \( F_d \) is

\[
V_2(s) = \frac{S}{S^2 + \frac{1}{T} (1 + SK + KK_b) S + \frac{K}{T} K_a} \frac{F_d}{m} (s)
\]  

(41)

If \( F_d \) were constant, then the resulting steady-state velocity error would be zero; thus
Fig. 21—Block-diagram representation of a velocity controller for longitudinal control of mainstream traffic.

\[ V_{ss} = \lim_{s \to 0} s V_2(s) = 0 \]  

(42)

However, the corresponding position deviation \( x_{ss} \) would not be zero for

\[ X(s) = \frac{V_2(s)}{s} = \frac{1}{s \left[ s^2 + \frac{1}{T} (1 + \delta K + KK_b) s + \frac{k}{I} k_4 \right]} \frac{F_d}{m} \]  

(43)

and

\[ \lambda_{ss} = \lim_{s \to 0} s X(s) = \frac{T}{KK_4} \frac{F_d}{m} \]  

(44)

The effect of the error can be noted by examining its value for a 44 fps head wind acting on a 4500 lb vehicle. If \( T \) and \( K \) were chosen as 20.5 and 1.72, respectively, and \( \delta, K_4 \) and \( K_0 \) were 10, 3, and 1 respectively, then using Eqns. (25), (40), and (44), one would obtain
Thus under normal conditions, and even under certain disturbance force conditions, the mainstream vehicles should remain close to their predicted distance-versus-time trajectories — at least over the distance from D\textsubscript{1} to D\textsubscript{4}. In this context, it was deemed unnecessary to add more than two sensors between D\textsubscript{1} and D\textsubscript{4}. Further, Bender has observed that at an average stream speed of 58.6 fps, the velocity variation associated with such a controller under full-scale conditions was ±0.16 fps with the corresponding headway deviation of some ±1.47 ft over a 4-minute period.\textsuperscript{76}

These considerations have involved only the expected quasi-steady-state behavior of the mainstream traffic and haven't considered the various abnormal situations which could arise as the mainstream traffic progressed from D\textsubscript{1} to D\textsubscript{4}. However, such cases would be handled in a relatively simple fashion; thus, if the abnormality were to result in a substantial change in the state of the detected gap — size, time-of-arrival at merge point, speed, etc. — the system, if it were to determine that the merging vehicle could not adjust its state so as to safely correspond to the changed state of the gap, would abort the merge.

Next consider the minimum number of sensors which must be located on the onramp. In an ideal situation, where there would be no changes in the state of the gap and the merging vehicle's state corresponded to the desired one, then no sensors would be required. In practice, it is clear that a detector (D\textsubscript{5} in Fig. 20) would have to be located just before the end of the ramp for purposes of checking the state of the merging vehicle so that it could be compared with that of the
mainstream gap just prior to merging. In practice, however, the use of only one checkpoint would be completely unsatisfactory as can be seen from the following example.

According to Eqns. (37) and (38), the velocity and distance deviations for a constant disturbance force approach a constant and a ramp function, respectively, for large \( t \). However, the error in the velocity would be relatively small and might be negligible in practice. Consider a merging situation where the stream speed, merging time, ramp length, and disturbance force were 102.6 fps, 20 sec, 1300 ft, and 140 lbs, respectively, with the latter corresponding to a 2.3% roadway grade plus a 44 ft/sec headwind. The resulting velocity deviation at the merge point would be some 0.9 ft/sec; however, the distance error would be 17 ft at \( t = T_m \). Thus, if the checkpoint \( D_5 \) were used to make a simple binary decision of the merge, it would probably abort the merging maneuver as the merging vehicle would enter the mainstream some 17 feet behind its target point. Such an undesired situation would probably not have arisen if the vehicle state had been checked and corrected earlier. The matter of concern then is the required number of onramp checkpoints and their locations.

In order to specify this quantity, it is convenient to first view the limiting attainable acceleration of a test vehicle — a specially instrumented 1965 Plymouth Sedan — which is hereafter considered to have typical passenger-car performance characteristics. Its maximum acceleration-versus-velocity characteristic was previously reported by Blackwell and is shown in Fig. 22. The dashed curve indicates the maximum design value of available acceleration and is mathematically de-
Wheel Spin, 0.59g

Fig. 22—Maximum calculated and limiting attainable acceleration of the test vehicle.
scribed by

\[ a_{\text{max}} = \sqrt{100 - \frac{16.78}{T_m} v^2} \]  

which was obtained using Eqns. (1) and (2). It is preferred to insert a vehicle into mainstream traffic with a non-negative acceleration; however, in practice a limiting minimum acceleration of \(-1 \text{ ft/sec}^2\) would be tolerated, as this would increase system flexibility. For example, in case of a delay in gap arrival, a ramp vehicle could decelerate and probably still be able to merge properly. The selected minimum value seems reasonable, for a vehicle traveling at 100 ft/sec would face a constant retarding acceleration of \(-.8 \text{ ft/sec}^2\) due to still-air drag — a force which would, of course, correspond to a coasting deceleration. Note the region of permitted accelerations as depicted in Fig. 22.

A checkpoint scheme based upon either time or distance considerations appears feasible as both of these quantities could be calculated with good accuracy. Here, for reasons of theoretical and simulation simplicity and availability of suitable logic circuitry, a checkpoint policy based upon the merging-vehicle travel time was selected.

It should be noted that while the merging controller is a closed-loop system with respect to acceleration control, it is only quasi-closed-loop with respect to the state of the mainstream traffic; i.e., this state information is only available to the vehicle controller at each of \(n\) checkpoints. Thus, the correction required at a given checkpoint would not only involve correcting for errors in the vehicle state with respect to its original desired state, but also for changes
in both the environment and the mainstream traffic. Note from Fig. 3 that all necessary information would be collected, and analysed by the control computer, and a modified trajectory selected -- if this were necessary. This selection would be communicated to the merging vehicle which would then have its reference trajectory -- at least until the next checkpoint were crossed. This entire process must be considered in the selection of a suitable checkpoint sampling time.

One practical scheme for determining the sampling intervals for on-ramp checkpoints can be envisioned with the aid of Fig. 23. Consider a merging situation in which trajectory 1 were selected as the desired one; however, external disturbance forces cause the ramp vehicle to follow trajectory 2. Clearly the resulting increasing acceleration error must be corrected before it becomes too large for a satisfactory correction to be made. For reasons of simplicity, it was decided to check this trajectory at each of n points equally spaced in time. Thus at $t = t_1$, a new trajectory would be selected, so that if ideally followed, the vehicle would arrive at the merge point $T_m$ with the velocity of the mainstream traffic. Thus, in the case considered, trajectory 3 would be selected at $t_1$. This process would continue until the ramp vehicle were inserted into the freeway. However, if at a checkpoint, say at $t_j$ in Fig. 23, the required acceleration trajectory were to exceed its limiting value as defined only by (41) (trajectory 5), then if possible an acceleration trajectory within the attainable limit of vehicle acceleration (trajectory 6) would be selected and the vehicle would be instructed to follow this trajectory. This would mean that the vehicle would be inserted into the traffic stream in a nonideal, but acceptable state. If
the error were continuously accumulating in one direction, there would be cases in which the checkpoint at $t_j$ (see Fig. 23) would be the last point in which the state of the merging vehicle could be updated. In such cases, the required acceleration might exceed its allowable limits; however, the state of the vehicle would be checked at the remaining checkpoints (if there are any), but it would be modified only if the required acceleration function were to drop back within the limits of available vehicle acceleration. This would only occur if a disturbing force of opposite direction were applied to the vehicle.

Consider the nature of the disturbance forces which can act on a merging vehicle. First, one has the type which is detectable before a merge is initiated (such as a constant roadway grade or constant wind...
force). Obviously, this should be considered in the calculation of a required acceleration trajectory. Second, there could be undetected and/or unpredicted on-ramp forces (such as unusual roadway conditions or a sudden gust of wind) which would cause the vehicle to deviate from its specified trajectory. The relation between sampling times \( T_s \) and the effects of such forces were examined by considering a computer-simulated merging situation in which a vehicle, initially at zero speed was required to accelerate to a mainstream speed of 102.6 fps in 19.7 sec and move over a distance of 1300 ft during this time.* This vehicle was subjected to a disturbance force of 140 lbs (corresponding to \( A_d = 1 \text{ ft/sec}^2 \)) which opposed its forward motion. Some typical results for two values of \( T_s \) (1 sec and 8 sec) are depicted in Figs. 24a and 24b, where both the selected (calculated) and the actual acceleration trajectories are plotted versus time. Note that, at the checkpoints, the vehicle required a greater acceleration than the selected one to overcome the errors in the state of the vehicle. This change is quite small for \( T_s = 1 \text{ sec} \) in comparison with \( T_s = 8 \text{ sec} \). This seems reasonable for a larger \( T_s \) would result in a larger displacement error (see Eqn. 38), which would in turn require a larger "correction" acceleration at the checkpoints. In both cases, the velocity errors are less than 0.7 ft/sec at all times. The distance error for \( T_s = 1 \text{ sec} \), was .25 ft at each of the first 19 checkpoints, and it was less than 0.1 ft at the merge point. The distance errors corresponding to \( T_s = 8 \text{ sec} \) are some 5 ft at the two checkpoints and 4.6 ft at the merging time. As shown in Fig. 24b, this relatively

* A complete discussion of this computer-simulation study is contained in Chapter III.
Fig. 24—Selected and actual acceleration trajectories corresponding to \( T_s = 1 \) and \( T_s = 8 \) for \( V_m = 102.6 \) ft/sec, \( T_m = 19.7 \) sec, and \( D = 1300 \) ft.
small final error was obtained at the expense of a large acceleration change at the last checkpoint and a large acceleration rate (jerk) between the last checkpoint and the merge point.

In the examination of data obtained for other values of $T_s$ (2 to 7 sec) it was noted that a large checkpoint-sampling time resulted in a larger error in the state of the merging vehicle, both at the checkpoints and at the merge point. This in turn, required sizable acceleration changes at the checkpoints which, in addition to resulting in passenger discomfort, frequently required an acceleration trajectory which exceeded the limiting attainable values. In such conditions, an acceleration trajectory within the capability of the vehicle, but not the required one was selected. As a result, the error at $t = T_m$ depended on the error at the last checkpoint in which the system was updated and the required acceleration that the vehicle could not provide.

A similar analysis was conducted for other merge velocities ranging from 44 to 88 fps, and essentially the same results were obtained. Thus, the larger values of $T_s$ generally resulted in large required acceleration changes at the checkpoints and large velocity and distance deviations at high merging speeds. Therefore, a choice of small $T_s$ (such as 1 sec), will most satisfactorily account for undetected and/or uncontrolled on-ramp disturbance forces affecting the vehicle at merging speeds from 44 to 102.6 fps. Theoretically, the system can best account for the disturbance forces if $T_s$ is so small that the input to the car will approximate a continuous signal. In practice, however, a very small choice of $T_s$ (such as $T_s = .1$ sec) is not recommended, for the increased number of the checkpoints would also increase the system costs.
A typical computer print out indicating the velocity and distance errors for a 102.6 fps merge using three different sampling times ($T_s = 1$ sec, $T_s = 4$ sec, and $T_s = 8$ sec) is contained in Appendix B.

Next consider the effects of unwanted variations in the mainstream traffic on the selection of the checkpoint-sampling intervals. Under normal conditions, and even in the presence of certain disturbance forces, the gap detected at $D_1$ would be expected to arrive at the merge point virtually unchanged. However, if a gap closure, a gap extension, or a delay (or advance) in the arrival time of a gap were to occur, then the system must respond effectively. Clearly, if a gap becomes less than some minimum acceptable value, no merge should occur and the ramp vehicle must be diverted. On the other hand, if a gap becomes larger than a minimum value, this by itself should pose no problem.

A late or early arrival of the gap would mean that a proper merge would be possible only if the merging vehicle travel time to the merge point were also increased or decreased as required. Furthermore, since the distance between the detection point and the merge point would remain constant, any change in the gap arrival time would usually be associated with a speed change in the mainstream traffic. Thus, if a gap were to arrive $\Delta t$ sec earlier, its speed also must have increased by some $\Delta v$ ft/sec. These changes would be communicated to the control computer which would modify the desired acceleration trajectory for the merging vehicle, and communicate this information at the next checkpoint. Here, the state of the vehicle would be checked and the necessary corrections would be made. If a suitable adjustment has been made or could be made by the time the vehicle arrives at the last checkpoint, a merge go-ahead
signal would be issued, or the maneuver would be aborted if a safe merge were not possible.

Since the information pertaining to the state of a gap is communicated to the merging vehicle only at each checkpoint, it is desired to establish these points so that the system could best respond to unexpected gap changes. To accomplish this, a worst-case condition was examined under various gap-state changes — a step increase in $V_m$ and a corresponding step decrease in $T_m$. Since the gap travel time (from detection point to the merge point) would be smaller, the merging operation would require an acceleration trajectory which would tend to be near, and possibly exceed, its limiting values. This study was conducted at the maximum permitted stream speed of 102.6 fps as a given constant change in $T_m$ would have a greater effect at high than at low speeds. For example, a .1 sec gap delay at 102.6 fps stream speed would (if not corrected) result in 10.26 ft headway error at the merge point, while the corresponding error for $V_s = 44$ fps would be 4.4 ft.

A computer program was written (see Appendix A) to determine system performance variability for different checkpoint-sampling times. This computational algorithm also determined the last time (after merge initiation) at which a ramp vehicle would be notified of some change in the gap state and still be able to correct its state and attain an acceptable-safe merging state when it reached the merge point.* The se-

---

*The permitted errors in a merging vehicle's state when it reaches $x(t) = D$ define the set of acceptable merging states. Such errors depend on factors such as the minimum size of an acceptable gap, the type of control exercised after the merging instant, and the control associated with the mainstream vehicles.
lected stream speed and merge time were 102.6 fps and 19.7 sec, respectively. Various stream velocity deviations with their associated gap arrival time changes were introduced at different times during the merging operation and the resulting final velocity and headway errors were calculated. Typical data for a case where a 4.4 fps gap speed increase with its associated 563 msec gap arrival time reduction was introduced at 6 sec after merge initiation, is contained in Table 2. Here, $\Delta V_m$ and $\Delta h$ are the merging-vehicle final velocity and headway deviations, respectively at $t = T_m$.

Note that when $T_s = 1$ sec, the merging-vehicle spatial position at the merge point is only 3.75 ft off the center of (behind) the gap, while for $T_s = 3$ sec and $T_s = 6$ sec this deviation increases to some 19 ft and 33 ft, respectively. The relatively small headway deviation for $T_s = 1$ sec is clearly due to more frequent updating and as a result, a better utilization of the available acceleration of the vehicle. Note that, in this case, the vehicle reaches a speed greater than the gap speed so as to correct its headway position. However, as the period

### Table 2

**The Effects of a 4.4 FPS Gap-Speed Increase on the Merging-Vehicle State at the Merge Point**

<table>
<thead>
<tr>
<th>$T_s$ (sec)</th>
<th>$\Delta V_m$ (fps)</th>
<th>$\Delta h$ (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+2.25</td>
<td>-3.75</td>
</tr>
<tr>
<td>3</td>
<td>-1.1</td>
<td>-19.04</td>
</tr>
<tr>
<td>6</td>
<td>-4.3</td>
<td>-32.92</td>
</tr>
</tbody>
</table>
(T_g) in which a vehicle travels on a selected trajectory increases, its chances of adjusting its state to an acceptable merging state becomes smaller. This can be clearly envisioned with the aid of Figs. 25a and 25b, where the calculated acceleration trajectories corresponding to the first two rows of Table II are shown. Note that in both cases, the vehicle travels on its initially selected trajectory to a point (t = 6 sec) where a gap-state change is introduced and detected by the ramp vehicle at the same time. The modified acceleration trajectories selected at this point are the same for both cases (see Figs. 25a and 25b); however, from this point to the completion of the merging maneuver, a larger value of acceleration is maintained for T_g = 1 sec; consequently, the final headway error for T_g = 1 sec is much less than for T_g = 3 sec with the absolute value of the velocity errors, for both cases, being approximately the same.

In the cases discussed above, the point at which a gap change occurred was taken to be in exact correspondence with a checkpoint; however, a case where a gap error is not simultaneously introduced and detected is considered next. This would correspond to a situation where a change in the gap state has actually taken place at some time t, but the ramp vehicle is traveling between two checkpoints, and thus, would not be notified of such error until it arrives at the next checkpoint at some \( \Delta t \) seconds later. Clearly, as the vehicle continues to travel on its selected path, without taking any corrective action against the existing errors, its capability to adjust to the gap state becomes smaller. For example, if the speed of the gap were to increase by 4.4 fps (\( \Delta T_m = -563 \text{ msec} \)) at 6 sec after the merge initiation and the ramp vehicle were un-
Fig. 25—Selected acceleration trajectories of a merging vehicle in the presence of a gap-state change.
aware of such a change until the next checkpoint located at 1 or 2 sec away, final $\Delta h$ would increase from 3.75 ft to 10.56 or 15.24 ft respectively, and $\Delta V_m$ would change from 2.25 to 1.91 or 1.69 fps respectively, if the vehicle were checked at every 1 sec as soon as the gap change was detected. Therefore, even with a 1 sec sampling time, there would be a noticeable headway error variation at the merge point if the gap-state change were to occur at such a time. Thus, to effectively correct for changes in the gap state, it would be necessary that the controlled vehicle receive information concerning the state of the stream traffic as frequently as possible. In essence, if such changes in the state of the mainstream traffic could occur, then one could effectively utilize nearly continuous information.

In light of this discussion, it is clear that the checkpoint sampling time should be small. However, an exact value of $T_s$ will depend on the merging situation, for example, if the maximum merging velocity and the maximum allowable disturbances were limited by 102.6 fps and 140 lbs, respectively, then $T_s = 1$ sec proved to be quite satisfactory. If these limits were to exceed the values mentioned, then a smaller checkpoint time and perhaps a continuous system updating would be necessary. Since the discrete errors (gap-state changes) could also be best accounted for if the ramp vehicle were continuously notified of such deviations, it appears that the proposed merging controller would function most efficiently when a continuous information regarding the state of both on-ramp and off-ramp disturbance forces were available. In practice, however, continuous or nearly continuous information would require a complete communication link for use in the merging operation. The re-
sulting complexity and expense would probably be unnecessary -- especi-
ally since the mainstream traffic would be tightly controlled and sudden
gap changes would be very unlikely. For most practical purposes,
\( T_s = 1 \) sec appears quite acceptable, for a smaller sampling time would
be mainly required for such gap-state changes.

G. Summary

In this chapter, the basic theory for an automatic merging con-
trol system has been defined both for an ideal case and an actual merging
maneuver. Several vehicle control functions have been presented and a
potentially practical one has been further studied in detail. A linear
mathematical model of the merging vehicle has been developed and its re-
sponse to both a vehicle command signal and external disturbance forces
have been analysed. A scheme for specifying the number of detectors and
checkpoints has been discussed in detail.

From the theoretical analysis of this chapter, the development
of an automatic control system for the longitudinal control of the ramp
vehicles' merging onto the freeways, appears quite feasible. A detailed
computer simulation of this controller is contained in the next chapter.
A. Introduction

The performance of the system discussed in Chapter II is examined in this chapter using computer simulation. An extensive study of the merging controller will thus be accomplished in the laboratory before proceeding with full-scale highway studies.

The need for such a simulation study results from the expense, the experimental difficulties, and possible safety problems associated with obtaining on-road test data under a wide variety of environmental and vehicular conditions. On the other hand, a computer-simulation study is a relatively inexpensive, safe and efficient method of studying system performance. This performance can easily be evaluated for various parametric combinations, and suitable parameters specified. Furthermore, because of its flexibility, the response of the system could easily be examined and verified under all important and expected physical situations. This would probably eliminate the need for much, but not all, full-scale testing of the system.

In the following, a simulation model is discussed together with the corresponding assumptions, and control algorithms. Then, merging system performance at different stream velocities under various external disturbance forces is studied. Finally, the operation of the controller
for merging ramp vehicles with a nonzero initial velocity is investigated.

This study was conducted on a digital computer, because of its superior speed, accuracy, and reliability with respect to an analog computer. Furthermore, the scaling requirements of an analog simulation were unduly time consuming and thus undesirable for an efficient simulation study.

B. Merging Control Algorithm Considerations

Briefly reconsider the linear control function discussed in Chapter II. This, in its basic form, appears as shown in Fig. 26, where the acceleration and velocity trajectories of a merging vehicle are plotted. The relationships between the variables of interest, at the merge point, would be

\[ V_m = V_s = \frac{a_i T_m}{2} \]  
\[ D = \frac{a_i T_m^2}{3} \]

(45)  
(46)

This assumes that the vehicle would reach the merge point with stream speed \( V_s \) and zero acceleration and subsequently merge into the stream.

However, this approach poses various practical problems including an inability to respond to a non-ideal merging situation. For example, \( D, V_s, \) and \( T_m \) are specified when a merge is initiated, and if a deviation in the ramp vehicle state (with respect to its desired state) were subsequently to develop at \( t = t_1 \), there would be only one parameter
a_1 = a_1(t_1) to specify for correcting this situation. However, a_1 could not satisfy the two constraints x(T_m) = D and v(T_m) = V_s, as can be noted. If a vehicle were required to follow trajectory 1, then the area under the acceleration and velocity curves would correspond to V_s and D, respectively. However, if the vehicle were actually traveling on trajectory 2, then a correction would be required at t = t_1. Specifically,
\(a_I(t_I)\) must be selected so that both the decrease in velocity and distance can be made up before \(t = T_m\). To accomplish this, the vehicle must be accelerated at a higher rate to eliminate the distance decrement; however, no single value of \(a_I\) would result in both \(x(T_m) = D\) and \(v(T_m) = V_s\). In particular, the latter condition could be met, without changing \(T_m\), if both the initial and final value of acceleration were available as parameters. Therefore, if the state of the system were to be appropriately corrected, nonzero final accelerations should be tolerated.

Next consider the ramp length requirement which is associated with Eqn. (46). In practice, it would be desirable to insert the vehicle into the stream traffic with a non-negative final acceleration so as to reduce this requirement. Thus, consider a situation where a vehicle would be required to reach a merge velocity of 102.6 ft/sec with initial and final acceleration of 10 and 0 ft/sec\(^2\), respectively. This would require \(D = 1400\) ft and \(T_m = 20.5\) sec; however, if \(a_I = 9.67\) ft/sec\(^2\) and \(a_f = 0.74\) ft/sec\(^2\), then \(D = 1300\) ft and \(T_m = 19.7\) sec would be required to reach the same merge velocity. Clearly, the latter approach would require both a smaller ramp length and a lesser \(T_m\).

In view of such considerations, it was decided that a merging vehicle could have a non-negative acceleration at \(T_m\). In effect, the situation would be as shown in Fig. 27, where a ramp vehicle would arrive at the merge point at \(t = T_m\), and have a velocity of \(V_s \pm \Delta V_s\) and a small positive acceleration. Here, \(\Delta V_s\) is the permitted variation in the vehicle's velocity at \(t = T_m\). If the merge point were "in" the traffic stream (insertion point in Fig. 27), control would soon be switched to that used for steady-state longitudinal control. However, if this point
were located as shown in Fig. 27, the situation would be somewhat more complex; certainly an automatic lane changing maneuver would be required to adjust the lateral position of the merging vehicle and, at some point, longitudinal control would have to be switched as before. In both cases, if the vehicle state were not within prescribed bounds, the merging maneuver would be aborted via a "reject" lane. It is clear that the latter scheme could easily be extended so that a merging vehicle could enter the mainstream traffic at any one insertion points. It is also noted that the acceptable bounds on the state of the vehicle at \( t = T_m \) are not explicitly defined in this study. Instead, since the emphasis is almost wholly on vehicle control during the merging maneuver, such bounds are later considered in only a general way.
C. Simulation Model

1. System Constraints and System Parameters

The extent to which a computer simulation can reproduce a real-world situation is largely dependent on the realism of both the system model and its inputs. Therefore, any constraints selected in model formulation must be consistent with those encountered in the corresponding physical situation. A maximum acceleration at standstill of 10 ft/sec$^2$ is assumed for a typical American sedan and the vehicle would be merged with an acceleration in the range from -1 to 1.61 ft/sec$^2$. Ideally, this latter acceleration should be smaller; however, this choice resulted in greater system flexibility in accounting for various environmental effects.

Consider now some important aspects of selecting $D$ and $T_m$. This can readily be done by considering merging vehicle performance as a function of both $D$ and $T_m$, for a vehicle traveling with the prescribed acceleration limits toward a merging speed of 102.6 ft/sec.

First, it was noted that for $D < 1150$ ft, the choices of available acceleration trajectories were so limited that when environmental disturbances arose, one generally would be forced to abort the merging maneuver. For $D > 1150$ ft, the number of possible choices of acceleration trajectories increases as can be seen from Figs. 28a, 28b, and 28c, where using Eqns. (12) and (13) the permitted acceleration-versus-time trajectories are plotted for ramp lengths of 1200 ft, 1300 ft, and 1500 ft, respectively. The shaded area in these figures represent the region of permissible operation in that any line passing through it would properly merge a ramp vehicle at the specified time-space location. Note
Fig. 28—Permitted range of available acceleration trajectories for $V_s = 102.6$ ft/sec and (a) $D = 1200$ ft, (b) $D = 1300$ ft, and (c) $D = 1500$ ft.
that as D increases, both $T_m$ and the range of choices of acceleration trajectory also increase.

Next consider the trajectories shown in Fig. 29a. Trajectory 1 corresponds to an ideal situation in which the merging vehicle would not be subjected to any disturbance forces. The vehicle would require 18.7 sec to traverse a 1200 ft ramp and enter the mainstream traffic with $V_B = 102.6$ ft/sec. However, if a disturbance force of $+140$ lbs or $-140$ lbs were present and detected before the merge were initiated, then trajectory 2 or trajectory 3, respectively would be selected. In all three cases, $T_m$ would be identical. The same three situations are depicted in Fig. 29b for a 1300 ft ramp length. Clearly, the system would satisfactorily respond to such disturbances for both ramp lengths; however, more flexibility of response is offered by the longer length. Further, it can be determined from Eqns. (12) and (13), that the system can, at time $t = 0$, simultaneously account for both a continuously acting disturbance force of $\pm 140$ lbs and a gap change of $\pm 0.1$ sec. This presupposes a ramp length of 1200 ft; if this were increased to 1300 ft, the gap change could be as great as $\pm 0.5$ sec.

Therefore, a greater choice of acceleration trajectories, together with a larger selection of gap sizes, would require a longer ramp length and a larger ramp-vehicle travel time. Thus, in the selection of these parameters one must consider the tradeoff between the flexibility and capability of the system on one hand, and the cost and system throughput on the other hand. In this study, a ramp length of 1300 ft appears to be reasonable, for such a choice would enable the vehicle to initially account for a disturbance force of $\pm 140$ lbs and an initial gap variation
Fig. 29—Selected ideal and non-ideal acceleration trajectories for $V_s = 102.6$ ft/sec and (a) $D = 1200$ ft, and (b) $D = 1300$ ft.
of ±0.5 sec for a maximum merging speed of 102.6 ft/sec.

Next consider the effects of vehicle parameters \((K_g, K_o, \text{and } K_a K_c)\) on system performance variability. The velocity and distance deviations due to external perturbation forces are given by Eqns. (37) and (38), respectively. Note that as time increases, \(v_d\) approaches \(K_A d\) and \(x_d\) is approximated by \(K_A d t\). Thus, one should select \(K_d\) as small as practical. The selection of an appropriate value is, in part, constrained by the physical properties of the vehicle, for note from Eqns. (24) and (34) that a small \(K_d\) implies a small \(K_a K_c\). Since the latter is associated with vehicle response capabilities, it is clear that it cannot be selected arbitrarily. In this simulation study it is convenient to use the values of 0.5 sec, 3, and 1 for \(K_a K_c, K_g\) and \(K_o\); respectively. This choice is based on values of \(T, K, \text{and } \delta\) of 20.47 sec, 1.72, and 10, respectively, which are values obtained experimentally from the test vehicle used in a later phase of this study.

2. The Basic Computer Program

A flow diagram of the simulation model is shown in Fig. 30. For each simulation run, the initial input to the system consisted of \(D, V_s, T_m, A_d\), and \(v_o\). The program generated a control function corresponding to the given inputs and specified acceleration constraints and initiated the merging maneuver. The state of the vehicle was checked at every \(T_s\) sec and updated, when necessary. The simulation output consists of \(a(t), v(t), \text{and } x(t)\). If at a checkpoint, the required acceleration

\[\text{It should be noted that the disturbance could be inserted at any time from } 0 \text{ to } T_m.\]
Fig. 30—A flow-diagram representation of the merging-vehicle simulation model.
trajectory exceeded the limiting curve (see Fig. 22), then the best attainable trajectory was selected. If this occurred, no further updating was possible, unless the required acceleration decreased to within its attainable limit. In such cases, the vehicle would be allowed to travel to the merge point (if the merge point were also the insertion point, then the vehicle would travel to the last checkpoint as shown in Fig. 27), where its state would be measured for the last time; subsequently it was inserted into the traffic stream if its state with respect to that stream were acceptable; otherwise the merge was aborted.

A Fortran program corresponding to the flow diagram in Fig. 30 is listed in Appendix A.

D. Simulation Results

The following situations were considered in this study:

(1) A disturbance force continuously acting on the merging vehicle;

(2) A suddenly discrete change in the state of mainstream gap; and

(3) Controller operation for merging vehicles with a nonzero initial velocity and the effects of disturbance forces on such operations.

It was previously noted that the system was designed for a maximum merging velocity of 102.6 ft/sec with $D = 1300$ ft. Therefore, the situations enumerated should be studied using these design values. However, as is subsequently discussed in Chapter IV, when full-scale highway tests of this system were undertaken, it was necessary to limit operations
to a ramp of 1200 ft in length and a maximum merging speed of $V_s = 69.6$ ft/sec. Thus, so as to adequately evaluate and compare the simulation data with full-scale data collected under corresponding conditions, it was decided to use these latter parameters in the simulation study. It should be noted, however, that results of a similar study for $V_s = 102.6$ ft/sec and $D = 1300$ ft are presented in Appendix B. In both cases, the vehicle parameters and the control algorithm were identical.

Although the data contained here do not pertain to all possible situations, or cover the whole range of terminal merging speeds ($44 - 102.6$ ft/sec), a sufficient number of cases are considered so that one would be able to extrapolate from the presented results to other situations.

1. System Response to a Continuously Acting Disturbance Force

The effects of both an opposing and an assisting continuously acting, perturbation force on the merging vehicle are considered here. It is assumed that the control logic is unaware of the existence of such a force and hence it is not accounted for in the selection of any of the "selected" trajectories. Thus, the logic can only respond to, and hopefully correct, errors introduced by that force. Further, it is assumed that the merging time ($T_m = 25.9$ sec) would remain invariant (i.e., no mainstream gap-state change would occur) and the sampling time is 3 sec. This latter choice was identical to that made in subsequent full-scale testing, where a maximum of 15 checkpoints could be established using available instrumentation. Since $T_m$ was selected as 25.9 sec -- a natural consequence of choosing $D = 1200$ ft and $V_s = 69.6$ ft/sec -- it was not
possible to choose $T_g = 1$ sec. By the choice of $T_g = 3$ sec rather than 2 sec, it was intended to emphasize the effectiveness of the system in compensating for disturbance forces even if $T_g$ were as large as 3 sec.

The effects of a continuously acting 140 lbs "opposing" disturbance force on the merging vehicle is shown in Fig. 31, where the selected acceleration, the actual acceleration, together with the corresponding velocity and distance traveled are plotted versus time. Note from Fig. 31a that, because of the existing retarding force, the vehicle acceleration was increased at each checkpoint. The result of such system updating is the relatively small velocity and distance deviations shown in Figs. 31a and 31b -- an error of less than 1 ft/sec at the checkpoints and a 1.6 ft/sec deviation between $v(T_m)$ and $V_m$. The corresponding distance errors at each checkpoint were all less than 1.5 ft, and the deviation between $x(T_m)$ and $D$ was less than 1 ft as is depicted on Fig. 31c.

The effects of an "assisting" force on the merging vehicle is shown in Fig. 32. As shown, the vehicle acceleration was decreased at each checkpoint so as to adjust the vehicle's final state to the required merging state. An examination of Figs. 32b and 32c indicate that the velocity and headway deviations at the checkpoints were less than 1 ft/sec and 1.5 ft, respectively and the errors in $v(T_m)$ and $x(T_m)$ with respect to $V_m$ and $D$ were some 1 ft/sec and 1 ft, respectively.

It is clear that if the disturbance force acting on the vehicle were to decrease or increase, the deviations in the vehicle state both at the checkpoints and on the merge point would change, accordingly. For example, if the vehicle were subject to a 90 lb "assisting" perturbation force (instead of 140 lbs), then at all times the velocity and distance
Fig. 31—Acceleration, velocity, and distance traveled of a merging vehicle subject to a continuously acting 140 lb "opposing" disturbance force.
Fig. 32—Acceleration, velocity, and distance traveled of a merging vehicle subject to a continuously acting 140 lb "assisting" disturbance force.
deviation would remain less than 1 ft/sec and 1 ft, respectively.

The data presented here and those contained in Appendix B indicate that the system response to a continuously acting disturbance force is precise and very effective. In all cases considered, both the final velocity and distance deviations were less than some 1.5 ft/sec and 1.5 ft, respectively. The data presented in Appendix B (for \( V_g = 102.6 \) ft/sec and \( D = 1300 \) ft), show that when \( T_g \) increases from 1 to 3 sec, the errors in \( v \) and \( x \) also slightly increase, but are still within the bounds mentioned above. Thus, the system, when updated, responds very effectively to the continuously acting disturbance forces and with a sampling time in the range of 1-3 sec, there would only be negligible errors in the merging state of the vehicle.

2. System Response to a Discrete Gap-State Change

Consider next the response of a merging vehicle to changes in the state of the mainstream gap. As pointed out earlier, any gap-state change would be communicated to the ramp vehicle only at the checkpoints in the form of changes in both gap speed and gap arrival time. If such deviations were to occur, then appropriate action must be taken to either adjust the vehicle's state to an acceptable merging state or abort the merging maneuver.

In order to determine the effects of sudden gap errors on the merging operation, three cases were considered. First, various gap-speed variations together with the associated changes in gap arrival time were introduced at various times during a merging operation. Then this process was repeated for different \( T_g \) and finally, cases where a vehicle was
not notified about a gap-state change until some time after it had occurred.

Consider a case in which a vehicle were initially required to travel a 1200 ft ramp in $T_m = 25.9$ sec and reach a merge velocity of 69.6 ft/sec. Twenty seconds after the merge was initiated, a discrete change of 4.4 ft/sec in the gap speed occurred, and the vehicle was thus required to change its target velocity to $V_m = 65.2$ ft/sec and $T_m$ to $T_m = 26.3$ sec. The corresponding velocity and distance traveled trajectories are shown in Figs. 33a and 33b. Note that when the change in gap state occurred, the system was updated, with this updating occurring every $T_s = 1$ sec until the vehicle reached the merge point at $t = T_m'$. The system responded so effectively in this case that the resulting vehicle velocity at merging was within 0.1 ft/sec of the desired value, and there was no deviation in $x(T_m')$.

The same gap change was also introduced at later times in the merging process -- 23 and 25 secs -- and the resulting system trajectories are also pictured in Fig. 33. The changes in $T_m$ were to $T_m' = 26.1$ and $T_m' = 26.0$, respectively. The corresponding final velocity deviations were 2.8 ft/sec and 4.6 ft/sec and the deviations in $x(T_m')$ were 9.3 ft and 4.1 ft, respectively -- clear evidence of the detrimental effects of such a change near the end of the merging maneuver. It should now be clear that if such a change were introduced for $t < 20$ (and $T_s = 1$ sec), the system would effectively compensate for it.

Note that if the size of the discrete changes in the gap were to increase or decrease, the errors in the vehicle state at the merging time would vary accordingly. For example, a gap-speed reduction of 1.46
Fig. 33—Velocity and distance traveled trajectories of a merging vehicle subject to a sudden 4.4 ft/sec gap-speed reduction at different times during a merging operation.
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ft/sec (1 mph) would not involve any errors in $v(T_m)$ and $x(T_m)$ if this error were not introduced later than $t = 24$ and if this gap error were to occur at this time, it would involve a 1 ft/sec and a 1.6 ft deviation in $v(T_m)$ and $x(T_m)$, respectively.

Next consider the relation between $T_g$ and the errors caused by a sudden gap change. Typical data corresponding to a 4.4 ft/sec gap-speed reduction and a 0.4 sec gap arrival time delay occurring simultaneously at $t = 20$ is shown in Fig. 34. Here, the velocity and distance trajectories corresponding to $T_g = 1$ sec, $T_g = 3$ sec, and $T_g = 5$ sec are shown, together with the continuation of the initially selected velocity and distance trajectories. Note that both $v(T_m)$ and $x(T_m)$ increase as $T_g$ increases. For example, note from Fig. 34a that the velocity deviation is negligible for $T_g = 1$ and $T_g = 3$, but for $T_g = 5$, it increases to 0.8 ft/sec. The corresponding deviations in $x(T_m)$ were 0.0 ft, 3.7 ft, and 6.4 ft, respectively. This deviation would clearly be greater if a larger gap error were to occur. Thus, as discussed in Chapter II, the system would more effectively cope with discrete disturbance forces if a smaller $T_g$ were selected.

Next consider a case where a gap change occurs while the ramp vehicle is traveling between two checkpoints. The velocity and distance-traveled trajectories of a merging vehicle subjected to a 4.4 ft/sec gap speed reduction at $t = 20+$ are shown in Fig. 35. System updating did not occur for 1, 2, or 4 sec (depending on $T_g$), and one should note that both velocity and distance errors increase as $T_g$ is increased. For example, if the gap error were to occur and be detected at $t = 20$, with a $T_g = 1$ sec, the vehicle would be able to perfectly adjust its final state
Fig. 34—Velocity and distance traveled of a merging vehicle subject to a sudden 4.4 ft/sec gap-speed reduction for $T_s = 1$ sec, $T_s = 3$ sec, and $T_s = 5$ sec.
Fig. 35—Velocity and distance traveled trajectories of a merging vehicle subject to an equal 4.4 ft/sec gap-speed reduction and .4 sec gap delay at different times during a merging operation.
to the desired one. However, if the vehicle were not notified of the gap error that occurred at \( t = 20 \) until \( t = 24 \), then with \( T_s = 4 \) sec its final velocity and distance traveled would involve errors of 4.54 ft/sec and 26.68 ft, respectively. Thus, it seems essential that the gap changes be communicated to the vehicle as frequently as possible.

From the data presented here, one concludes that the system can, to a high degree, compensate for gap-state changes if these errors occurred toward the beginning of a merging operation. The system is less capable of accounting for very large and/or very "late" gap changes, for the available acceleration of the vehicle is limited. Also, the system responds more effectively to sudden gap changes if a smaller checkpoint-sampling time \( (T_s) \) were used.

3. Controller Operation for Vehicles with Nonzero Initial Velocity

Consider a situation where upon the arrival of a ramp vehicle at the control station, an appropriate gap for merging would be available if the vehicle were to continue without stopping; i.e., the merging vehicle would have a nonzero initial velocity. The control computer, which would determine the availability of such a gap, would calculate an acceleration trajectory (see Eqns. (12) and (13)) for the merging vehicle.

Consider the situations depicted in Fig. 36 which illustrates two merging situations -- one with \( v_o = 0 \), and a second with \( v_o = 44 \) ft/sec. The required merging speed is 69.6 ft/sec, which would ideally be reached by the initially stationary vehicle in 25.9 sec and in 20 sec by the initially moving one. Note from Fig. 36a that, where \( v_o = 44 \) ft/sec, the required initial acceleration is considerably smaller and \( a_f \) is
Fig. 36--Comparison of the selected acceleration, velocity, distance traveled trajectories of a merging vehicle with $v_o = 0$ ft/sec and $v_o = 44$ ft/sec.
slightly larger than their counterparts when $v_o = 0 \text{ ft/sec}$. As a result of this relatively small slope, the velocity of the moving ramp vehicle changed very slowly as shown in Fig. 36b. There was no difficulty in reaching the desired merging state as can be seen from this figure and Fig. 36c.

Next compare the effects of a continuously acting disturbance force with those noted earlier for a stationary vehicle merging. The merging vehicle, with $v_o = 44 \text{ ft/sec}$, was subjected to a 140 lb "opposing" force and its response was calculated with the result shown in Fig. 37. In comparison with Fig. 31a, a relatively smaller and flatter acceleration trajectory was required. However, at the checkpoints, relatively large acceleration changes -- up to $3.5 \text{ ft/sec}^2$ -- were required to overcome the effects of the disturbance force. A velocity deviation of $1.2 \text{ ft/sec}$ was present at the merge point together with a corresponding deviation in $x(T_m)$ of 1 ft per Fig. 37c. These deviations resulted from the constraint of $-1 \text{ ft/sec}^2$ which was placed on the acceleration trajectory at $t = 15 \text{ sec}$. At this point an interesting possible tradeoff is noted; if $a(t)$ were permitted to decrease to less than $-1 \text{ ft/sec}^2$, the merging conditions could be met. However, this would increase the jerk levels at the end of the merge with some possible resulting passenger discomfort.

Alternatively, deviations could be reduced by the selection of a smaller $T_s$. Typical data for the case where $T_s = 1 \text{ sec}$ with $v_o = 44 \text{ ft/sec}$ is shown in Fig. 38. Note that the required acceleration changes at the checkpoints are noticeably smaller and a flatter acceleration is maintained. Also, the deviations in $v(T_m)$ and $x(T_m)$ were reduced from
Fig. 37—Acceleration, velocity, and distance traveled of a merging vehicle subject to a 140 lb "retarding" disturbance force, with $v_0 = 44 \text{ ft/sec}$ and $T_s = 3 \text{ sec}$. 

Note that trajectory if continued terminates at $-1 \text{ ft/sec}^2$. 

(a) 

(b) 

(c)
Fig. 38—Acceleration, velocity, and distance traveled of a merging vehicle subject to a 140 lb "retarding" disturbance force, with $v_0 = 44$ ft/sec and $T_s = 1$ sec.
1.2 ft/sec and 1 ft to 0.8 ft/sec and 0.1 ft, respectively. Thus, if a smaller $T_s$ were selected, more effective system response would result. Here, it should also be noted that the system response would be improved if the initial velocity were to be smaller.

E. Summary

A detailed examination of the merging process was accomplished via computer simulation. First, various relationships between the ramp length and merging vehicle travel time were developed which were consistent with various dynamic limitations of a typical American sedan. The system performance variability under various continuously acting disturbance forces and discrete mainstream gap-state changes were studied, and the use of the proposed controller for merging vehicles with nonzero initial velocities was also investigated.

Although the simulation data presented here has proved the validity of the selected theoretical model, it should be supplemented with corresponding on-road test data. The collection and evaluation of such data are discussed in the next chapter.
A. Introduction

In this chapter, the basic theory, analysis, and general system requirements discussed in Chapters II and III are incorporated into the design of a practical ramp-vehicle merging control system. This was laboratory tested and subsequently installed onboard an instrumented vehicle for full-scale road testing. The results of this testing are reported in this chapter.

B. Experimental Overview

The required physical layout for merging system operation was depicted in Fig. 20, which shows a control station as having control over the merging maneuver. Specifically, information from the mainstream traffic, the environment and the merging ramp vehicles would be communicated to a digital computer in this station, which would compare the latter vehicles' states against their desired states and compute whatever changes in the corresponding acceleration trajectories would be necessary for each vehicle to arrive at the merge point in the proper state. The necessary change(s) would be transmitted to each vehicle as it passed each checkpoint.
It is clear that complete full-scale testing of this system would require at least the following:

1. Vehicle detectors and other instrumentation in the mainstream traffic lane;
2. Instrumentation in the merging ramp;
3. A road-computer-vehicle communication system; and
4. A digital computer at roadside.

Unfortunately, such facilities were not available when the system of interest here was tested; therefore, it was necessary to use an approach which was used by Blackwell and Bender and Fenton in earlier vehicle tests.

In essence, this approach consisted of representing all vehicles external to the one being tested by voltage signals. If this were done, and the control computer were located onboard the test vehicle, then the merging operation could be studied by simply using the one vehicle and a limited quantity of external instrumentation. This approach, which has been referred to as the "phantom-car" approach to testing, was used in the present study.

In this context, the initial goal of this study was the design and implementation of a merging controller which would function for mainstream traffic speeds in the range from 44 to 102.6 ft/sec. However, shortly before the experimental work started, a long section of unopened highway, on which it had been planned to conduct tests, became unavailable, and it became necessary to test on a much shorter section. In addition, various physical limitations of available measuring equipment,
made it essential that tests not be conducted above 80 ft/sec. For these reasons, the system designed and tested was intended to merge a vehicle at a stream speed of 69.6 ft/sec using a ramp length of 1200 ft. Subsequently, this speed was changed to 55.7 ft/sec for reasons discussed later.

C. Instrumentation and Design

It is convenient to consider the physical testing as being comprised of three related entities — the test vehicle and its instrumentation, the merging control system and the test roadway. Each of these are considered in turn.

1. Test Vehicle Instrumentation

An instrumented 1965 Plymouth Sedan was used in testing the merging control system. The three main control functions — braking, acceleration, and steering — were accomplished using electrohydraulic control systems. The steering wheel and accelerator pedal were removed; however, as a safety precaution, the hydraulic brake actuator was connected such that it engaged the brake-pedal assembly. The original brakes were thus intact and available for emergency use. When necessary, the vehicle was manually controlled via a control stick which was mounted to the right of the driver.

A hybrid computer and the necessary circuitry was also installed in the test vehicle as shown in Fig. 39. The computer consisted of 15 potentiometers, 4 function switches, a network of NAND logic, and 20 solid-state operational amplifiers. The computer control circuitry —
Fig. 39—Onboard analog computer mounted on a rack in the rear seat of the test vehicle.
integrated-circuit logic units, semiconductor switches, and relay drivers — performed any required logic operations. The computing elements were also used both for system compensation (per the discussion in Chapter II) and in data collection.

Normally, all necessary information pertaining to the state of the merging vehicle would be derived from instrumentation in the ramp. As previously noted, however, such instrumentation was not available, and it was necessary to use vehicle-mounted equipment for this task. This consisted of the 5th wheel shown in Fig. 40, which together with circuitry developed by Dodds, provided the necessary state information — \( a(t) \), \( v(t) \) and \( x(t) \) — during a merging maneuver. The vehicle was also equipped with a six-channel, strip-chart recorder for recording performance data.

Note from Fig. 39 that the analog computer was mounted in a rack over the left half of the rear seat and all the other computational and sensing circuitry, together with the chart recorder were installed on the right half of the front seat. The computer, control circuitry, and recorder were all located so that they could be easily operated by the experimenter from the right-rear seat.

2. Merging Control System

It is envisioned that the heart of this system would be a digital computer located adjacent to the merging area. Here, as previously noted, it was necessary to incorporate all of the decision-making logic into the vehicle and utilize the phantom-car approach.

In terms of the single-vehicle merge considered here, it is
Fig. 40—Instrumented vehicle equipped with the 5th wheel.
necessary to implement the merging control algorithm given in Eqns. (12) and (13), which are repeated here for convenience:

\[
a_i = \frac{6(D + 2v_m + 2v)(T_m - t)}{(T_m - t)^3} \quad 0 \leq t \leq T_m
\]  \hspace{1cm} (12)

\[
a_f = \frac{2(v_m - v)}{T_m - t} - a_i
\]  \hspace{1cm} (13)

A block-diagram representation of this algorithm is shown in Fig. 41. It seems worthwhile to now consider its operation in some detail.

The state of the vehicle — \( a(t) \), \( v(t) \) and \( x(t) \) — was obtained via the 5th wheel and some associated circuitry. Specifically, an optical shaft encoder was coupled to the axle of this wheel, and its pulsed output comprised the input to some computational circuits. The vehicle speed was directly proportional to the number of output pulses per second, \( a(t) \) was obtained by continuously subtracting two averaged successive values of \( v(t) \) over a 0.1 sec time period, and \( x(t) \) was obtained via a pulse-counting procedure.

Note from Fig. 41 that \( v(t) \), \( x(t) \), \( D \), \( v_m \) and \( T_R \) \( (T_m - t = T_R \), the time remaining to the desired merge time) comprised the inputs to a second circuit which calculated \( a_i \) in accordance with Eqn. (12). Here \( T_R \) was obtained via a free-running integrator which had an initial value of \( T_m \). The calculated value of \( a_i \) was then used, together with \( v \), \( v_m \), and \( T_R \) to generate the slope \( (a_i - a_f)/T_R \) of the required acceleration trajectory. Note from Eqn. (13) that
Fig. 41—Operational block diagram implementing the control algorithm of a merging vehicle.
Both \( a_i \) and \( (a_i - a_f)/T_r \) are computed at each checkpoint, and, of course, remain fixed at least until the next checkpoint were reached. This is accomplished via the two sample-and-hold circuits which clamp their respective inputs to the values computed at the previous checkpoint.*

The sampled values of \( a_i \) and \( (a_i - a_f)/T_r \) comprised the input to a circuit which generated the required acceleration trajectory \( a_v \). This signal was then compared with the measured vehicle acceleration \( a_v \) to provide a command signal \( A \) to the vehicle. If a deviation were to occur in the vehicle state, then a modified acceleration trajectory \( a_{v'} \) would be selected at the next checkpoint; otherwise, the vehicle would continue on its previously selected trajectory.

3. Practical Circuit Considerations

Since the measurement and computational circuits used here were comprised of analog elements, they embodied the inherent inaccuracies and physical limitations associated with such elements. As a result, the voltage equivalents of \( D, V_m, \) and \( T_m \) had to be constrained in accordance with the limitations on the power supply, operational amplifiers, and analog dividers. For example, since the effective dynamic range of available dividers was limited to \( 1 - 10 \) volts, then the choice of a volt-

\[
a_i - a_f = 2a_i - 2\frac{(V_m - \nu)}{T_r}
\]

*These circuits were designed to have sample-and-hold times in the range from 1 to 8 sec, and the control signal \( c \) was provided by the logic circuitry which also provided the start-stop indications for the merging operation. In addition, a digital counter could provide as many as 15 samples; i.e., as many as 15 checkpoints during a merging operation.
age-to-time scale was sharply limited. For example, if $T_m$ were specified to be 30 sec, then 1 volt would correspond to 3 sec. However, if this were the case, then errors would result in the division process for $T_r < 3$ sec (1 volt) — as there are four divisions by $T_r$ per Fig. 41 and Eqns. (12) and (13). Such errors can cause much larger errors in the selection of the desired acceleration trajectory at a checkpoint.* Further, because of the dynamic limitations of system operational amplifiers and the available measurement circuitry, the ramp length was represented by a voltage signal not exceeding 12 volts.

It is also noted that care was required in selecting the parameters associated with the vehicle control system (see Fig. 18). Following Bender and Fenton, $K$ and $T$ were assumed to be 1.72 and 20.47, respectively. This left the choice of $K_aK_c$, $K_g$ and $K_o$ to be made. The following two sets of these parameters were empirically chosen, and both resulted in satisfactory vehicle performance as is subsequently described:

$$K_aK_c = 0.5 \text{ sec} \quad K_aK_c = 0.25$$

$$K_g = 3 \quad \text{and}\quad K_g = 5$$

$$K_o = 1 \quad K_o = 1.$$  

*In laboratory tests of both the dividers used here, and other commercially available dividers, it was noted that offset errors as high as 300 mv and gain errors of 8% were not uncommon. Such errors would become quite important toward the end of a merging operation when the divisor $T_r$ approaches zero; clearly, the resulting errors could be excessive. The obvious solution to this problem, and one that will be incorporated into subsequent testing activities, involves the use of digital computational circuitry.
4. Test Roadways

The roadway used for testing was a section of Interstate Freeway 270 in Columbus, Ohio which was not open to public use. This roadway was located in relatively open country so that wind and other environmental forces could freely act on the merging vehicle. In addition, the section of the road available had a 2% grade which in effect constituted a continuously acting opposing or assisting force on the vehicle.

D. Experimental Studies -- Pilot Study

The experimental studies were comprised of two parts. The first was a pilot study, the purpose of which was to check out the system installed in the vehicle, and the second was a full-scale study of a merging maneuver. The former consisted of two parts -- an examination of the performance of the merging control circuitry with the test vehicle at standstill and subsequent testing of the 5th-wheel and its associated circuits for determining $a(t)$, $v(t)$ and $x(t)$ with the vehicle in motion.

To test the former, a merging situation was simulated wherein $D = 1200$ ft, $V_m = 69.6$ ft/sec, and $T_m = 25.9$ sec. The sampling time was chosen as 3 sec, and it was assumed that no environmental disturbances were present. The dynamics of the merging vehicle were simulated on the onboard computer in the vehicle (see Fig. 42), and the "vehicle" outputs were used as inputs to the control circuitry shown in Fig. 41. The output of the latter ($a_y$) was the input to the merging vehicle dynamics as can be noted from an examination of Fig. 41. The expected values of velocity ($v$) and distance ($s$) were obtained from this quantity by simple integration.
The theoretical acceleration trajectory for the merging situation defined here can be obtained from Eqn. (1), and the result is plotted in Fig. 43a. Typical data are also shown here (Figs. 43b, c, d and e) with $a_v$, $v$, $s$ and $T_r$ plotted versus time. Note that $a_v(t)$ closely corresponds to $a(t)$ everywhere, but at the last two checkpoints where $T_r$ (the denominator of the dividers shown in Fig. 39) became too small to have an accurate divider output. To partially overcome this problem, time scale factors were reduced by as much as possible ($1\text{ volt} = 2.5\text{ sec}$) and also it was decided not to update the system when $T_r$ became small.

The important ramifications of this decision are discussed later in this

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*The manufacturers' specifications on these dividers specify that the denominator should be greater than 1 volt for a divider accuracy of ±1%. In laboratory tests of the dividers, however, it was found that when the denominator was near one volt, an error of up to ±8% could occur in the divider output. Note from Fig. 43b, that at the last checkpoint, $T_r = 2\text{ sec}$, which corresponded to 0.8 volts, a large and unwanted change in the command acceleration occurred.*
Fig. 43—Laboratory test result of the control circuitry.
In the second part of the pilot study, the performance of the 5th wheel and its associated circuitry for obtaining \( a(t) \), \( x(t) \) and \( v(t) \) was examined via the following procedure. The test vehicle, which was initially at rest, was started by applying a step command signal to the vehicle and measuring \( a \), \( A \), and \( v \). In addition, the velocity of the vehicle \( (v^*_t) \) was obtained from a tachometer, which was coupled to the driveshaft.

The data obtained from a typical run are shown in Fig. 44, where \( a(t) \), \( v(t) \), \( v^*_t(t) \), \( A(t) \) and the command step input are plotted versus time. First note the digitized acceleration function which is quite noisy (Fig. 44a). Next note that the two curves closely approximated one another once some 6 seconds had elapsed and the effects of acceleration noise were not as noticeable. In essence, adequate, but not error-free, signals can be obtained from this circuitry; consequently one should expect this to contribute errors to the system output under full-scale testing.

E. Experimental Studies -- Full-Scale Study

1. Experimental Design

It was initially desired to conduct a wide variety of on-road tests -- many of which would be in 1:1 correspondence with those previously performed in the laboratory. However, this was not accomplished for several reasons -- not the least of which was the simultaneous advent of both cold winter weather and major problems with some equipment in the vehicle -- and thus only an abbreviated preliminary test program
Fig. 44—Dynamic test result of the measurement circuitry.
was undertaken.

Data were collected under two sets of conditions as shown in Table 3. These cases are defined and the number of runs for each condition are listed. These were collected from tests in both directions on a highway with a nearly continuous 2% grade; thus, the response of the system with both an aiding and opposing "disturbance" force present could be examined.

After data were collected for these conditions, a failure occurred in the circuit for obtaining $a(t)$, $v(t)$ and $x(t)$ from the 5th wheel. Subsequently, this circuit was repaired to the extent, that testing could be resumed for a lower merging speed, and it was decided to continue testing; however, no additional useful data were obtained, because of repeated circuit failures.

**TABLE 3**

NUMBER OF FULL-SCALE RUNS FOR EACH CONDITION

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Merging Parameters</th>
<th>$T_s$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>
| 1       | $D = 1200 \text{ ft}$
          | $V_m = 69.6 \text{ ft/sec}$
          | $T_m = 25.9 \text{ sec}$ | 2 | 4 | 2 | 3 |
| 2       | $D = 1200 \text{ ft}^*$
          | $V_m = 69.6 \text{ ft/sec}$
          | $T_m = 25.9 \text{ sec}$ | - | 5 | 2 |

*The parameters associated with the vehicle compensation and feedback circuits were $K_{ac} = 0.5$, $K_g = 3$ and $K_o = 1$ for this case (see Fig. 18).
2. Experimental Procedure

The physical setup for system testing was as depicted in Fig. 45 below. The test vehicle, which was initially at standstill was positioned at one end of the available section of highway. The experimenter, who was inside of this vehicle, would set $D$, $V_m$ and $T_m$ to the values selected for that run, and also program the computer so that any planned changes in the merging situation (e.g., a sudden change in the gap length) could be inserted at the proper time during the merging maneuver.

![Diagram](image)

Fig. 45—Physical layout of test roadway.

The longitudinal control of the vehicle would next be turned over to the automatic system; however, vehicle lateral control was always achieved manually via the side-mounted control stick shown in Fig. 46. The merging operation was next initiated and the required data -- $a(t)$, $v(t)$ and $x(t)$ -- recorded on the strip-chart recorder until $t > T_m$. The experimenter would then regain complete manual control of
the vehicle. The vehicle was now turned in the opposite direction and prepared for a test run in this direction.

3. Experimental Results

Typical on-road test data corresponding to Set 2 (see Table 3) with $T_s = 3$ sec and an assisting grade "force" are shown in Fig. 47, where $a$, $a_v$, $v$, and $x$ are plotted versus time together with the corresponding theoretical calculated functions $v$ and $x$ which are superimposed on the recorded data. It is worth considering this figure in some detail. First note that at low speeds the acceleration output (Fig. 47a) is quite noisy and, as a result, both $v(t)$ and $x(t)$ are slightly larger than their expected values. The resulting error was
Fig. 47—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_s = 3$ sec.
detected at the first checkpoint \((t = 3 \text{ sec})\), and as one can note from Fig. 47b, an acceleration trajectory with a lesser amplitude was selected. It is important to note that subsequently, the system repeatedly selected similar trajectories so as to overcome the effects of the continuously acting assisting grade force. This is clearly evident toward the end of the merging operation where at the seventh checkpoint a negative initial acceleration was chosen. Note that, in accordance with previous discussion, system updating was not accomplished at the eighth checkpoint \((t = 24 \text{ sec})\) because of the associated small value of \(T_r\) and anticipated unpredictable behavior of the analog dividers. Instead, the trajectory chosen at the seventh checkpoint was simply "extended" to \(T_m\). An examination of Figs. 47c and 47d at this time shows that a final velocity error of some \(3 \text{ ft/sec}\) and a distance deviation of less than \(5 \text{ ft}\) resulted. It is interesting to note that such accuracy can be achieved despite the erratically varying estimate of vehicle acceleration which was available (Fig. 47a).

In a nearly identical situation (Set 2 with \(T_g = 3 \text{ sec}\)), a test was performed when an opposing grade "force" was present with the results shown in Fig. 48. The same erratic behavior in \(a(t)\) (Fig. 48a) is again evident, with one result of this being that the initial values of \(v\) and \(x\) were slightly greater than desired. An appropriate "downward" correction was made in the acceleration function. Note also that very little correction was required at the next 5 checkpoints in spite of the continuously acting opposing force. However, at the seventh checkpoint, it was necessary to make the shown "upward" correction, which was required, at least in part, to account for this force. This
Fig. 48—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_g = 3$ sec.
last trajectory was, as in the previous case, extended to the merging time.

It is interesting to note that data were collected from an essentially identical merging situation except that 8 instead of 7 checkpoints were used.* These data, which are contained in Appendix C, clearly show the undesired, and indeed unpredictable, behavior of $a_v$ between the seventh and eighth checkpoints.

In order to demonstrate the effect of a larger sampling time on system performance, typical on-road data for $T_s = 7$ sec and a continuously acting 2% grade force is shown in Fig. 49. The expected vehicle response under the same merging condition is superimposed on the experimental data. As predicted in the simulation studies of Chapter III, the required changes in the acceleration at the checkpoints are considerably greater than those already examined as can be seen from Fig. 49b. In other respects however, the same conditions previously noted are also present here — considerable variability in $a(t)$, initial errors in $v(t)$ and $x(t)$, and a predictable lag in response at the last checkpoint. The errors at $t = T_m$ in velocity and distance traveled were 4 ft/sec and 40 ft, respectively. Similar data for $T_s = 2$ sec and $T_s = 4$ sec are contained in Appendix C. Essentially, the same effects as noted here were also present in these data.

After the data thus far discussed were collected, the measure-

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*These data were collected for the following parameter values which are defined in Fig. 18: $K_a K_c = 0.25$, $K_o = 1$, and $K_g = 5$. However, system performance here was essentially the same for this and the other set previously specified.
Fig. 49—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_g = 7$ sec.
ment circuitry associated with the 5th wheel failed, with the results shown in Fig. 50. Note the degradation of both $a(t)$ and $a_v(t)$ relative to that shown in Figs. 47 - 49. The resulting velocity-versus-time relation (see Fig. 50c) is quite erratic — especially as $t \to T_m$, which resulted in sizeable errors in the vehicle's state at $t = T_m$. An attempt was made to repair the afflicted circuit; however, subsequent data collection was essentially unsuccessful. Therefore, collection of additional data was deferred until a later date.

F. System Performance Near the Merging Point

A block-diagram representation of the proposed merging controller was shown in Fig. 17. Note from this figure that the system is, in essence, an acceleration controller, hence, in non-ideal situations, the velocity and distance traveled by the merging vehicle would tend to deviate from the desired values — especially in the presence of disturbance forces. The deviations for the case of a constant disturbance force were previously derived and are repeated here for convenience:

\[
v_d(t) = k_d A_d \left( 1 - e^{-t/T_d} \right)
\]  

(37)

\[
x_d(t) = k_d A_d t - k_d A_d T_d \left( 1 - e^{-t/T_d} \right)
\]  

(38)

Note that as time increases, $v_d$ approaches $k_d A_d$ and $x_d$ approximates $k_d A_d t$. Thus, near the end of a merging operation, the magnitude of $v_d$ and $x_d$ could be excessive if the time difference between the last updating point and the merge point were large; i.e., if $T_r$ were large. Thus, to insure
Fig. 50—On-road test data indicating measurement circuitry failure.
a small value of $T_r$ for all merging situations with different merging times, a small sampling rate must be selected so that a small value of $v_d$ and $x_d$ would be expected at $t = T_m$.

The effects on system response of a large $T_r$ can be clearly envisioned if one considers a merging situation with $T_m = 25.9$ sec and two different sampling rates -- $T_s = 1$ sec and $T_s = 7$ sec. If the vehicle parameters were selected to be set no. 1 (see Table 3), and it were assumed that $F_d = 140$ lbs, then in the former case, $T_r$ would be $0.9$ ($T_r = 25.9 - 25(1) = 0.9$) and a velocity and distance deviation of $0.49$ ft/sec and $0.25$ ft, respectively would result. In the latter case $T_r$ would be $4.9$ and $v_d$ and $x_d$ would be $0.89$ ft/sec and $3.4$ ft, respectively at $t = T_m$. Therefore, if the system updating at the final check-point were eliminated, a large velocity and distance deviation could result especially if $T_r$ were large.

This undesirable result would be enhanced if a sudden mainstream gap change were to occur between the last system updating and the merge time. In many such cases, the merging maneuver would have to be aborted if the error were excessive. Therefore, to overcome this problem, the free-running time from the last updating point to the merge point must be minimized. This would require a $T_n$, which in turn, would mean a smaller value of $T_r$ at the last checkpoint. Alternatively, an intermediate value of $T_s$ could be used -- say $T_s = 5$ sec with $n = 5$ -- so as to reduce $T_r$; however such a choice, as previously noted, could result in undesirably large changes in acceleration at the intermediate checkpoints.
A system capable of merging both initially stopped and initially moving-ramp vehicles was designed and constructed. Subsequently, preliminary full-scale tests were performed and data were collected for several vehicle parameter combinations and highway conditions. These data were later compared with those obtained from previous simulation studies with results which were quite encouraging. In brief, the vehicle response was quite close to that predicted from the earlier studies. It was noted that the final state errors at $T_m$ were less than 4 ft/sec and 5 ft -- errors which could certainly be reduced by relatively straight-forward modifications in system design.

Although there is insufficient data available to fully evaluate this system, and indeed much more extensive full-scale tests would be required before such an evaluation could be made, it seems clear that the system as designed has considerable promise. Its inherent flexibility, its effective reaction to disturbance forces, and its relative simplicity make it a worthwhile candidate for such future evaluation.
CHAPTER V
SUMMARY AND CONCLUSION

Highway automation is one promising partial solution to some of the problems posed by an ever-increasing number of motor vehicles, as it could result in considerable improvement of highway traffic flow and a reduction of the number of highway accidents and fatalities. Other potential advantages of an automatic highway system are increased highway capacity, greater safety and reliability of operation, more predictable travel times, reduced driver effort and increased driver convenience.

One subsystem required by virtually all proposed highway automation schemes involves the automatic longitudinal control of vehicles merging into main-stream traffic. The nature of this control mode is extremely important, for it affects the maximum flow capacity of an automatic highway. In order to safely and efficiently achieve an optimum or near-optimum traffic flow rate, it is essential that the ramp vehicles merge in a precise and predictable manner with the moving traffic stream. Here, the system performance should be such that the merging maneuver is accomplished with a minimum disturbance to the main-stream traffic.

The objective of the research reported here is the development of an automatic longitudinal control system for safely and efficiently merging a ramp vehicle into a moving stream of automated traffic. An
ideal merge was first defined and the basic system requirements were enumerated. Various practical system constraints associated with an actual merging situation were enumerated together with the physical dynamic limitations of a typical passenger sedan. An approximate linear mathematical model of a merging vehicle together with a number of vehicle control algorithms were presented, analyzed, and compared. Some of the latter involved checking the state of a merging vehicle n times during the merging maneuver and correcting this state at such of these times as was required. An approach for specifying n was also presented.

A computer-simulation model of the proposed controller, which can be used for studying the system performance under diverse environmental and vehicular conditions, was developed. An analysis of the data obtained from this model revealed that the specified system could respond to fairly large environmental disturbances and/or sudden changes in the state of the mainstream traffic.

In addition, a practical counterpart of this system was designed, constructed, and preliminary testing was conducted under full-scale conditions. The results of these tests were compared with those obtained from both the simulation and the theoretical studies.

In all cases, the results of these studies compared favorably and clearly indicated the feasibility of such controller. Although there is insufficient data available to fully evaluate this system, and indeed much more extensive full-scale tests would be required before such an evaluation could be made, it seems clear that the system as designed has
considerable promise. Its inherent flexibility, its effective reaction
to disturbance forces, and its relative simplicity make it a worthwhile
candidate for such future evaluation.

It should be noted that this study was essentially a pre-
liminary one in which a primary goal was to establish the general feasibility of the selected approach. Thus, as noted, an exhaustive intensive study of all system behavior was not undertaken and clearly some problems remain unsolved. Hence, definitive conclusions as to the overall efficacy, accuracy, and reliability of the proposed merging controller can be drawn only after more extensive on-road testing under a wide variety of merging situations.

The automatic merging control system studied here, was basically concerned with the insertion of a single vehicle from a single lane ramp into a moving traffic stream at one specified point. However, it is believed that because of the high degree of flexibility and adaptability of the system, the controller action could be extended to merging k ramp vehicles simultaneously at either 1 or more insertion points.

It is clear that much theoretical and experimental work remains to be done to develop a fully operational system. This must include the following:

(1) More accurate methods of vehicle-state measurement should be developed;

(2) Computational accuracies must be increased; therefore, the need for a digital computer to replace the avail-
able analog circuits is essential;

(3) A better method of data recording is needed so that data can be more accurately read out;

(4) Additional experimental data must be collected in a wide variety of merging situations under many different roadway conditions;

(5) The problem of interfacing the ramp vehicle with the mainstream traffic must be carefully dealt with so that once the vehicle reached the merge point, it could be safely and quickly switched to the appropriate mode of both automatic longitudinal control and automatic lateral control;

(6) A reliable communication system must be developed so that a secure information transmitting and receiving channel is maintained between the subsystems of the merging control system; and

(7) A detailed study of the simultaneous control of k ramp vehicles.

It is believed that all the problems listed above can technically be solved. If so, it would appear that an excellent controller for the merging of ramp vehicles into mainstream traffic would result.

The potential of a system such as this is enormous. When perfected, control of the merging vehicle would be completely removed from the driver. Thus his slow perception and reaction times would be replaced by an extremely fast and reliable computer control system.
This would not only increase the safety of merging operations but also remove a primary impediment to smooth traffic flow. Further, this study was basically directed toward application to inter-city highway travel; however, since the proposed controller is capable of merging low-speed vehicles as well as high-speed ones, it could probably be effectively applied to both inter-city and intra-city freeways served by a dual-mode system.
APPENDIX A

COMPUTER PROGRAM

A listing of the Fortran program which was used to examine the system performance variability under different situations is contained in this appendix. Both continuously acting and discretely acting disturbance forces can be considered in this simulation.

Four primary functions are performed in this program: first, the required input information for the overall program is read into memory; second, the necessary calculations for determining the selected and actual value of vehicle state are performed; third, the best possible acceleration trajectory at each checkpoint is selected; and, finally, the calculated and the true values of the vehicle state at the checkpoints and at \( t = T_m \) are printed out.

The main program requires the following inputs:

- \( D \) ramp length
- \( VS \) gap speed
- \( TG \) gap arrival time from detection point to the merge point
- \( VO \) merging vehicle initial velocity
- \( TS \) checkpoint-sampling time
- \( KD \) vehicle parameter per equation (34)
- \( TD \) vehicle parameter per equation (35)
VDIN  velocity deviation due to initially known external disturbance forces
XDIN  distance deviation due to initially known external disturbance forces
TELCON elapsed time after merge initiation at which a continuously acting disturbance force is introduced
TEGROR elapsed time after merge initiation at which a sudden mainstream gap change is introduced
AD    disturbance acceleration per equation (33)
VDGAP  gap-speed change

The program listing is contained on the following pages.
INPUT THE DATA PERTAINING TO A MERGING SITUATION (THAT IS, SET D, VS, TG=12.6, 0.69, 6166, 25.9/

VM=VS
TM=1.6
V=V
X=0.2
TS=1.0
KD=2.75
TD=1.125
VDIN=2.2
XDIN=2.2
D1=VS/10
T=2.0
TELCON=0.0
TGEROR=0.2
MERPT=2.0

CALCULATE THE INITIAL VALUES OF AM, AI, AND AF,
AM=SORT(120, -16.78, V/17.68)
AI=6.0*(D+XDIN-X)/TM-2.0*(VM+VDIN+2.0*V)/TM
AF=2.0*(VM+VDIN-V)/TM-AI
A=AI
ATRUE=AI
WRITE(6, 1000)
FORMAT(1H0, 5X, 5HXCALC, 7X, 5HVTRUE, 7X, 15HVTRUE, 7X, 5HVCALC, 8X, 1HA, 8X, 2HTA, 28X, 2HAF, 9X, 1HT)

XCALC=X
XTRUE=X
VTRUE=V
VCALC=V
WRITE(6, 1010) XCALC, XTRUE, VTRUE, VTRUE, VCALC, A, AI, AF, T
FORMAT(1H0, 4(1X, F16.4), 4(1X, F8.3, 1X))
TT=TM-1
IF(T, L7, TELCON) GO TO 15

AD=+1.3

VE AND XE ARE THE VELOCITY AND DISTANCE ERRORS OF THE CLOSED-LOOP SYSTEM FROM T TO TM PROVIDED NO FURTHER UPDATING WOULD TAKE PLACE.
VE=KD*AD*(1.-EXP(-TT/TD))
XE=KD*AD*(TT-TD*(1.-EXP(-TT/TD)))
AITRUE=6.0*(D+XE-X)/TT-2.0*(VM+VE+2.0*V))/TT
AFTRUE=2.0*(VM+VE-V)/TT-AITRUE
SLOP=(AITRUE-AITRUE)/TT
138

SLOPE = (AI - AF) / TT

15 IF (MERPT.EQ.1, ) GO TO 50

C INCREMENT T BY TS (THAT IS, ADVANCE TO THE NEXT
C CHECKPOINT) AND COMPUTE THE VEHICLE STATE
C FOR BOTH WITH AND WITHOUT THE PRESENCE
C OF CONTINUOUS OR DISCRETE ERRORS.

20 T = T + TS

25 IF (T.GE.TM) GO TO 21

T = TS

GO TO 22

22 T = TT

MERPT = 1.

AREAL = AIREL - SLOPE * T

VINEW = V + AI * T1 - SLOPE * T1 * T1 / 2,

XINEW = X + V * T1 + AI * T1 * T1 / 2, - SLOPE * T1 * T1 / 6,

T0 = TD * (1, - EXP(-T1/1D))

T1 = K6 * (T1 - TO * (1, - EXP(-T1/1D)))

VNEW = VINEW + V0

XNEW = XINEW + XD

IF (MERPT.EQ.1, ) GO TO 200

IF (T, NE, TERROR) GO TO 30

V0GAP = -3.0

D2 = VS * T

VS = VS + V0GAP

TRG = (D1 - D2) / VS

VM = VS

TR = TRG

TM = T + TR

GO TO 35

30 TR = TM - T

35 DR = D - XNEW

VR = VM - YNEW

C COMPUTE THE REQUIRED ACCELERATION
C TRAJECTORY, IF IT EXCEEDS THE ATTAINABLE
C VALUE, SELECT THE BEST POSSIBLE ONE.

AM = SQRT((12.0 - 16.75 * VNEW / 17.68)

AFNEW = (6.0 * DR / TR - 2, * (VM + 2.0 * VNEW)) / TR

AFNEW = (2.0 * (2.0 * VM + VNEW) - 6.0 * DR / TR) / TR

IF (AFNEW.GE.AM) GO TO 43

IF (AFNEW.LE.-1.) GO TO 50

A1 = AFNEW

GO TO 120

40 AI = AM

GO TO 120

50 A1 = -1,

100 IF (AFNEW.GE.1.61) GO TO 60

IF (AFNEW.LE.-1.) GO TO 70

AF = AFNEW

GO TO 200

60 AF = 1.61
GO TO 200

70  AF=-1,
200  VI=VINew
     XI=XINew
     V=VNEW
     X=XNEW
     IF(MERPTEQ.1.) GO TO 201
C  GO BACK AND LIST THE VEHICLE STATE AND
C  INCREASE T BY TS AND REPEAT THE PROCESS
C  UNTIL T=TM,
     GO TO 1001
201  T=TM
     GO TO 1001
500  STOP
     END
APPENDIX B

SIMULATION RESULTS

The simulation data corresponding to 4 merging situations where $D = 1300 \text{ ft}$, $v_m = 102.6 \text{ ft/sec}$, and $T_m = 19.7 \text{ sec}$ are presented in this appendix. It was assumed that the merging vehicle was subject to an "opposing" 140 lb disturbance force, and the sampling times considered were 1, 3, 4, and 8 sec. As noted in Figs. 51-'54 these data correspond to the results predicted from the theoretical analysis of Chapter II. Note that when $T_g$ is varied from 1 to 8 sec, there are only slight variations in the velocity error at $T_m$, while the corresponding distance deviation varies from 0 to some 4.7 ft/sec. Also, note from the acceleration trajectories that as $T_g$ increases, the acceleration changes at the checkpoints become greater. The effects of this can be noted from the relatively large velocity and distance traveled deviations which occur at the intermediate checkpoints.
Fig. 51—Acceleration, velocity, and distance traveled of a merging vehicle subject to a continuously acting 140 lb "opposing" disturbance force with $T_g = 1$ sec.
Fig. 52—Acceleration, velocity, and distance traveled of a merging vehicle subject to a continuously acting 140 lb "opposing" disturbance force with $T_b = 3$ sec.
Fig. 53—Acceleration, velocity, and distance traveled of a merging vehicle subject to a continuously acting 140 lb "opposing" disturbance force with $T_s = 4$ sec.
Fig. 54—Acceleration, velocity, and distance traveled of a merging vehicle subject to a continuously acting 140 lb "opposing" disturbance force with $T_g = 8$ sec.
APPENDIX C
EXPERIMENTAL RESULTS

The conditions under which additional data (i.e., that not reported in the text) were collected are shown in Table 4. The conditions and the number of runs per condition, are defined here. The data corresponding to Set 1 are shown in Figs. 55 - 64 and that associated with Set 2 are depicted in Figs. 65 - 69.

TABLE 4
NUMBER OF FULL-SCALE ON-ROAD TEST DATA

<table>
<thead>
<tr>
<th>MERGING PARAMETERS</th>
<th>VEHICLE PARAMETER SET No.*</th>
<th>$T_e$ (sec)</th>
<th>Roadway Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D=1200$ ft</td>
<td>$V_m=69.6$ ft/sec</td>
<td>$T_m=25.9$ sec</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

*The parameters associated with each set are defined in Table 3.
Fig. 55—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_S = 2$ sec.
Fig. 56—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_g = 2$ sec.
Fig. 57--On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_s = 3$ sec.
Fig. 58—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_g = 3$ sec.
Fig. 59—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_g = 3$ sec.
Fig. 60—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_s = 3$ sec.
Fig. 61—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_B = 4$ sec.
Fig. 62—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_g = 4$ sec.
Fig. 63—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_g = 7$ sec.
Fig. 64—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_8 = 7$ sec.
Fig. 65—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "assisting" grade force with $T_s = 3$ sec.
Fig. 66—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_b = 3$ sec.
Fig. 67—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_s = 3$ sec.
Fig. 68—On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_s = 4$ sec.
Fig. 69--On-road test data corresponding to a case where the merging vehicle was subject to a 2% "opposing" grade force with $T_e = 4$ sec.
REFERENCES


