REPORT NO. UMTA-RD-CA-06-0088-76-1

AUTOMATED MIXED TRAFFIC VEHICLE CONTROL AND SCHEDULING STUDY

(NASA-CR-149279) AUTOMATED MIXED TRAFFIC VEHICLE CONTROL AND SCHEDULING STUDY Final Report, Feb. - Oct. 1976 (Jet Propulsion Lab.) 65 p HC A04/MF A01 CSCL 13F
N77-14956
Unclas
G3/85 58978

DECEMBER 1976

AUTOMATED GUIDEWAY TRANSIT TECHNOLOGY PROGRAM

U.S. DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration
Office of Research and Development
Washington, D.C. 20590

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This document was prepared for
United States Department of Transportation
by Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTA-RD-CA-06-0088-76-1		

4. Title and Subtitle Automated Mixed Traffic Vehicle Control and Scheduling Study	5. Report Date December 1976
	6. Performing Organization Code
7. Author(s) Ted K. C. Peng and Kilnam Chon	8. Performing Organization Report No. JPL 5040-45
9. Performing Organization Name and Address Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DOT-AT-60008 UMTA-RD-CA-06-0088
12. Sponsoring Agency Name and Address **U.S. Department of Transportation** **Urban Mass Transportation Administration** **400 7th Street, S.W.** **Washington, D.C. 20590**	13. Type of Report and Period Covered Final 2/76 - 10/76
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This study analyzes the operation and evaluates the expected performance of a proposed automatic guideway transit system which uses low-speed Automated Mixed Traffic Vehicles (AMTVs). Vehicle scheduling and headway control policies are evaluated with a transit system simulation model. The effect of mixed-traffic interference on the average vehicle speed is examined with a vehicle-pedestrian interface model. Control parameters regulating vehicle speed are evaluated for safe stopping and passenger comfort.

The report also includes in its appendices some preliminary data on the cost and operation of an experimental AMTV system. This data is the result of a separate task conducted at JPL, and is included here as background information.

17. Key Words	18. Distribution Statement
Automated mixed traffic vehicle, Automated guideway transit system, Scheduling, Headway control, Vehicle/pedestrian interface, Transit system simulation	**Available to the Public Through the National Technical Information Service Springfield, Virginia 22161**

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	65	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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ACKNOWLEDGEMENT

This project was sponsored by the U. S. Department of Transportation, Urban Mass Transportation Administration (UMTA) under contract UMTA-RD-CA-06-0088. The research was conducted with the cognizance of Mr. George Izumi of the UMTA Office of Research and Development, Automated Guideway Transit Technology Program.

The work was performed at the Jet Propulsion Laboratory, California Institute of Technology, by agreement with the National Aeronautics and Space Administration, to which Caltech/JPL is a prime contractor.

SUMMARY

This study analyzes the operation and evaluates the expected performance of a proposed automatic guideway transit system which uses low-speed Automated Mixed Traffic Vehicles (AMTVs).* A transit system simulation model was developed to compare passenger waiting times and system load factors for various scheduling and headway control policies. A vehicle-pedestrian interface model was developed to simulate and examine the effect of mixed-traffic interference on the average speed of an AMTV. An analytical method was also developed to evaluate vehicle-control parameters that ensure passenger comfort while satisfying vehicle-stopping requirements. Findings of the study lead to the following conclusions:

1. Optimal headway-control policies can achieve significant reduction in the average waiting time of passengers. During non-busy periods, when an average passenger can expect to get on the first vehicle he sees at a station, a headway should be prescribed to be slightly less than the even headway that would evenly space the vehicles on the transit loop. During busy periods, vehicles should not be held at the stations to satisfy any prescribed headway.

2. Vehicle scheduling affects both passenger waiting times and system load factors. During busy hours, the transit system should not hold vehicles at the stations to satisfy any prescribed schedule. During non-busy periods, the optimal vehicle schedule depends upon the average cycle time for a vehicle to complete a transit loop, an average time reflecting the intensity of mixed traffic interference. When passenger arrivals become very infrequent, the frequency of vehicle dispatch should also be reduced to avoid inefficient use of vehicles. In this case, fixed-time schedules or demand-activated dispatch system should be used to benefit the passengers.

*An AMTV is a driverless transit vehicle which shares its guideway with pedestrians and/or other vehicles. Possible urban applications include transit services within public malls, large commercial/industrial/educational/government facilities, business districts, or residential zones. Currently, a low-speed (7 mph) AMTV is undergoing experimental operation at Jet Propulsion Laboratory.

3. When the passenger arrival becomes more and more frequent, the transit system must put more vehicles in the system to keep the average passenger waiting time below a predetermined level. The needed increase of number of vehicles can be obtained as a function of passenger arrival frequency, as demonstrated in the text.

4. Mixed-traffic interference, particularly crossing pedestrians, can significantly reduce the average velocity of an AMTV. To improve transit system efficiency, and to enhance public safety, it is desirable to give AMTVs the right of way for most part along the guideway and to give pedestrians the right of way in prescribed crossing zones.

5. An AMTV must allow for a longer stopping distance than the stopping distance of the vehicle cruising at maximum speed. For the AMTV to satisfy the stringent stopping requirement and to minimize discomfort to the passengers, the on-board speed control parameters should be selected as indicated in this study.

A concise but essentially self-contained explanation of these conclusions is given in Chapter 2, entitled Major Results.

The methodology developed and the results obtained in this study are readily extendable to further studies which are important for the application and implementation of transit systems using the AMTV concept. Potentially fruitful areas for follow-on studies are:

1. An urban implementation study.
2. A larger-scale AMTV transit system.
3. A higher-speed AMTV transit system.

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1.0 INTRODUCTION

1.1 Background and Motivation

The concept of an Automated Mixed Traffic Vehicle (AMTV) was crystalized at JPL in early 1975 (Ref. 1). The AMTV is a driverless vehicle which follows a fixed route by means of a buried electrical guidewire. It carries passengers from one station to the next, sharing its right-of-way with pedestrians and other road vehicles, slowing down or stopping to maintain a safe distance from frontal objects. All this is accomplished by means of on-board proximity sensors, automatic control mechanisms, and devices to receive wayside signals.

An example of the AMTV system is the experimental AMTV system which is currently operating inside the JPL facility (Appendix C). The system contains one test vehicle and a single-loop route with six passenger stations. The vehicle has six seats and runs at a maximum speed of seven miles per hour. Current hardware development at JPL has proceeded toward perfecting a reliable vehicle for this low speed operation; an AMTV capable of safe operation at higher speed (e.g., 15 to 20 mph) would require significant additional development effort.

An AMTV system can be expected to have cost advantages over conventional transit systems in many possible urban applications since the system needs neither human operators nor exclusive guideways. A low-speed AMTV similar to the 7-mph experimental system at JPL appears to be most suitable for transit services in public malls and large facilities (shopping centers, universities, government complexes, and industrial plants). It is also suitable for limited-size business districts, and limited-size residential areas. A higher-speed AMTV system can conceivably be used to replace automobiles in central cities.

When put into actual use in an urban environment, the AMTV system is expected to behave quite differently from either an ordinary city-bus system or the proposed exclusive-guideway transit systems such as PRT (Personal Rapid Transit) or GRT (Group Rapid Transit) as described in References 2, 3, 4, and 5. Compared to a city bus with a human driver, an AMTV of reasonable price cannot be expected to have the versatile sensing, judging, and adapting capability of a bus driver. Compared to exclusive-guideway vehicles, an AMTV must encounter random, mixed-traffic interference in normal operation while an exclusive-guideway vehicle will not. A fleet of AMTV's, therefore, cannot be expected to maintain line speed, headway, and schedules with the same precision achievable in an exclusive-guideway system.

This study intends to establish a basic understanding of the predicted behavior of an AMTV transit system and to identify desirable control and management strategies. The results of this study should help to form a basis on which system designs for specific urban applications can be readily developed in the future.

1.2 Objectives and Scope

The purpose of the study is to initiate the development of automated-vehicle management techniques and algorithms in order to gain a quantitative understanding of the AMTV in operation. The study is directed toward developing methodology to evaluate control and scheduling algorithms for the AMTV automatic guideway transit system.

The scope of the study includes analysis of an AMTV system of multiple vehicles in low speed operation along single-loop or multiple-loop guideways. These vehicles must be capable of handling themselves in the presence of fixed and moving guideway obstacles. The scope also includes an initial effort toward developing algorithms for (1) vehicle scheduling, (2) routing and guideway layout, and (3) headway control.

1.3 Approach

The study has been carried out at both the vehicle and the system levels. The vehicle-level analysis emphasizes safe, smooth, and efficient operation of the vehicle in mixed traffic. The system-level analysis emphasizes efficient scheduling and headway control of multiple vehicles to minimize passenger waiting time. At each level the study predicts vehicle and system performance, develops alternate control and management schemes, compares these strategies and identifies control requirements.

In this study, analysis and evaluation are done with the help of computer simulation models and analytical models which are developed to attack these specific problems. Simulation models have been extensively used in the study since most of the problems encountered do not lend themselves to close-form analytical solutions; these problems are non-linear in nature and involve stochastic processes which describe passenger or pedestrian behaviors affecting AMTV performance in actual operation. Conclusions have been drawn based on the quantitative results of these models and their logical derivatives.

Major performance figures measured for the operation of the AMTV automatic transit system are the average waiting time of passengers at the stations and the related average load factor, or percent of seats occupied, of the system. System control strategies in both vehicle scheduling and headway control are evaluated. These controls are studied in detail by computer simulation for a single-loop, two-vehicle, six-station system. The results are then extended to cover AMTV systems of larger scales.

Major performance indicators of the vehicle are (1) the average vehicle velocity as affected by mixed-traffic interference, and (2) the rates of acceleration/deceleration and of acceleration-changes (jerk), which determine the stopping distance of a vehicle and affect passenger comfort. The impact of pedestrian interference at various intensities and the effect of restricting pedestrian crossings along the guideway are studied by simulation. Optimal acceleration and acceleration-change rates are evaluated analytically.

The problem of intersection control is also discussed, in a preliminary manner, from a safety point of view. A comprehensive treatment of the intersection problem requires an understanding of the impact of the low speed AMTV on the flow of regular traffic. These analyses are beyond the resource of the current study; they are important items to be addressed in further studies.

The questions of routing and guideway layout are highly dependent upon the particular urban environment in which the AMTV system is to operate. They must also include the impact of low-speed AMTVs on regular street traffic at higher speeds. In our opinion, these questions can only be meaningfully addressed when the application is specified, and they can only be adequately answered after we have a chance to study the impact of AMTVs on the regular street traffic. These questions, therefore, are not treated in this study.

Major results of the study are summarized in Chapter 2. Detailed analysis and evaluation are presented in Chapters 3 and 4. Since this study is an initial effort toward understanding the characteristics, requirements, and potential strength and limitations of the AMTV system for urban application, we have selected a list of priority subjects for further study. These subjects are briefly discussed in Chapter 5. References and supporting materials are included in the appendices. Specifically, a description of the current-version AMTV and its experimental operation inside the JPL facility is presented in Appendix C, along with some preliminary data concerning the results of the experimental operation.

2.0 MAJOR RESULTS

2.1 Vehicle Scheduling and Headway Control

2.1.1 Problem Description

AMTV operating systems with various configurations are simulated and analyzed under various control schemes. System control for each configuration includes both headway control and vehicle scheduling. Headway control involves maintaining a sufficient distance between vehicles to minimize the average waiting time of passengers at the stations. Vehicle scheduling involves specifying the rules governing the departure of a vehicle from station(s) along its route, Types of vehicle scheduling considered in this study include (1) fixed-time scheduling, in which the complete schedule of each vehicle for one day's operation is prescribed and the clock for scheduling is reset to zero only at the beginning of the day; (2) cycle-time scheduling, in which the cycle time between successive departures of a vehicle from the same station, after the vehicle completes a loop, is prescribed; and (3) inter-station scheduling, in which time intervals between departures of a vehicle from consecutive stations are prescribed.

Both headway control and vehicle scheduling are implemented by measuring time and holding the vehicle at a station. The vehicle is held at the station if it is either ahead of schedule, according to schedule control, or the actual headway measured in time from the departure of a preceding vehicle is closer than a number prescribed by headway control. No control can be applied to a vehicle behind schedule since the vehicle speed is not allowed to exceed its prescribed cruising speed at any time. The control of headway and schedule can be implemented either at every station in the loop or once per cycle at a central station.

In the AMTV systems simulated, the vehicles leave the stations according to the system control schemes discussed above. The travel time of a vehicle between stations is a variable which is expressed as the sum of two numbers: a constant reflecting the minimum travel time corresponding to the maximum vehicle speed, and an exponentially distributed random number reflecting the time delay due to mixed traffic interferences and passenger boarding. Passengers arrive at each station at random, with interarrival time exponentially distributed, and wait for the next vehicle. Once on board, the departures of the passengers at various stations are also randomly distributed.

A prototype AMTV system with a loop of six stations and two vehicles, each containing six seats, is extensively simulated and analyzed. Cases simulated represent a wide range of passenger arrival rates and include both homogeneous and non-homogeneous systems. Homogeneous systems consist of stations with identical characteristics such as passenger arrival rates, passenger departure rates, and vehicle driving time between stations. Non-homogeneous systems consist of stations with varying characteristics to reflect actual operating conditions for an AMTV system.

Simulated data are analyzed to obtain average passenger waiting time at the stations under various vehicle scheduling and headway control schemes. The effectiveness of these schemes is measured by the average passenger waiting time. The evaluation of these schemes is presented in the following section. Also evaluated are the size of the operating fleet to maintain an acceptable level of average passenger waiting time and the applicability of these conclusions, obtained in the simulation of single-loop systems, to the multiple-loop systems.

2.1.2 Findings - Vehicle Scheduling and Headway Control

Headway control was found to be most effective in minimizing the average passenger waiting time for an operational AMTV system. During non-busy periods, the average waiting time was minimized when the prescribed headway was set at 70% to 90% of the even headway, i.e., the average cycle time for a vehicle to complete a loop divided by the number of vehicles in the loop. This strategy achieved a 20% reduction in the average waiting time as compared with the same case with no headway control (Fig. 3.4a). During busy periods, the minimum average waiting time was achieved when the prescribed headway was set in the range from zero (no headway control) to 20% of the even headway. Any additional time spent in holding the vehicle increased the average passenger waiting time (Fig. 3.4b).

As to the impact of scheduling on the average passenger waiting time, the difference between fixed-time scheduling and cycle-time scheduling was found to be insignificant. The third method, inter-station scheduling, appears to be inferior to the two methods mentioned above as it showed slightly higher simulated average waiting time and is likely to cost more to implement.

According to the simulation results (e.g., Fig. 3.2a), the time period between successive departures of a vehicle from the same station during non-busy periods should be made to equal the average cycle time for the vehicle to complete a loop, whether fixed-time scheduling or cycle-time scheduling is used. Longer departure periods were shown to prolong passenger waiting; shorter departure periods did not significantly reduce the waiting time. During busy periods, holding a vehicle at a station to satisfy any departure schedule only increases the simulated average passenger waiting time; therefore, the vehicles should not be restricted by any schedule for these periods.

The choice between fixed-time scheduling and cycle-time scheduling depends, in our opinion, on the expected passenger waiting time. If the expected waiting time is long, fixed-time scheduling is better since it helps the passengers to plan their own schedule. If the waiting time is expected to be short, cycle-time scheduling is better since it is easier to implement.

Implementation of scheduling and headway control, through time measurement and vehicle holding, should be done at one central station instead of at all stations since holding the vehicle at multiple stations increased the simulated average passenger waiting time and is likely to be more costly. An exception occurs when the expected interarrival time of vehicles at a station becomes so long that passengers would rather have a precise AMTV schedule to plan their own time; control at all stations should be implemented in this case.

Simulations of homogeneous and non-homogeneous cases have shown similar results when the above mentioned control policies are compared. The optimal policies indicated above are applicable to both cases.

When the passenger arrival frequency increases, more and more vehicles are needed in the loop to maintain the average passenger waiting time below certain levels. The required increase of the size of an AMTV fleet in response to increased passenger arrival rate for the prototype six-station system is indicated in Fig. 3.8.a and Fig. 3.8.b.

The recommended control policies for single-loop systems discussed so far will also apply to multiple-loop systems unless the loops are long and the number of vehicles is small. Otherwise, the multiple loop systems can be treated as a collection of independent single loops with modified passenger arrival rates at the stations close to the loop intersections, where passenger transfer takes place. Otherwise, more elaborate control systems allowing for schedule matching, inter-loop routing, and area-wide system management may be needed. These topics, which pertain to the operation of large scale AMTV systems, are recommended as a proposed further study in Chapter 5.

2.2 Vehicle Performance and Speed Control

2.2.1 Problem Description

The performance of an AMTV operating in mixed traffic in the low-speed mode is evaluated in this study in terms of (1) the simulated average velocity of the vehicle under random pedestrian interference, which affects the service efficiency of the system, and (2) the rates of acceleration/deceleration and of change of acceleration (jerk), which determine both safety and passenger comfort. The vehicle-pedestrian interface is important because the low-speed AMTV is most likely to have frequent encounters with pedestrians in actual application such as at shopping malls or airports. Deceleration rate and acceleration-change rate must be sufficiently high to insure a safe stopping distance; they must also be kept low to ensure passenger comfort.

The vehicle-pedestrian interface (Fig. 4.1) is simulated with a vehicle model representing the automatic sensing and control characteristics of the current-version vehicle developed at JPL. Simulated encounters between pedestrians and a moving vehicle take place when the pedestrians come to the side of the guideway ready to cross the sensing range in front of the vehicle.

The time interval between these encounters is assumed to be a random number with exponential distribution. The encounter distance between the vehicle and the pedestrian is assumed to be probabilistic, with lower probability near the vehicle and higher probability at the far end of the sensing range. The time it will take a pedestrian to cross the sensing range is also assumed to be random, ranging from one to three seconds.

In simulation, a pedestrian's decision to cross in front of a moving vehicle is determined by a risk calculation which involves his estimation of the vehicle speed, the encounter distance, and his crossing time. The decision also depends on the pedestrian's behavior: either he competes with the vehicle for the right of way, knowing that the vehicle will slow down for him, or he takes a non-competitive attitude, possibly as a result of public instructions or regulations. If a pedestrian is competitive, his risk calculation is based on the traveling distance of a decelerated vehicle. If a pedestrian is non-competitive, his risk calculation is assumed to be based on the traveling distance of a vehicle maintaining its current speed. Both estimations of the traveling distance are represented as random numbers in simulation to reflect the inaccuracies in a pedestrian's instant calculation

Average vehicle speeds are simulated for a wide range of encounter frequencies and a varying degree of pedestrians' competitiveness regarding the right of way. Major findings of the simulation study are presented in the following section.

A separate analysis of the speed control of a vehicle has determined the optimal rates of acceleration, deceleration, and acceleration changes which satisfy the prescribed stopping-distance requirements and ensure passenger comfort. Also presented is the result of an examination of control requirements of AMTV's at intersections.

2.2.2 Findings - Vehicle Performance and Speed Control

The average speed of the simulated AMTV was not reduced significantly from its 7-mph maximum cruising speed (Fig. 4.2) when pedestrian cross traffic was light. When cross traffic was dense, however, significant speed reduction resulted. The average velocities were within 10% of the maximum speed when the encounter frequency was lower than once per 15 seconds. Once the frequency reached a higher level ranging from once per 5 seconds to once per 2 seconds (a frequency possible in a busy shopping mall), the vehicle was slowed down 25% to 50% of the cruising speed.

Pedestrian's attitude emerges as an important factor affecting the AMTV performance. The simulated average velocity of the vehicle was significantly improved when the pedestrians did not compete with the AMTV for the right of way. At an encounter frequency of once per 5 seconds, the simulated average velocity was 5.2 mph when all pedestrians were competitive, 6.5 mph when all pedestrians were non-competitive, and 5.7 mph when half of the pedestrians were competitive and half were not. The simulated average velocities for these cases at a frequency of once per two seconds were 3.8 mph, 5.3 mph, and 4.1 mph, respectively.

The simulation results also confirmed, as expected, that the emergency brake on the vehicle was activated more often when pedestrians compete for the right of way instead of yielding to the vehicle.

The results suggest that rules or instructions which regulate or guide the behavior of pedestrians may be necessary for AMTV applications in which heavy pedestrian traffic is expected. Provision of pedestrian crossing zones where pedestrians are given priority for a period of time could also be helpful in achieving a certain degree of separation, although the effect of this provision has not been analyzed.

Examination of the AMTV speed control requirements revealed that an AMTV must allow for a longer stopping distance than the stopping distance from the maximum cruising speed. According to the model used in this study, the worst case stopping distance is about 40% longer than the nominal stopping distance from maximum cruising speed. This occurs if the vehicle senses an obstacle while accelerating at full rate toward maximum cruising speed. Because of the finite rate of change of acceleration, the vehicle must take extra time to reduce acceleration from full rate to zero before it can start to reduce its velocity; this results in a longer stopping distance.

Since the worst-case condition may happen quite often during normal AMTV operations, the selection of the pair of acceleration-change rates must satisfy strict requirements in order to insure safe stopping within a prescribed distance. Boundaries of allowable acceleration rates and the corresponding acceleration-change rates that satisfy various stopping requirements are given in Fig. 4.3. The rates to be adopted for implementation must be within the boundary corresponding to a specified stopping requirement, and should also be kept low to ensure passenger comfort. Good candidates satisfying these two requirements are represented by the shaded areas in Fig. 4.3. For example, one possible candidate for a 22-foot stopping requirement is to set acceleration rate at 5.0 fps^2 and acceleration-change rate at 6.6 fps^3 For an 18-foot stopping requirement, the two rates can be set at 6.0 fps^2 and 9.8 fps^3.

The methodology developed is readily extendable to the search for a complete set of good acceleration and acceleration-change rates for various initial velocities and accelerations of the vehicle under various stopping requirements. This extension, not done in this study, could allow the vehicle to exercise more flexible speed control, such as coming to a quick stop when the vehicle is fast and the detected obstacle is near, and a slower stop when the vehicle is slower and the detected obstacle is distant.

An implementable control algorithm for smooth transition of desirable speed levels was developed in the course of the simulation study. Simulation results have demonstrated the versatility and precision of this algorithm as a vehicle control scheme in the mixed-traffic environment. The algorithm can be considered as a candidate for implementation in the next version vehicle to improve the smoothing performance of the current vehicle.

Control requirements of an AMTV at an intersection were briefly examined. The most important additional capabilities for an AMTV to turn safely at an intersection were found to be sideway sensing capabilities and associated vehicle control schemes. Some intersection control rules currently in use can provide safe passing to AMTV's if the AMTV's do not need to proceed "defensively." Comprehensive evaluation of the intersection traffic control must await a deeper study into the effect of the low-speed AMTV's on regular traffic flow.

3.0 VEHICLE SCHEDULING AND HEADWAY CONTROL

System behavior of an Automated Mixed Traffic Vehicle (AMTV) has been studied through system analysis and simulation. The AMTV system studied consists of one loop with several vehicles and six stations. Each vehicle has six seats for passengers. Passengers arrive at a station at random. Travel time of a vehicle from one station to the next is also random, with a maximum speed of seven miles per hour. Departure of passengers from the vehicle at the following stations is also random. Headway of the successive vehicles and the schedules of the vehicles can be regulated for optimal system performance.

Two criteria were established to arrive at a measure of system behavior. These include (1) the average waiting time of passengers at stations, and (2) the average load factor for each vehicle. The study simulates an AMTV system under varying conditions and some results lending to recommendations for system control policies are obtained.

3.1 System Modeling

The simulation model incorporates the following:
The AMTV is operated on the loop with six stations. At each station, passengers arrive at random and wait for a vehicle to arrive. The probability distribution for the arrival of passengers is assumed to be a Poisson distribution. In other words, the inter-arrival time distribution is the exponential distribution. When a vehicle arrives at a station, some of the passengers in the vehicle may get off; and the waiting passengers at the station, if any, get on if the vehicle is not full. Each vehicle has a capacity of six seats for passengers. Travel time of the vehicle between two adjacent stations is random, and its probability distribution is the composite of a constant and the exponential distribution. The constant reflects the minimum travel time determined by the maximum vehicle speed, and the exponential distribution reflects fluctuation of vehicle speed due to mixed traffic interference and passenger loading. Departure of passengers at the following stations is random, and the destination of each passenger is decided by a prescribed probability function. No vehicle can pass another vehicle on the loop (unless the latter vehicle is in the storage area off the loop).

3.1.1 Control Schemes

System control of the AMTV's include both headway control and vehicle scheduling. Headway control attempts to keep the minimum allowable gap, measured by time, between the two vehicles. The control may be done either (A) at one central station, or (B) at all stations. The vehicle is held at the station until its headway to another vehicle ahead of it equals the minimum allowable headway set by the system operator. Headway control is not to be confused with vehicle spacing which is to maintain a distance between adjacent vehicles to avoid collision. Headway control is done at all times except possibly at stations. It is not applicable to a single vehicle system.

Scheduling of vehicles involves the measure of travel time of a vehicle against the standard time and holding the vehicle if its travel time is less than the standard time, i.e., if it is ahead of schedule. Three types of scheduling are considered in this study:

(1) Fixed-time Scheduling
The complete schedule of each vehicle for one day's operation is prescribed. The clock for scheduling is reset only at the beginning of the day.

(2) Cycle-time Scheduling
The cycle time between successive departures of a vehicle from the same station, after completing a loop, is prescribed. The clock for scheduling is reset to zero every time the vehicle leaves a central station.

(3) Inter-station Scheduling
The time intervals between departures of a vehicle from consecutive stations are prescribed. The clock for scheduling is reset to zero at every station.

The time measurement and vehicle holding for scheduling and headway control are done at the departure time of each vehicle either (a) at all stations, or (b) at one central station. A vehicle is held at a station until conditions of both headway and scheduling controls are satisfied.

Fixed-time scheduling is similar to a municipal bus operation in which vehicles are dispatched according to a complete schedule covering the operating hours of a day. When the schedule is controlled at every station, in a manner similar to that used for long-distance bus routes, the vehicle is held at any station if it is ahead of schedule at that station. The schedule can also be controlled at a central station, as in the case of short-distance bus routes. In this case, the vehicle is held at the central station only.

Cycle-time scheduling is almost identical to fixed-time scheduling except that the clock is reset every time the vehicle leaves a central station upon completion of a loop. This control is commonly applied to shuttle buses. If the vehicle arrives at the following stations too soon, it will be held. As in fixed-time scheduling, this control can also be implemented either at a central station or at all stations.

Inter-station scheduling involves measuring the travel time between two successive stations and holding the vehicle if the travel time is shorter than the minimum set by the system operator. This control must be done at all stations.

There is also demand scheduling in which a vehicle is dispatched on demand. This control will be most appropriate for the least busy periods and is not discussed further.

3.2 Studies of Simulated Cases

Several cases have been studied by simulation since simulation can handle these cases better than an analytical approach due to the complexity of multiple probability distributions. The first model is a one-vehicle homogeneous system with six stations. The second model is a two-vehicle, homogeneous system with six stations. A homogeneous system consists of stations with identical characteristics such as passenger arrival rates, passenger departure rates, and distance between stations. A non-homogeneous system consists of stations with different characteristics. The third model is a two-vehicle, non-homogeneous system with six stations. This model simulates the existing configuration at the Jet Propulsion Laboratory modified to include two vehicles. The fourth model is also a two-vehicle, non-homogeneous system with six stations but simulates a much larger loop such as between the main gate and the east parking lot at the same facility. This loop is about two miles long; the first three models have a 2000-foot loop.

All possible control scheme combinations mentioned in 3.1.1 have been simulated and studied. The main criteria of comparison of the control schemes are (1) the overall average waiting time of a passenger at a station, and (2) the overall average load factor of the vehicles. The models and the results are shown in the following sections.

3.2.1 One-Vehicle, Homogeneous System

The system specifications for the one-vehicle homogeneous system are as follows:

1. One 2000-foot loop.
2. One vehicle with capacity of six passengers.
3. Six stations.
4. Interarrival time of passengers has an exponential distribution.
5. Travel time between the adjacent stations has composite probability distribution with the mean, $u = 40_D + 10_E$ (in seconds). The minimum travel time is 40 seconds and the variation of travel time is represented by the exponential distribution with a mean of 10 seconds.
6. The departure rate is as follows:
   40% of passengers get off at the next station,
   40% of passengers get off at the second station,
   20% of passengers get off at the third station.

The waiting time distribution and the load factor distribution are shown in Figures 3.1a and 3.1b for fixed-time scheduling. The results for cycle-time scheduling are almost identical to those of fixed-time scheduling. The inter-station scheduling yields a slightly longer waiting time than the other two cases. Similar results were found when the varying portion of the traveling time was increased, $u = 30_D + 20_E$ seconds. Evaluation of these results are given in Section 3.3.

3.2.2 Two-Vehicle, Homogeneous System

The system specifications for the two-vehicle, homogeneous system are as follows:

1. One 2000-foot loop.
2. Two vehicles with capacity of six passengers each.
3. Six stations.

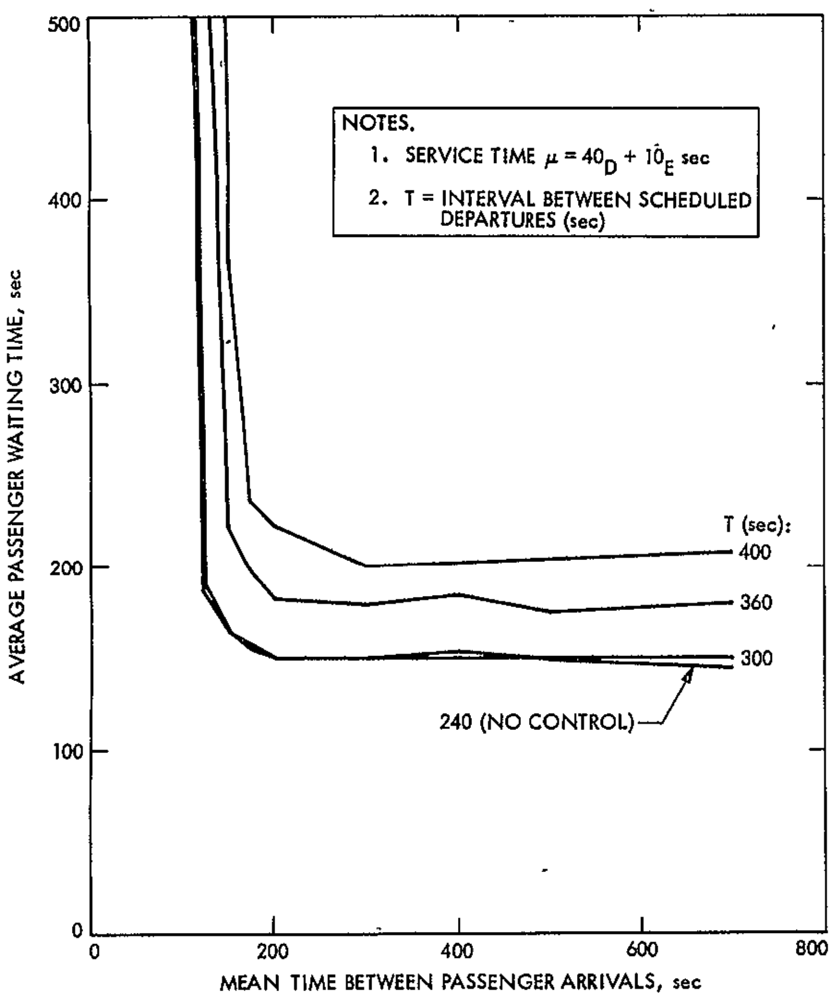


Figure 3.1a. Passenger Waiting Time in a One-Vehicle, Homogeneous System with Fixed-Time Scheduling

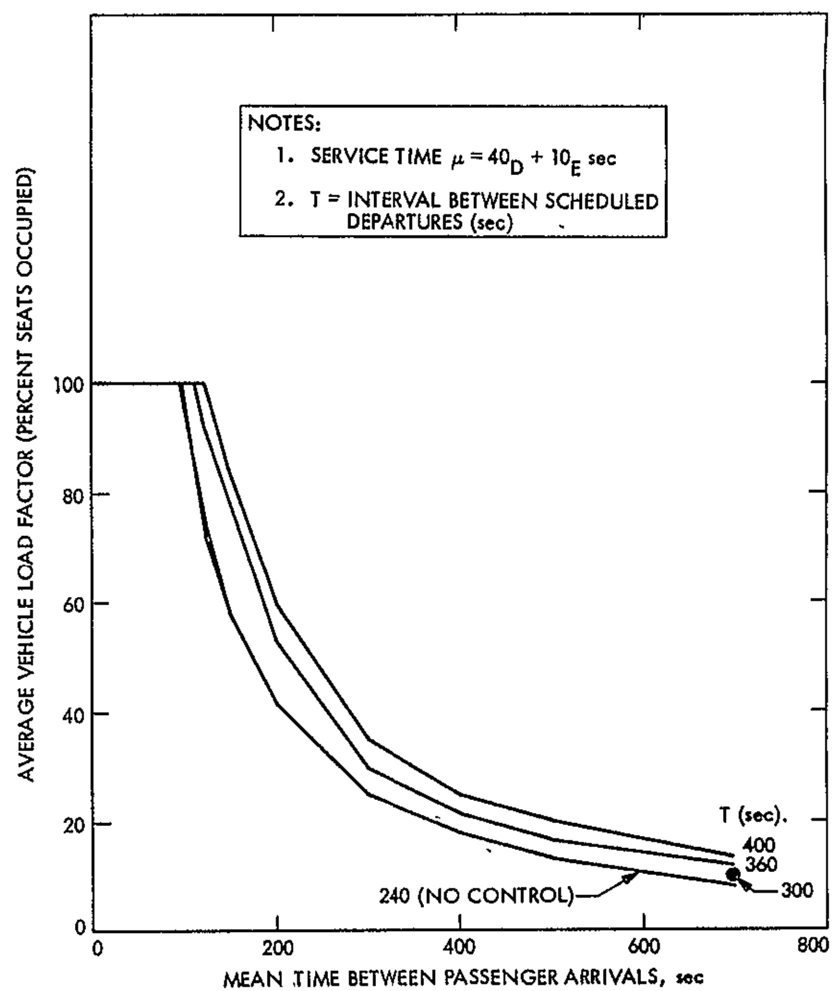


Figure 3.1b. Vehicle Load Factor in a One-Vehicle, Homogeneous System with Fixed-Time Scheduling

4. Interarrival time of passengers has an exponential distribution. The cases of the following average interarrival time are considered: 700, 500, 300, 200, 150, 100, 80, 60 and 50 (seconds).
5. Travel time between the adjacent stations has a composite probability distribution, $u = 40_D + 10_E$ (seconds). The minimum travel time is 40 seconds, and the variation of travel time is represented by an exponential distribution with a mean of 10 seconds.
6. The departure rate is as follows:
   40% of passengers get off at the next station,
   40% of passengers get off at the second station,
   20% of passengers get off at the third station.

The waiting time distribution and the load factor distribution are shown in Figures 3.2a and 3.2b for fixed-time scheduling with a prescribed headway of 150 seconds controlled at one station. Figure 3.2c shows the case without headway control. Similar results were found where the travel time variation was larger, $u = 30_D + 20_E$ seconds, as shown in Figure 3.3. Cycle-time scheduling and inter-station scheduling show almost identical results.

Figure 3.4a shows waiting time as a function of the prescribed headway which varies from 0 to 150 seconds with fixed-time scheduling for the non-busy period. Figure 3.4b shows the same information for the busy periods.

3.2.3 Two-Vehicle, Non-homogeneous System

The system specification for the two-vehicle, non-homogeneous system is as follows:

1. One 2000-foot loop.
2. Two vehicles with capacity of six passengers each.
3. Six stations.
4. Inter-arrival time of passengers for the stations 1, 3, 4, and 6 is exponentially distributed with the following variation of means (in seconds): 500, 200, 100, 80, 70, 60, and 50. The rest of the stations have the same probability distribution with mean values twice as large.

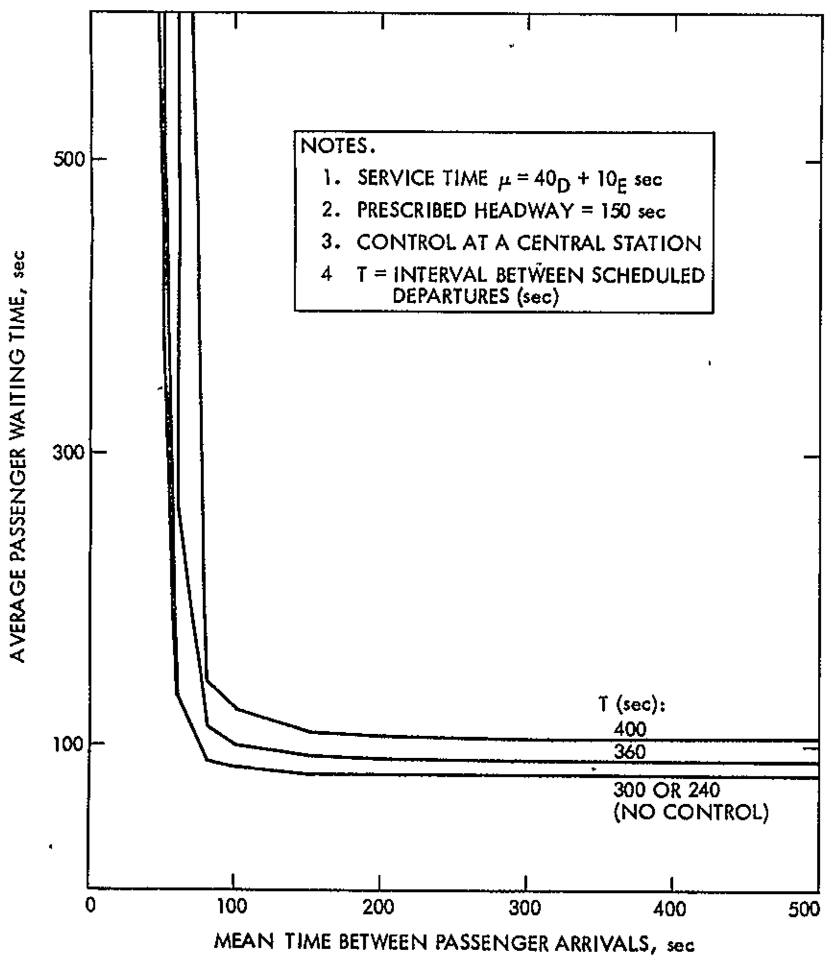


Figure 3.2a. Passenger Waiting Time in a Two-Vehicle, Homogeneous System with Fixed-Time Scheduling and Headway Control

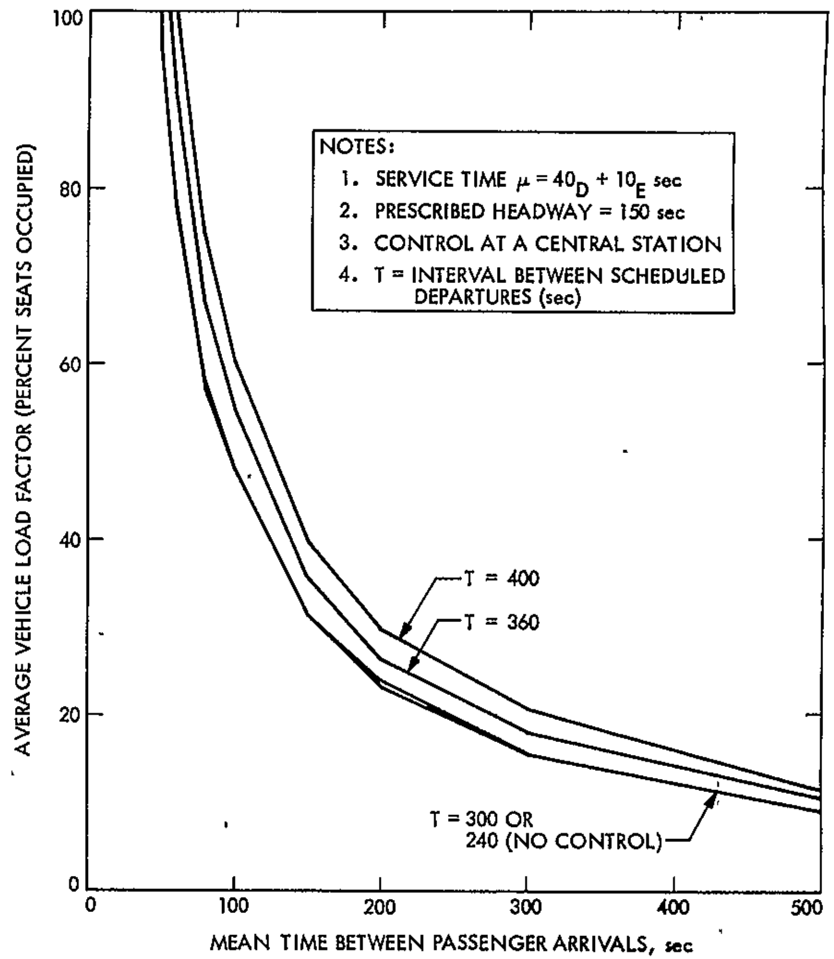


Figure 3.2b. Vehicle Load Factor in a Two-Vehicle, Homogeneous System with Fixed-Time Scheduling and Headway Control

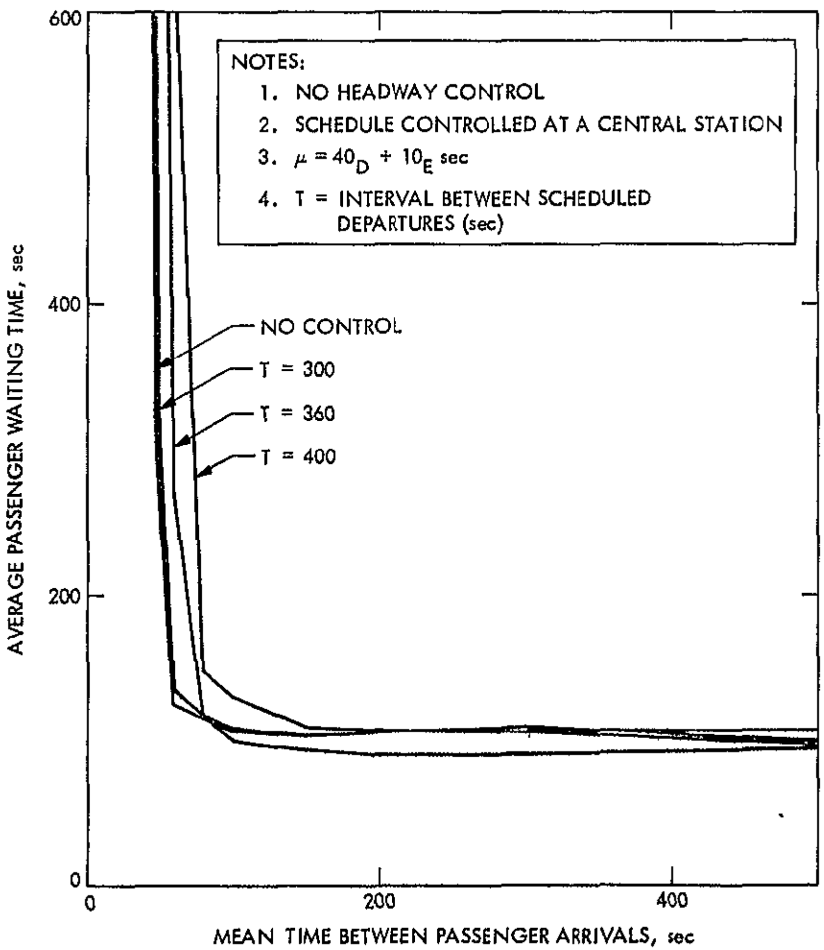


Figure 3.2c. Passenger Waiting Time in a Two-Vehicle, Homogeneous System with Fixed-Time Scheduling and No Headway Control

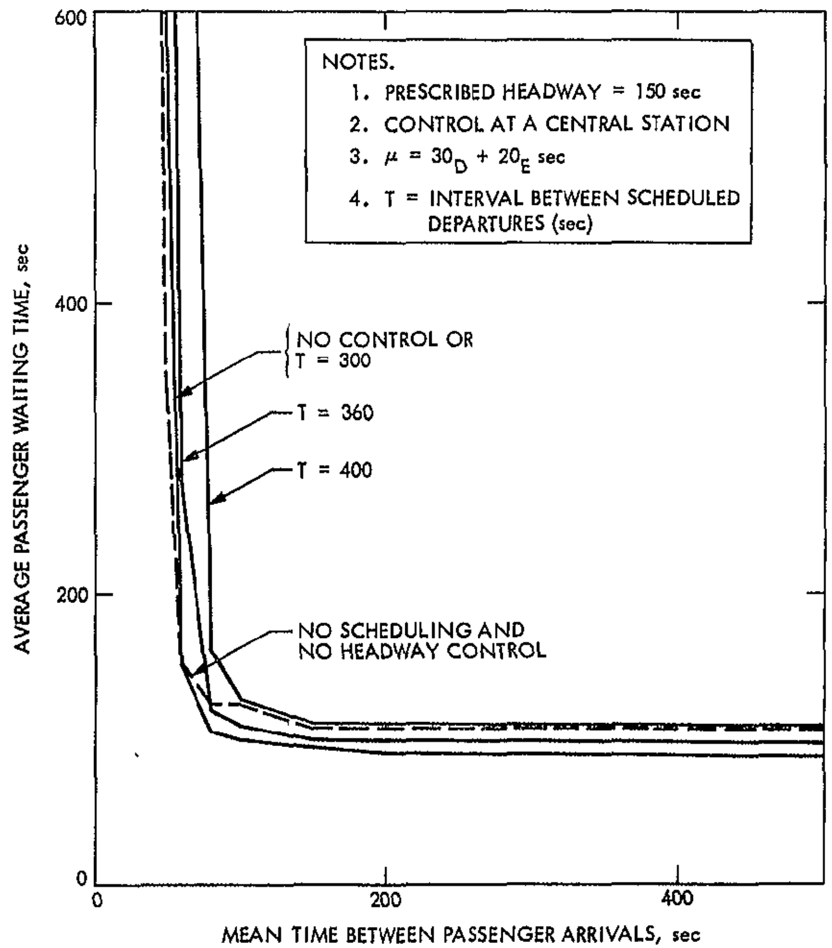


Figure 3.3. Passenger Waiting Time in a Two-Vehicle, Homogeneous System with Fixed-Time Scheduling, Headway Control and a Larger Variation in Vehicle Service Time

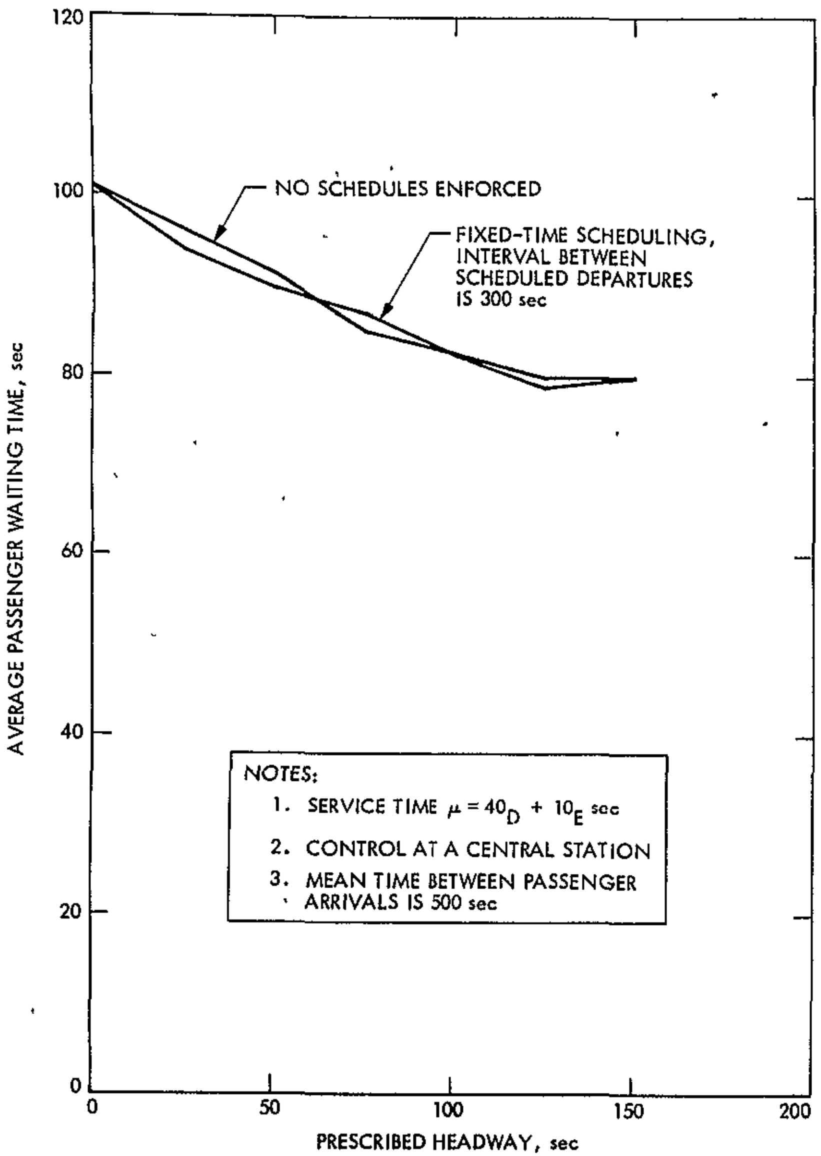


Figure 3.4a. Passenger Waiting Time vs Prescribed Headway; Non-Busy Periods[3]

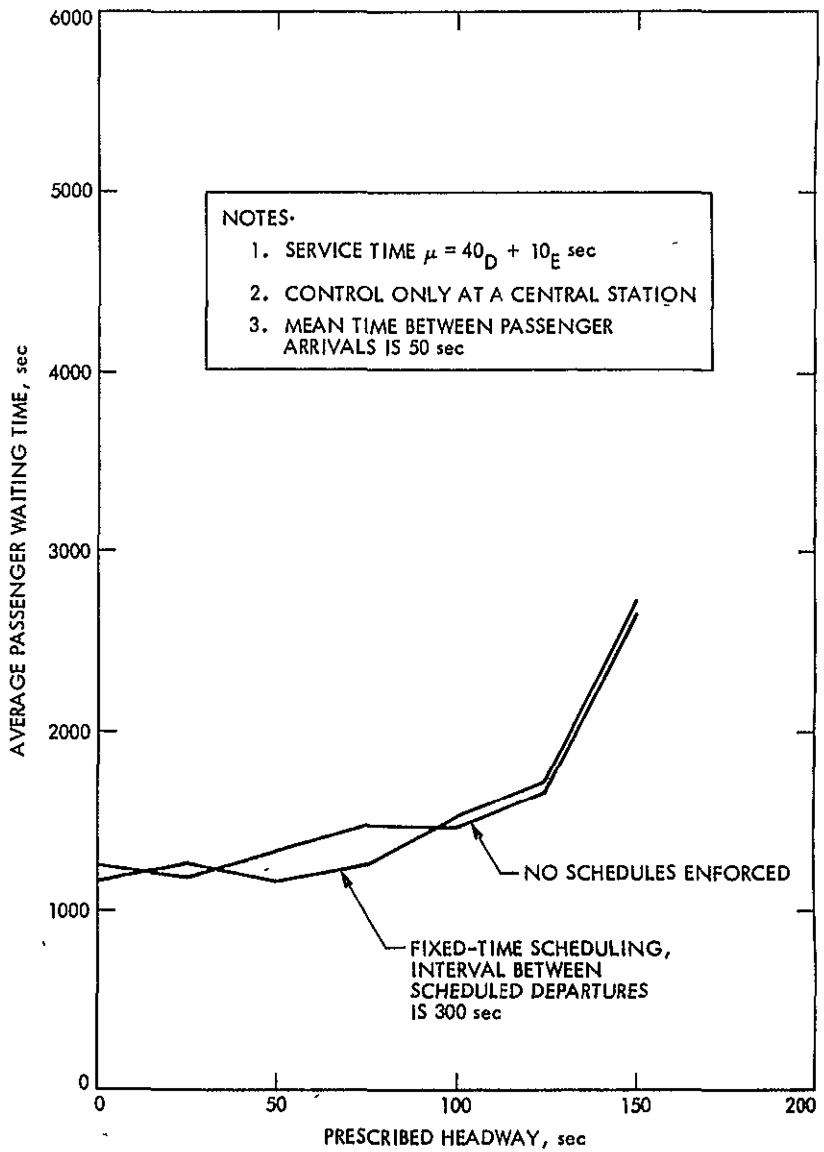


Figure 3.4b. Passenger Waiting Time vs Prescribed Headway; Busy Period[3]

5. Travel time has the following distribution (in seconds):

Station	Minimum Time	Fluctuation (mean)
1-2	50.0	12.6
2-3	46.0	11.4
3-4	8.0	2.0
4-5	46.0	11.4
5-6	50.0	12.6
6-1	12.8	3.2

6. The departure-rate distribution is as follows:

From Station \ To Station	1	2	3	4	5	6
1	-	.4	.3	.3	0	0
2	0	-	.6	.3	0	.1
3	.1	0	-	0	.4	.5
4	.1	0	0	-	.4	.5
5	.3	.1	0	0	-	.6
6	0	.4	.3	.3	0	-

The average time to complete one cycle is 300 seconds. The above case represents 80% constant travel time and 20% variation with an exponential distribution. The result for fixed-time scheduling controlled at one station with and without headway control is shown in Figure 3.5, where the headway is half of one average cycle. The result for the fixed-time scheduling and headway control implemented at all stations is shown in Figure 3.6.

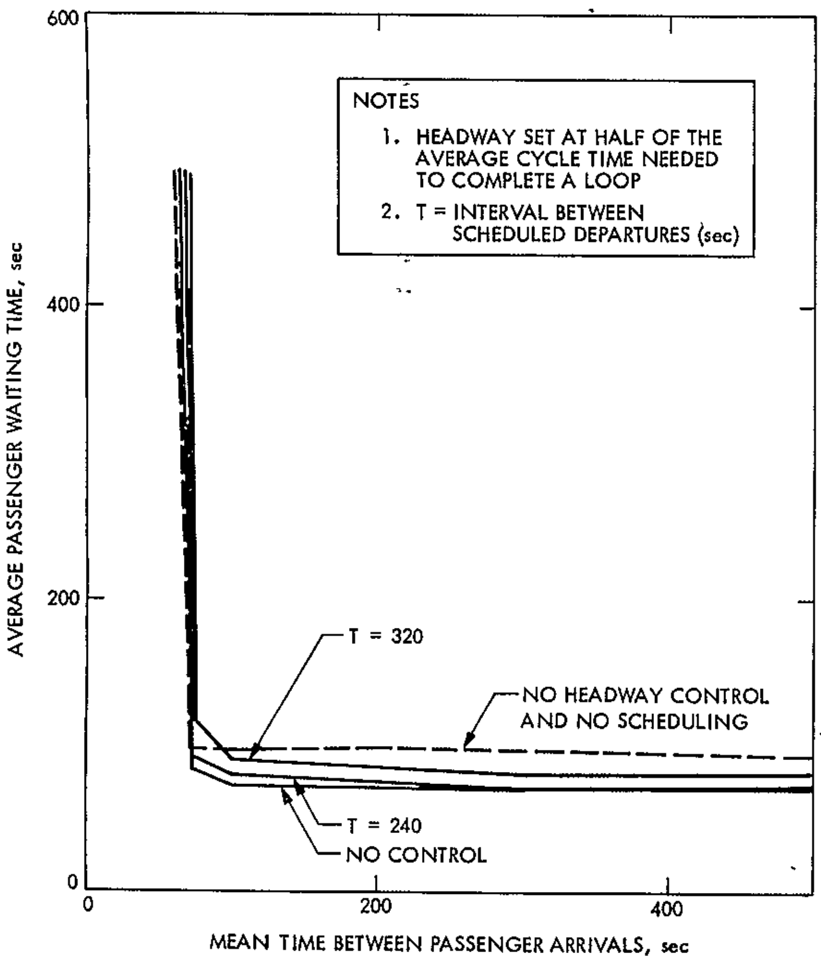


Figure 3.5. Passenger Waiting Time in a Two-Vehicle, Non-Homogeneous System, with Fixed-Time Scheduling and Headway Control Implemented at a Central Station

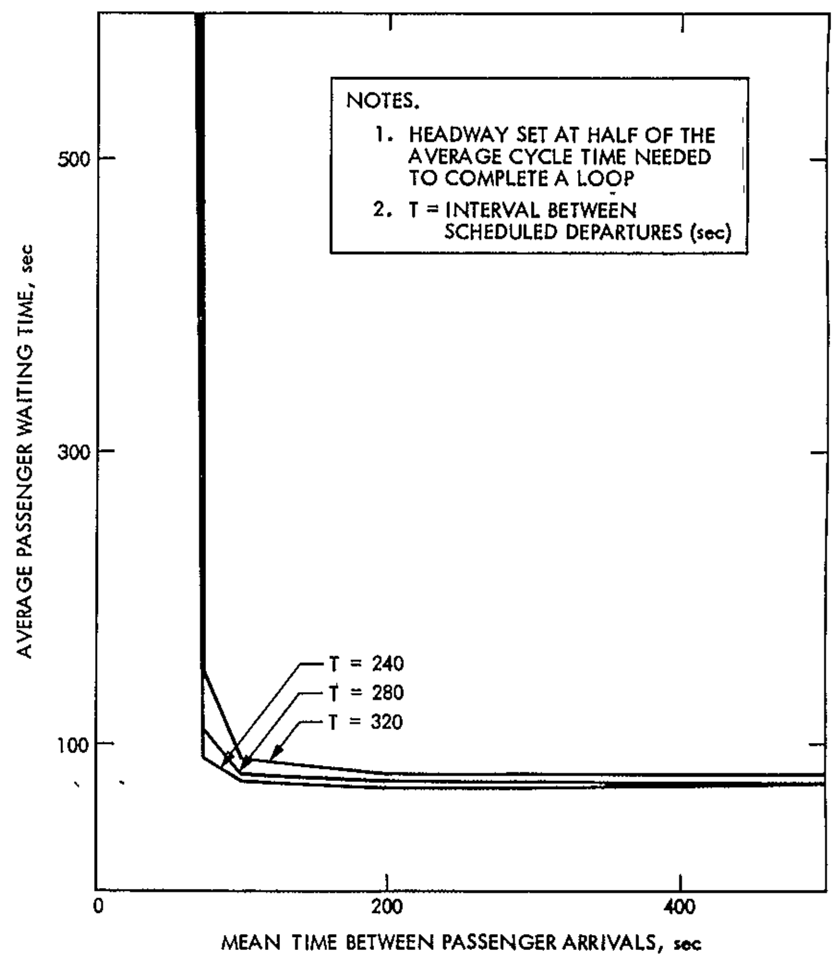


Figure 3.6. Passenger Waiting Time in a Two-Vehicle, Non-Homogeneous System, with Fixed-Time Scheduling and Headway Control Implemented at all Stations

3.2.4 Two-Vehicle, Non-homogeneous System with a Larger Loop

The system specifications for the two-vehicle, non-homogeneous system with the large loop is as follows:

1. One two-mile loop.
2. Two vehicles with capacity of six passengers each.
3. Six stations.
4. Inter-arrival time of passengers has the exponential distribution with the following means (in seconds):

Station	Mean Inter-arrival Time
1	200, 300, 400, 500
2	1000
3	2000
4	500
5	500
6	3000

5. Travel time has the following distribution (in seconds):

Station	Minimum Time	Fluctuation (mean)
1-2	152.6	16.9
2-3	212.9	23.7
3-4	129.2	14.3
4-5	129.2	14.3
5-6	212.9	23.7
6-1	152.6	16.9

6. Departure rate has the following specifications:

From Station \ To Station	1	2	3	4	5	6
1	-	.1	.6	.3	0	0
2	0	-	.65	.35	0	0
3	0	0	-	1.0	0	0
4	.6	0	0	-	.2	.2
5	.7	0	0	0	-	.3
6	1.0	0	0	0	0	-

The waiting time distribution is shown in Figure 3.7.

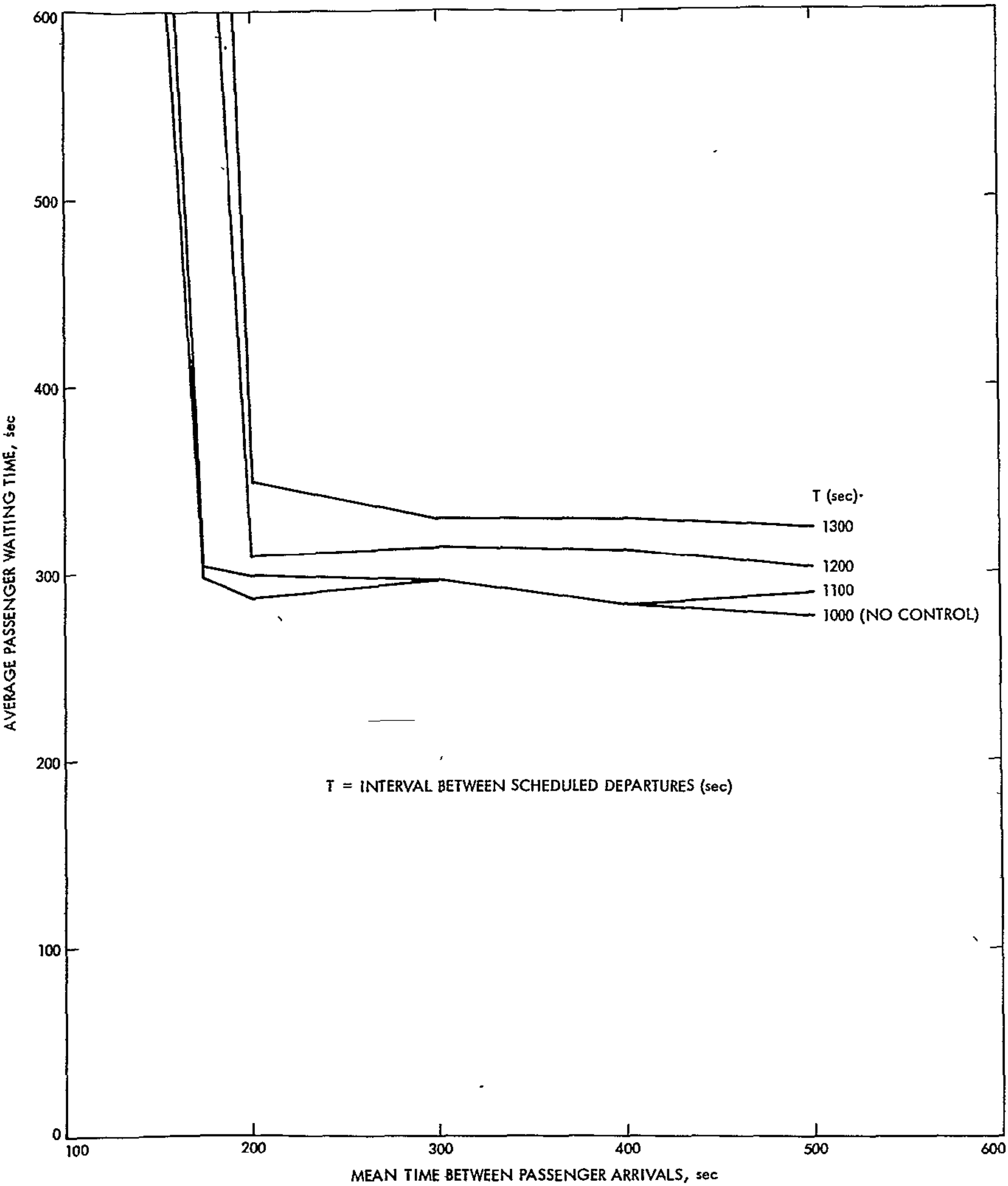


Figure 3.7. Passenger Waiting Time in a Two-Vehicle, Non-Homogeneous System with a Larger Loop; Fixed-Time Scheduling and Headway Control Implemented at a Central Station

3.3 Analysis of Vehicle Scheduling and Headway Control

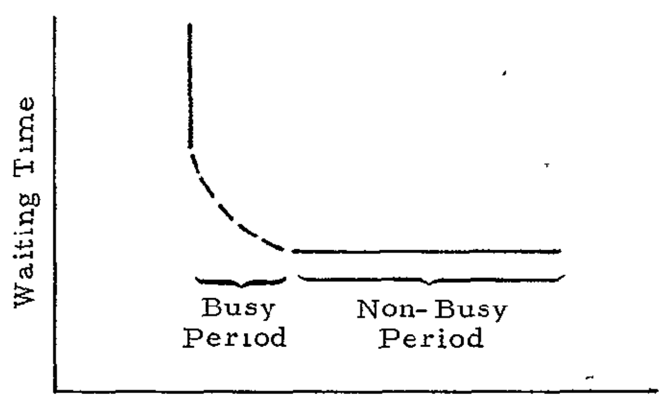
3.3.1 Waiting Time Analysis

For a one-vehicle system, average waiting time has the lower bound of half the average cycle time, (the time required for the vehicle to complete the loop). For a two-vehicle system, average waiting time has the lower bound of one-fourth the average cycle time. In general, the theoretical lower bound of the average waiting time is expressed by average cycle time divided by 2n, where n is the number of vehicles in a loop. The average waiting time approaches infinity as the utilization factor approaches one, i.e., as the arrival rate goes to the capacity of the system. The utilization factor for homogeneous cases can be expressed as follows:

$$\text{Utilization Factor} = (A)\cdot\left(\frac{T'}{T''}\right)\cdot\left(\frac{N}{S}\right)\cdot\left(\frac{1}{V}\right)$$

where A = Average length of travel
T' = Average travel time to next station
T'' = Average interarrival time of passengers
N = Number of stations
S = Number of seats
V = Number of vehicles

The formula is more complicated for non-homogeneous cases. These two bounds give the outline of the waiting time function shown in the following figure.



From the results of the system simulations and study, we can conclude the following:

(1) Headway Control

Headway control is most effective in lowering the average waiting time in non-busy periods by around 20% for a two-vehicle system. The percentage increases as the number of vehicles in the system increases. Figure 3.4a shows the curves of the average waiting time for non-busy periods as a function of headway control for the two-vehicle, homogeneous system with and without scheduling. According to Figure 3.4a, the optimal headway should be set at 70∿90% of the even headway, i.e., the average cycle time divided by the number of vehicles in the loop. The average waiting time will not change much between 70% to 100% of the even headway.

From Figure 3.4a it appears that prescribing a minimum allowable headway at slightly shorter than the even headway minimizes average passenger waiting time. This is because when the minimum allowable headway is shorter, simulated actual headways average around even headway. But when the even headway is adopted as the minimum allowable headway, the actual headways average at a number higher than the even headway, resulting in a higher waiting time to passengers.

Curves showing the simulated average passenger waiting times during busy periods are given in Figure 3.4b. In this case, shorter waiting time was achieved with short headway because the average waiting time of a passenger was many times longer than the average cycle time for a vehicle to complete a loop. When the passenger waited many cycles before getting on a vehicle, the accumulated time delays due to holding the vehicle for headway control became a dominant factor in the waiting time, and the initial time-saving because of a more balanced headway became relatively unimportant.

(2) Vehicle Scheduling

As to the impact of scheduling on the average passenger waiting time, the difference between fixed-time scheduling and cycle-time scheduling was found to be insignificant. The third method, inter-station scheduling, appears to be inferior to the two methods mentioned above because it showed slightly higher simulated average waiting time, as discussed in Sections 3.2.1 and 3.2.2, and is likely to cost more to implement.

During the non-busy period, using either cycle-time scheduling or fixed-time scheduling makes no significant difference in average passenger waiting time, provided that the time intervals between departures in both methods are the same. For this period, it is recommended that, using either cycle-time scheduling or fixed-time scheduling, the average cycle time (the time required for the vehicle to complete a loop) be used as the minimum allowable cycle time. For the busy period, the minimum waiting time can be obtained by not having any scheduling control at all.

In case of longer loops where one cycle takes a longer time and arrivals of vehicles are less frequent, passengers may prefer punctual scheduling to minimized waiting time. In this case, fixed-time scheduling would be preferable to cycle-time control. To implement fixed-time scheduling, it is advisable to provide an algorithm to reset the clock in such a way that the vehicle skips one cycle if it is too far behind schedule to catch up within reasonable time.

The simulated load factors shown in Fig. 3.1b and Fig. 3.2b indicate that when passenger arrivals become less frequent, the load factors decrease accordingly. This results in uneconomical operation. To increase the load factor without prolonging waiting times for individual passengers, the transit system can schedule vehicles at a lower frequency and use fixed-time scheduling so that passengers can plan their own time. The system can also change to a demand-scheduling mode in which the vehicles are dispatched on demand.

Implementation of scheduling and headway control, through time measurement and vehicle holding, should be done at one central station instead of at all stations since holding the vehicle at multiple stations increased the simulated average passenger waiting time and is likely to be more costly. An exception occurs when the expected interarrival time of vehicles at a station becomes so long that passengers would rather have a precise AMTV schedule to plan their own time; control at all stations should be implemented in this case. As shown in Figure 3.8b, more vehicles should be dispatched for service as the average waiting time increases. For the busy period, all available vehicles are in service, and headway control and scheduling control are suspended. The system therefore needs space to store unused vehicles for use in busy periods. This is also true for passenger-activated, demand-responsive vehicle systems in which space may be necessary at many stations.

3.3.2 Number of Vehicles Needed in a Loop

Figure 3.8a presents a set of curves showing the average passenger waiting time with varying number of vehicles in the loop. These curves were drawn for the

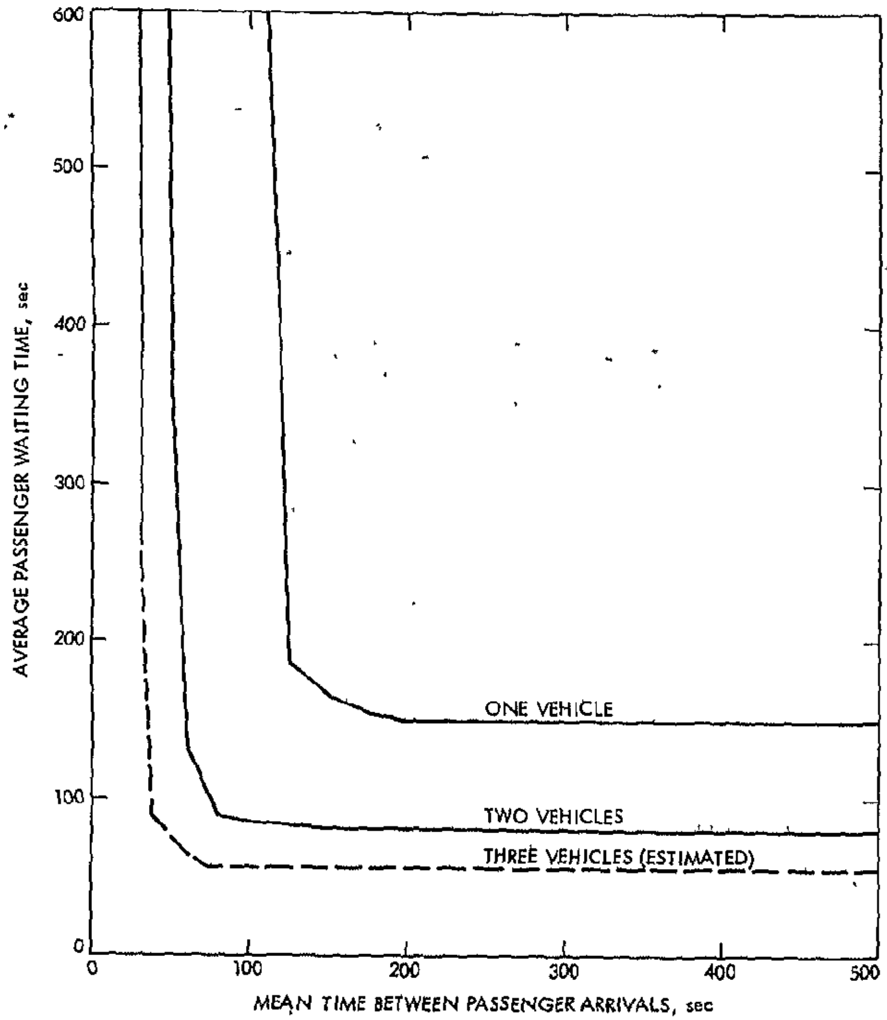


Figure 3.8a. Minimum Achievable Passenger Waiting Time for Varying Number of Vehicles

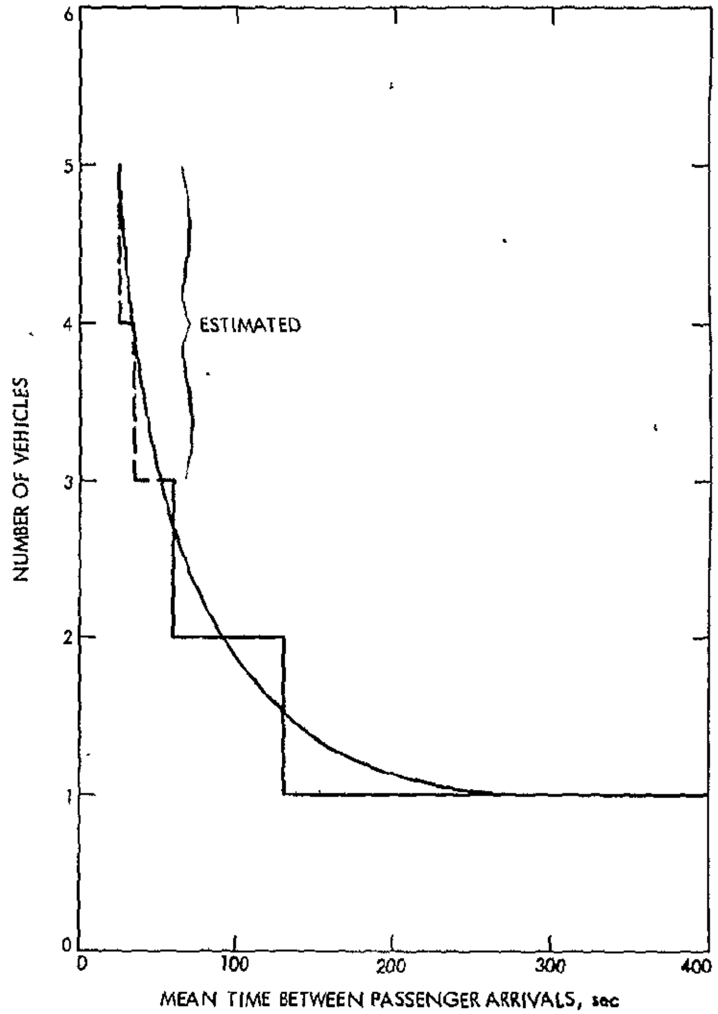


Figure 3.8b. Number of Vehicles Needed to Keep Waiting Time Less Than 3 Minutes

homogeneous systems described in Section 3.2, but non-homogeneous systems give the same results. The systems represented are the following:

(1) One-vehicle system, no schedule control.

(2) Two-vehicle system, no schedule control, prescribed headway set at half of even headway.

(3) Three-vehicle system, no schedule control, prescribed headway set at half of even headway, waiting times estimated according to the formula in Section 3.3.1.

The curves shown in Figure 3.8a represent the lowest passenger waiting times attainable with any headway control and vehicle scheduling schemes. Based on these curves, the number of vehicles needed in the loop to maintain the average passenger waiting time below a predetermined time can be derived, such as the function given in Figure 3.8b with the predetermined time set at three minutes. This type of policy can be implemented either on a real-time basis or according to historical passenger arrival statistics.

3.4 Multiple Loop System

There are two classes of multiple loop systems. One is the fixed-route system where the vehicle cannot change its route from one loop to another. The other is the variable-route system where the vehicle can change its route from one loop to another.

The fixed-route system can be treated as a collection of single-loop systems without interactions among them. An exception is the system in which distances between stations are very large and/or the number of vehicles in the system is small. In this case, the average waiting time at the transfer point is very long and, therefore, fixed-time scheduling with coordinated transfer will be necessary. Reducing waiting time at transfer points is important since transfer from one loop to another will be common in a fixed-route system.

The variable-route system can eliminate the transfer of passengers and may handle point-to-point service. This system must resolve the conflict of destinations between passengers. It requires much more complicated route-control algorithms which heavily depend on loop configurations, route characteristics, and passenger arrival rates. Flexible route systems are not analyzed in this study. As indicated in Chapter 5, they are included as a part of our proposed further study of large-scale AMTV systems.

4.0 VEHICLE PERFORMANCE AND SPEED CONTROL

Several topics are discussed in this chapter. Section 4.1 examines the speed degradation of an AMTV in the presence of pedestrians crossing at random. Section 4.2 evaluates the on-board automatic control parameters to achieve safe stopping and passenger comfort. Section 4.3 describes a simple automatic control algorithm, implementable with an on-board microcomputing device, which can maintain smooth and precise speed control when the vehicle encounters random traffic disturbances.* Section 4.4 presents a preliminary analysis of the AMTV and roadside control requirements at intersections.

4.1 Average Vehicle Speed in Mixed Traffic

Average vehicle speed refers to the statistical average of the speed of an AMTV when it experiences random, mixed-traffic disturbances. Speed variations due to deceleration, stopping, and acceleration near a passenger station are not included since the emphasis here is on evaluating the impact of the mixed traffic on the vehicle performance. In this study, we have focused on the interference of the crossing pedestrians since pedestrians are likely to be the most frequent obstacles encountered by the low-speed AMTV in its normal operation. The average speed is estimated using a simulation model incorporating two categories of information: those characterizing the vehicle, and those characterizing random pedestrian disturbances. The procedure is illustrated in Figure 4.1, and is described in the following sections.

4.1.1 Characteristics of the Current-Version AMTV

The vehicle characteristics adapted in this model resemble the characteristics of the current version of the vehicle operating at JPL. They are based upon specifications contained in the original design book (Ref. 1) with minor modifications to reflect some recent development and to account for a time delay in the present sensor/controller interface. As indicated in Figure 4.1, the vehicle data can be further divided into the following groups:

*This capability is not yet fully developed in the current-version AMTV.

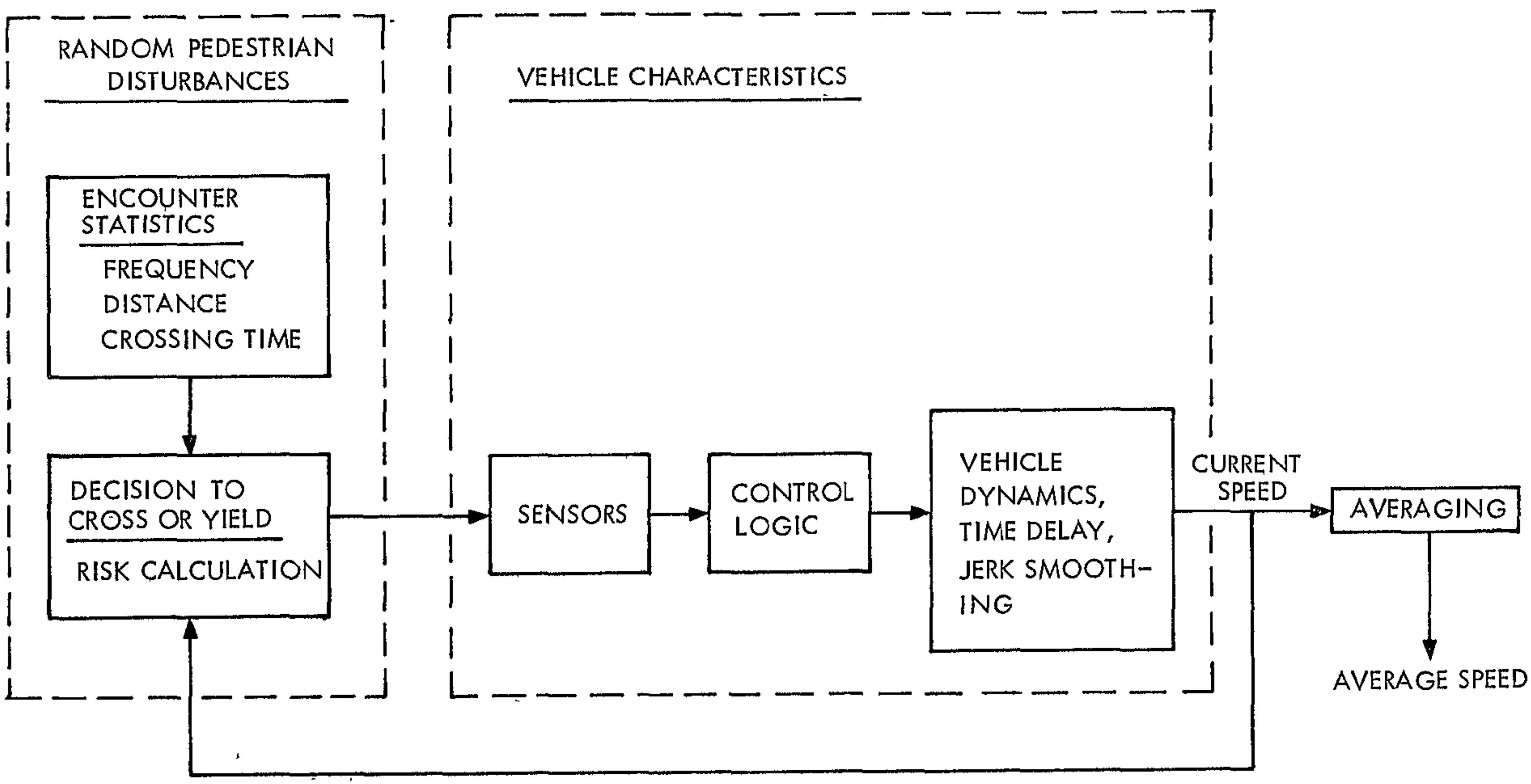


Figure 4.1 AMTV - Pedestrian Interface Model

A. Sensing Capability

When the vehicle comes near an obstacle in front, the obstacle can be detected by the primary sensor at 25 feet, by the secondary sensor at 5 feet, and by the contact sensor (the "bumper") at 3 feet. The vehicle cannot sense the relative velocity of a moving vehicle in front, but information on its own speed and acceleration is available.

B. Speed Control Logic

The vehicle has a maximum cruising speed of 7 mph and an intermediate cruising speed of 2 mph. It does not move backward. Discounting the effect of jerk-smoothing, which prevents abrupt changes of acceleration, the vehicle normally accelerates or decelerates at a rate of 0.1g (3.2 ft/sec^2). When making an emergency stop, the deceleration rate is about 10 ft/sec^2. The speed control logic can best be represented as a matrix showing the level of acceleration or deceleration within a particular speed range and a particular distance range. This is given in Table 4.1. For example, the last column of Table 4.1 states that if there is no obstacle within 25 feet, the vehicle accelerates at 3.2 ft/sec^2 to 7 mph. The third column states that if the nearest obstacle is within a 5 to 25 foot range, the vehicle at 7-mph cruising speed will slow down to 2 mph. It will maintain the speed until the vehicle comes within 5 feet of the obstacle. Then the vehicle will decelerate again until it comes to a stop.

C. Vehicle Dynamics, Jerk-Preventive Smoothing, and Time Delay

The actual longitudinal dynamics of the vehicle are represented by a third order system in which the rate of change of acceleration is a constant.* The only parameters which are instantaneously changeable are the direction of the acceleration change (increase or decrease) and the conditions controlling the duration of the change. The nominal accelerations shown in Table 4.1 are the starting points and destinations of these constant-rate acceleration changes. The

*An exception is the emergency-stop deceleration scheme, which attains the maximum deceleration rate immediately, instead of gradually.

Table 4.1 AMTV ACCELERATION/DECELERATION RATES AS A FUNCTION OF VEHICLE SPEED AND DISTANCE FROM NEAREST OBSTACLE

CURRENT-VERSION VEHICLE*

(in ft/sec^2)

Vehicle Velocity (MPH)**	DISTANCE FROM NEAREST OBSTACLE (ft)			
	0-3	3-5	5-25	>25
$0-2_-$	-10	-3.2	+3.2	+3.2
$2_- - 2_+$	-10	-3.2	0	+3.2
$2_+ - 7_-$	-10	-3.2	-3.2	+3.2
$7_- - 7_+$	-10	-3.2	-3.2	0

* Actual speed control includes additional smoothing mechanism allowing for gradual changes of acceleration.

** Subscript "+" denotes a number slightly larger than the original number. Subscript "-" denotes a slightly smaller number.

constant speed levels (7, 2, 0 mph's) constitute another set of constraints for the acceleration change algorithms to meet. This finite-rate acceleration-change procedure is a smoothing procedure which serves to reduce the unpleasant jerkiness caused by abrupt changes of acceleration during normal vehicle speed changes. It also helps to reduce the effect of limit-cycle oscillations when the vehicle is following another vehicle running at a lower speed. The change rate of acceleration is assumed to be 0.1g per second for this simulation.* This simulation also includes an estimated 0.2 second time delay between sensing and control actuation. This is consistent with the anticipated characteristics of an improved vehicle.*

4.1.2 Characteristics of Random Mixed-Traffic Disturbances

Mixed-traffic disturbances are of several kinds, depending on the types of urban application. Since the current vehicle is designed for low-speed operation, we have chosen to analyze the impact of crossing pedestrians on the average speed of such a vehicle. The results of the simulation study will be restricted to pedestrian disturbances; the methodology, however, can be extended to cover other kinds of disturbances.

For lack of real data applicable to this new mode of transit operation, we have made the following assumptions and estimates in describing the behavior of pedestrians.

A. Random occurrences of pedestrians encountering the vehicle.
We have assumed that these potential disturbances are mutually independent and that time periods between successive encounters are exponentially distributed. Simulations have been carried out for a spectrum of mean-time-between-encounters to study the changing impact on the average vehicle speed. These encounters are only potential disturbances since some of these pedestrians may be discouraged by the vehicle speed and decide not to cross the guideway in front of the vehicle.

*Per conversation with Dr. A. Johnston at JPL.

B. Random encounter distance from the pedestrian to the vehicle.

We have assumed that just before a pedestrian enters the primary sensor range (0~25 feet in front of the vehicle), his distance from the vehicle can be anywhere between 7 and 25 feet, with a distribution density function showing higher probability near the 25-foot end, and diminishing probability near the 7-foot end.*

C. Random crossing time.

We have assumed that the time duration for a pedestrian to cross the frontal area of an AMTV (about 8 feet from side to side; see Ref. 1) follows a truncated normal distribution with a mean of 2 seconds, and a standard deviation of 1/3 second, so that over 99% of the pedestrian disturbances stay in the vehicle frontal area from one to three seconds.

D. Pedestrians yielding to the approaching AMTV.

We have assumed that before crossing, each encountered pedestrian will perform one of two possible risk calculations, depending upon his attitude toward competition for the right of way with the approaching vehicle. Both calculations involve estimation of the vehicle speed, the encounter distance, and the pedestrian's crossing time. If the pedestrian takes a competitive attitude, he reckons that if he crosses, the automated vehicle will slow down and stop for him. In this case, he will estimate the stopping distance of the moving vehicle and compare it with the encounter distance. If the stopping distance is short, he will cross; otherwise, he will yield. If the pedestrian takes a non-competitive attitude, either because of public instructions or regulations or out of his own decision, he will not take advantage of the automatic deceleration of the AMTV. In this case, he will estimate the traveling distance of the vehicle based on its keeping its current speed for the next three seconds (the upper bound of the pedestrian's estimated crossing time). If the estimated traveling distance of the vehicle is shorter than the encounter distance, he will cross the guideway; if the traveling distance is longer, he will yield.

*On a normalized distance scale x ranging from 0 to 1, where 0 corresponds to 7 feet and 1 corresponds to 25 feet, the assumed density function is $3x^2$.

In this study the estimated stopping distance and traveling distance are both assumed to be random numbers with normal distribution. Their means are set to equal the true stopping and traveling distances. The randomness represents the uncertainties in the pedestrians' estimations. Dependence of the risk calculations upon estimated vehicle speed, encounter distance, and crossing time reflects the normal human tendency to cross a street (where rules against jay-walking are not enforced) when the approaching vehicle is relatively distant and relatively slow.

4.1.3 Simulation Results

A simplified flow chart of the simulation model is given in Appendix E. Simulation results showing the average vehicle speed under various circumstances are plotted in Figure 4.2. In this figure, the horizontal axis represents the density of the pedestrian traffic along the AMTV route in terms of mean time between encounters. The three distinct curves represent the average vehicle speed generated by the model according to three different assumptions of pedestrian's attitude toward the AMTV. The three assumptions are:

Case 1: No encountered pedestrians will compete with the AMTV for right of way. A pedestrian will decide to cross the guideway only if, according to his own estimation, he judges the vehicle to be at least three seconds away at its current speed. However, his judgment may be wrong due to uncertainties in his estimation.

Case 2: All of the encountered pedestrians will compete with the AMTV for right of way. They will take advantage of the fact that the AMTV will slow down and stop for crossing pedestrians. In this case, a pedestrian will decide to cross the guideway if he determines that, according to his own estimation of current vehicle distance and speed, the vehicle will come to a stop before hitting him. Again, his estimation has uncertainties.

Case 3: Of all the pedestrians, 50% will compete with an AMTV as in Case 2, and 50% will not, as in Case 1.

Eighteen cases were simulated, corresponding to six different values of mean time between encounters (from 1 second to 32 seconds) and three different assumptions of pedestrians' behavior. In each case, the vehicle speed was averaged after the vehicle had encountered 300 pedestrians; multiple simulation runs were made to assure statistical consistency.

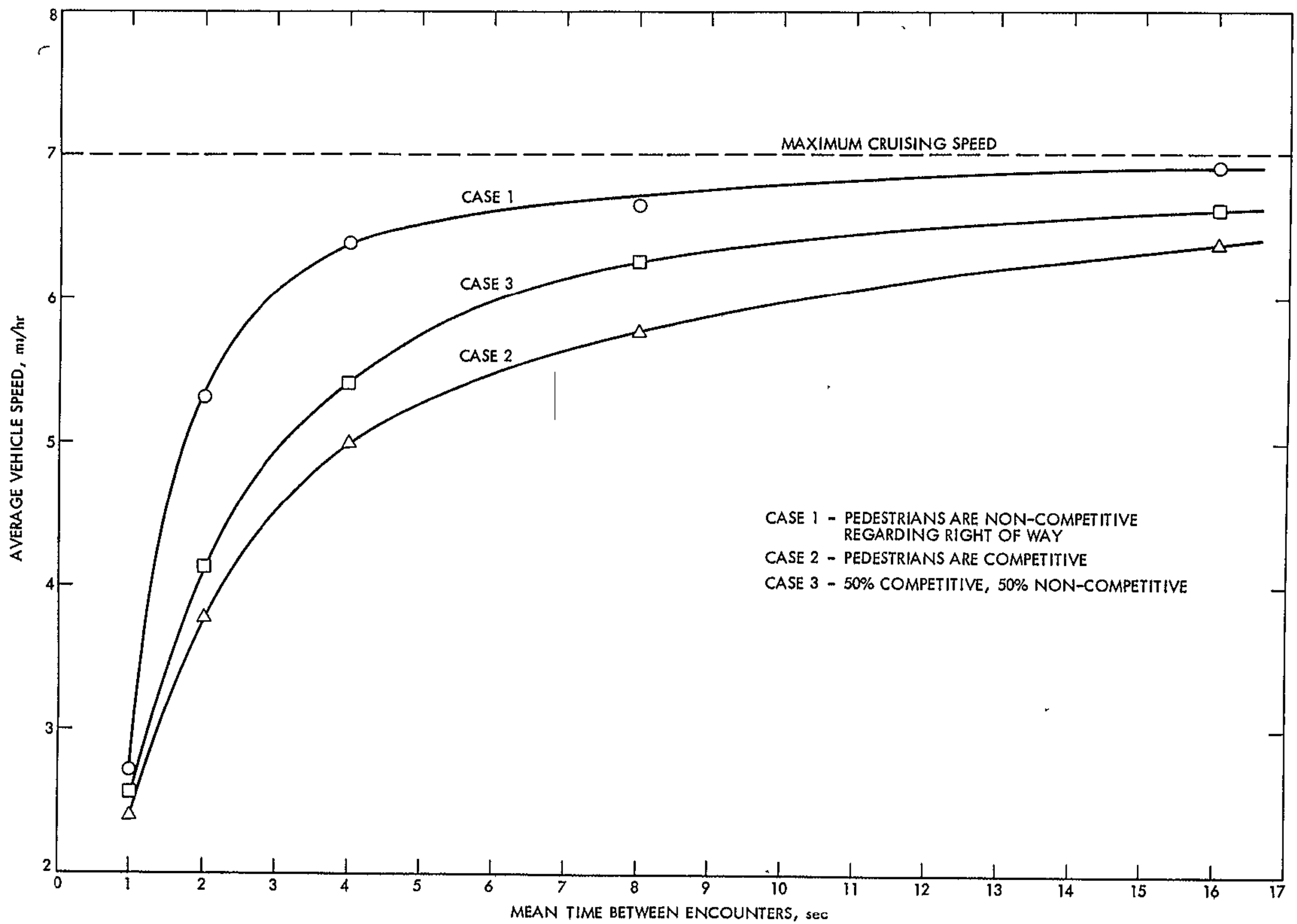


Figure 4.2. Average Speed of an AMTV Under Pedestrian Disturbances

The data on Figure 4.2 brings forth the following points:

A. The average speed of an AMTV is close to its maximum cruising speed when its encounters with pedestrians are infrequent. (The curves show less than 10% speed degradation for mean time between encounters longer than 16 seconds.)

B. The average speed of an AMTV can be lower than half of its maximum speed when the pedestrian traffic is dense. (The Case 2 curve shows a 25% to 50% speed degradation for mean time between encounters as low as 5 or 2 seconds, a pedestrian traffic quite possible during busy hours in a large shopping mall.)

C. Significant improvement of average vehicle speed can be achieved if pedestrians are not competitive with the AMTV regarding right of way. (Data in Case 1 shows large speed increase over the data in Case 2, the largest being a 40% increase for a 2-second mean time between encounters.)

D. The average speed of an AMTV will be more uniform and less sensitive to the variations of pedestrian traffic if pedestrians do not compete with the AMTV. (Comparing Case 1 and Case 2, the curve in Case 1 remains relatively flat from right to left until the mean time between encounters reaches 1 second.)

For the above simulated cases, we have also recorded the frequency of use of emergency brakes when the vehicle comes within 3 feet from a pedestrian in front. The absolute levels of these frequencies are likely to be inexact once some actual data becomes available in the future, but the relative magnitude between various cases is quite indicative. The approximate numbers of emergencies for every 100 pedestrian encounters are listed in Table 4.2.

Table 4.2 NUMBER OF TIMES THE EMERGENCY BRAKES ARE USED PER HUNDRED ENCOUNTERS

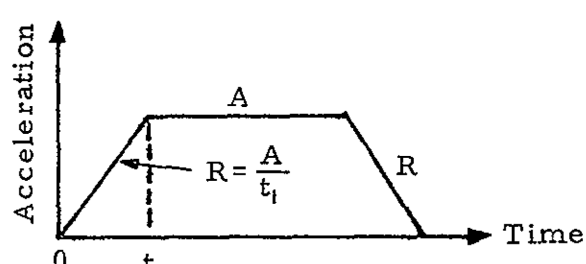
Mean-Time-Between Encounters (sec)	All Pedestrians Are Non-Competitive	Half of Pedestrians Are Competitive, Half Are Not	All Pedestrians Are Competitive
1	1	1	1
2	1	2	5
4	1	3	6
8	1	4	8
16	1	5	8
32	1	6	9

As would be expected, Table 4.2 indicates that the accident rate is likely to be reduced if pedestrians are instructed to yield to the AMTV.

4.2 Vehicle Speed Control

The longitudinal control of an AMTV discussed here refers to the choice of acceleration rate and the acceleration change rate (sometimes called "jerk rate" in transportation literature, Ref. 2, page 296) to meet the requirement of safety and achieve passenger comfort in operation. The safety requirements are needed to ensure an acceptable stopping distance which does not exceed the maximum sensing range of the AMTV. These requirements define a boundary for allowable acceleration and acceleration-change rates; the choice of these rates which will determine the degree of smoothness and comfort to the passengers.

Using control system terminology, the longitudinal dynamics of the vehicle constitute a third order system in which only the acceleration-change rate can be instantaneously changed by the control system. To accomplish a velocity change, the acceleration has to be changed first according to the profile shown in the following figure.



Finite-Rate Change of Acceleration

In this figure, A is the steady-state acceleration rate and R is the magnitude of the acceleration-change rate.

Such a dynamic system with finite acceleration-change rates cannot reduce the vehicle speed immediately if the vehicle is initially in the course of acceleration. Therefore, the worst-case stopping distance is actually longer than the nominal stopping distance of the vehicle which is cruising at its maximum speed. An exclusive-guideway vehicle may rarely meet an obstacle when accelerating, but a mixed-traffic vehicle may find itself in this situation very often. This problem is analyzed in the following sections.

4.2.1 Safe Stopping Requirements

Stopping from maximum cruising speed

Assume that the vehicle is cruising at its maximum speed V (fps). The stopping distance X_1 will then be

$$X_1 = \frac{V^2}{2A} + \frac{AV}{2R} \quad \text{ft} \tag{4.1}$$

where A is the steady-state deceleration rate in f/sec^2, and R is the acceleration-change rate in f/sec^3. The corresponding stopping time is

$$T_1 = \frac{V}{A} + \frac{A}{R} \quad \text{sec} \tag{4.2}$$

If D is the predetermined maximum allowable stopping distance, such that $X_1 \leq D$ is to be satisfied, it follows from Eq 4.1 that both the deceleration A and the acceleration-change rate R have to be large enough:

$$A > 0.5 \frac{V^2}{D} \tag{4.3}$$

$$R \geq \frac{VA^2}{2DA-V^2} \tag{4.4}$$

The equations 4.3 and 4.4 define a zone of allowable A's and R's that assure safe stopping within D feet. The zones for a 7 mph maximum speed (V = 10.27 fps) and various maximum allowable stopping distances are shown in Figure 4.3, to the right of the broken lines. The upper limit of A is the equation

$$A \leq \sqrt{RV} \qquad (4.5)$$

which assures that the vehicle does not change direction while decelerating.

Worst-case stopping

The longest stopping distance occurs when the vehicle is at a speed lower than the maximum cruising speed V but is accelerating toward V. Assume that the steady-state acceleration rate equals the steady-state deceleration rate, A, as was implemented in the current-version AMTV, and that the acceleration-change rate is still R. The worst case would then start at an initial acceleration A and an initial velocity V_o, where

$$V_o = V - 0.5\frac{A^2}{R} \quad \text{fps} \qquad (4.6)$$

The stopping distance is then

$$X_2 = \frac{V^2}{2A} + \frac{AV}{2R} + \left(\frac{AV}{R} - \frac{A^3}{6R^2}\right)$$

$$= \frac{V^2}{2A} + \frac{3AV}{2R} - \frac{A^3}{6R^2} \text{ ft} \qquad (4.7)$$

The quantity in the parenthesis is the additional stopping distance, as can be compared with Eq. 4.1. The stopping time is greater than in the previous case:

$$T_2 = \frac{V}{A} + \frac{2A}{R} \quad \text{sec} \qquad (4.8)$$

To find the safety design zone for allowable R's and A's such that $X_2 \leq D$, we can simplify the analysis by assuming

$$A = a\frac{V^2}{D} \quad \text{fps}^2 \qquad (4.9)$$

$$R = r\frac{V^3}{D^2} \quad \text{fps}^3 \qquad (4.10)$$

where a, r are dimensionless. Then, it can be shown that a, r must satisfy:

$$3.875 > a > 0.5 \qquad (4.11)$$

$$a < \sqrt{r} \qquad (4.12)$$

$$r \geq \frac{0.5a^2}{2a-1}\left(3 + \frac{1}{\sqrt{3}}\sqrt{31-8a}\right) \qquad (4.13)$$

Equation 4.12 and the lower limit in Eq. 4.11 are the same as Eq. 4.5 and Eq. 4.3. The upper limit in Eq. 4.11 and the relationship in Eq. 4.13 are particular to this worst case.

The safe design zones for A's and R's are shown in Figure 4.3 as the zones to the right of the solid lines.

Discussion

A. It is seen in Figure 4.3 that these worst case stopping requirements are much more stringent than the requirements to stop a vehicle cruising at the maximum speed. For example, the control parameters chosen for the current version ($A = 3.2\ fps^2$ and $R = 3.2\ fps^3$) are sufficient to stop a 7 mph cruising AMTV in 22 feet, but the acceleration-change rate R must be at least $6.5\ fps^3$ with a corresponding acceleration rate at $5.0\ fps^2$ to stop an accelerating AMTV in the worst case within the same distance.

B. Curves in Figure 4.3 represent boundaries of zones of allowable acceleration and acceleration-change rates if the maximum velocity and safe stopping distance are specified. Similar curves can be easily generated, using the equations previously derived, for a family of initial velocities and desirable stopping distances. These curves not only lay out safety requirements but also provide flexibility in choosing the combinations of acceleration and acceleration-change rates that satisfy additional smoothness and ride-quality criteria*.

C. Usually a physical delay on the part of the control system in responding to a sensed obstacle further lengthens the actual stopping distance. The time delay with the first-version AMTV was estimated to be about 0.2 seconds+ which would increase the stopping distance by less than 2 feet. This small perturbation was left out from the previous analysis for simplicity.

*It is generally felt that acceleration rate and acceleration change rate should both be low to provide a comfortable ride. To this end, the curves in Figure 4.3 are helpful. A critical evaluation of the criteria of comfort is beyond the scope of this study.

+Per conversation with Dr. A. Johnston at JPL.

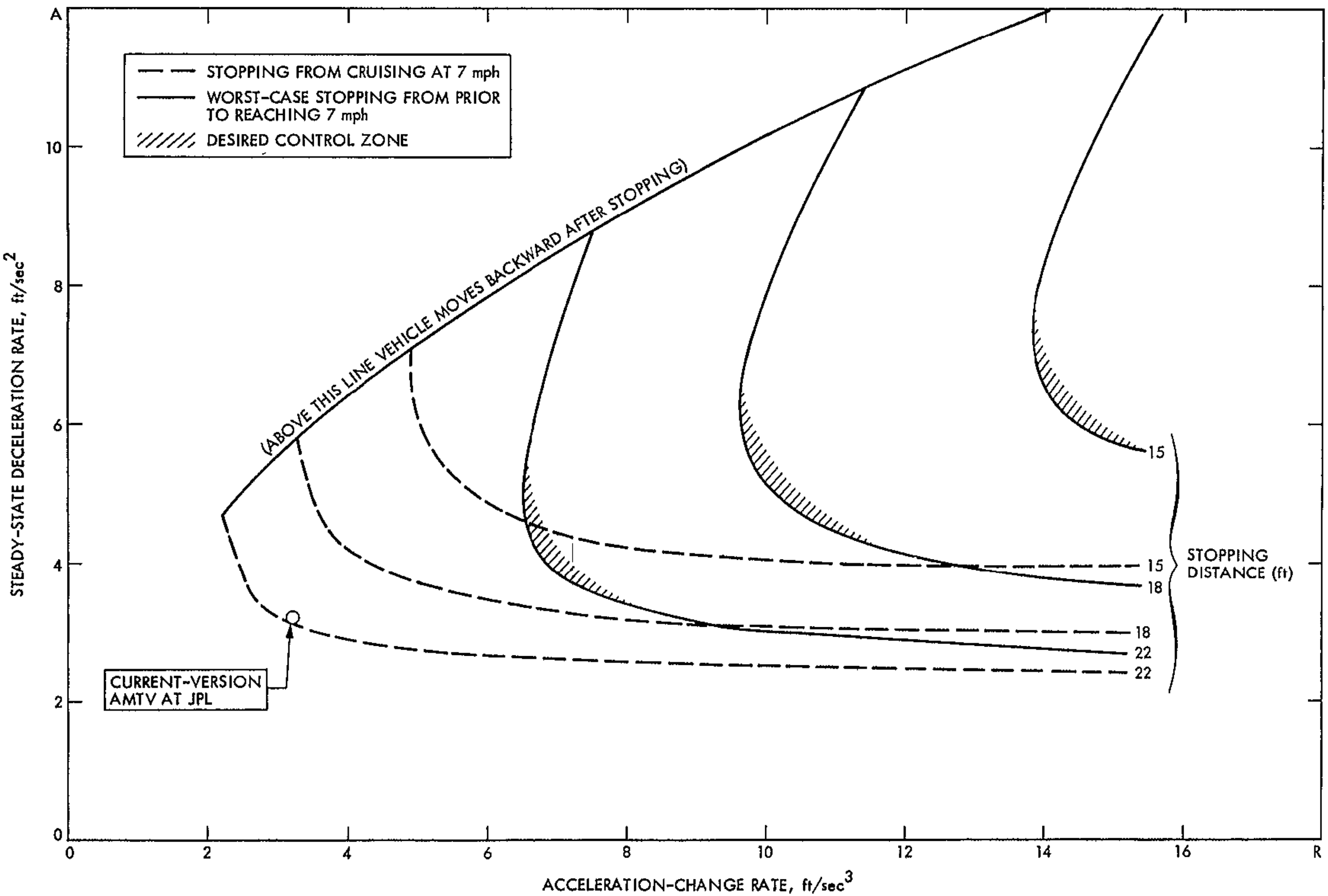


Figure 4.3. Boundaries of Allowable Speed-Control Parameters Satisfying Various Stopping-Distance Requirements

4.2.2 Vehicle-Following Requirements

A variety of safety criteria have previously been considered regarding the spacing of vehicles in a car-following condition for collision avoidance in case of emergency (Ref. 2, pp 295-311). The most conservative criterion assumes that the preceding vehicle may be stopped instantaneously, a condition sometimes referred to as a "brick-wall" stop. In this worst case situation, the following vehicle must be provided with a headway space to come to a gradual stop without collision. A more optimistic criterion would assume that the preceding vehicle will not come to a "brick-wall" stop. This criterion allows the vehicle spacing to be reduced to a minimum corresponding to the response time of the following vehicle, and is similar to the official highway-driving guideline which advises the driver to keep a distance proportional to his current speed from a preceding car.

Given the overriding importance of safety in public transit operations, it appears that the conservative criterion is more appropriate to the operation of AMTV systems since an AMTV must stop more frequently, for random mixed-traffic disturbances, than exclusive-guideway vehicles. This conservative car-following criterion is the same as the stopping criterion discussed in the previous section, and the control strategies discussed in the previous section should be applicable to vehicle-following. In this case, the sensing device only has to sense relative distance.

If the more risky stopping criterion is adopted, a relative-velocity sensing device is necessary. The following vehicle will make less stops but the accident rate is likely to be higher.

When an AMTV follows another vehicle which is traveling at a slightly lower speed, the passengers on the AMTV may feel some longitudinal vibrations. This is because the AMTV will first catch up with the preceding vehicle. When the sensor on the AMTV detects the preceding vehicle, it will begin to decelerate until the preceding vehicle leaves its sensing range. At that moment, the AMTV will speed up. Eventually, it will catch up with the preceding vehicle again, thus causing periodic motions. This undesirable vibration is reduced by the effect of a time delay in the sensor/controller interface and by the velocity-smoothing process which ensures gradual changes of acceleration.

4.3 Algorithm for Smooth Velocity Transition

Implementation of the control profile as shown on page 29 requires a predictor-type algorithm. When the velocity approaches a constant level, the controller must start reducing the acceleration or deceleration according to a predetermined acceleration-change rate. It must do this at the right moment to ensure that the velocity will be precisely the desired velocity, and that acceleration will be zero at the end of the acceleration-change period. An effective algorithm is therefore required to accomplish this smoothing. The algorithm must ensure smooth transition not only when the vehicle makes predictable velocity changes, such as arriving at and leaving a station, but also when it makes unpredictable changes due to random mixed-traffic disturbances. In addition, this algorithm must also consider the physical time delay in the sensor/controller interface in order to minimize errors.

An algorithm has been developed in the course of the simulation study based on the dynamics and speed-control logic of the current-version vehicle operating at JPL. At any moment, the vehicle is either accelerating or decelerating toward one of three possible steady-state speed levels: 7 mph, 2 mph, and zero speed. Based on the current speed and acceleration of the vehicle, the algorithm will predict the velocity level at the end of a smoothing period during which the acceleration or deceleration will level off to zero. If the predicted velocity has exceeded the target speed, the vehicle will start the process of smoothing. If the predicted velocity has not yet reached the target speed, the vehicle will go on with its current course without starting the smoothing process. In predicting the end velocity, a 0.2-second delay in the physical system which precedes the actual beginning of the smoothing action is also taken into consideration.

An unsmoothed system characterized by instantaneous changes of acceleration rate gives the simulated velocity-time diagram shown in Figure 4.4. In this case, a pedestrian traffic interference with a 2-second mean time between encounters was simulated. All the downturns are caused by the detection of pedestrian disturbances, and all the upturns are caused by their disappearance from the sensing range. The effect of applying the smoothing algorithm to the same case in simulation is demonstrated in the velocity-time diagram shown in Figure 4.5. The output was drawn by an on-line machine plotter.

Since the current-version AMTV does not have a fully developed smoothing scheme that promises the same degree of precision in speed control in a mixed-traffic operation with random perturbations, the scheme developed for this simulation study appears to be an easily implementable algorithm for actual application.

4.4 Control at Intersections

The presence of an AMTV at an intersection poses problems to both safety and traffic flow. Safety problems include possible collison with other vehicles or pedestrians at the intersection. Traffic problems arise because any traffic regulations allowing for safe passage of low-speed automated vehicle will almost certainly impair the regular capacity of the intersection in handling traditional street vehicles. Both aspects require a much deeper analysis than allowed within the resource of the current study. However, we shall discuss some important requirements of additional on-board sensing capabilities and evaluate the sufficiency of current traffic rules so that an AMTV can at least be allowed to go through a four-way intersection without causing serious safety problems. We shall analyze the situations at an intersection with a traffic light, with a four-way stop, and with a two-way stop to determine these safety requirements.

4.4.1 Intersections with traffic signals.

The problems confronting an AMTV at a regular signaled intersection, which does not allow protected turns (green arrows), are the following:

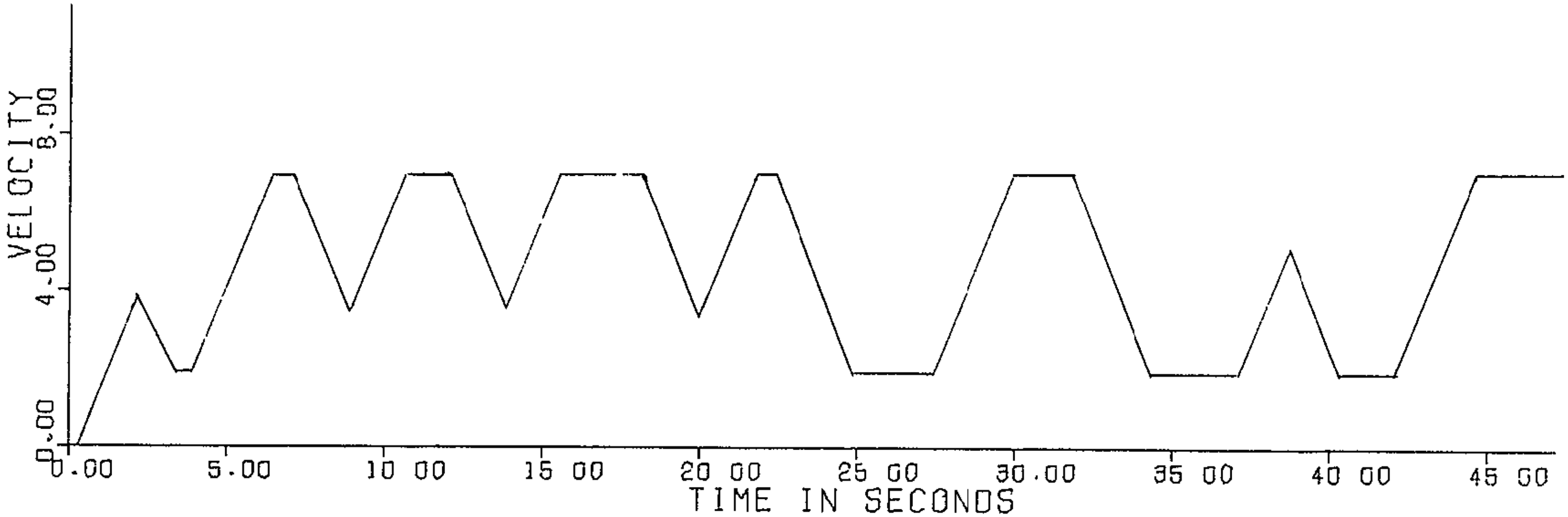


Figure 4.4. Unsmoothed Vehicle Dynamics Simulated at a Pedestrian Interface of Two-second Mean-Time-Between-Encounters

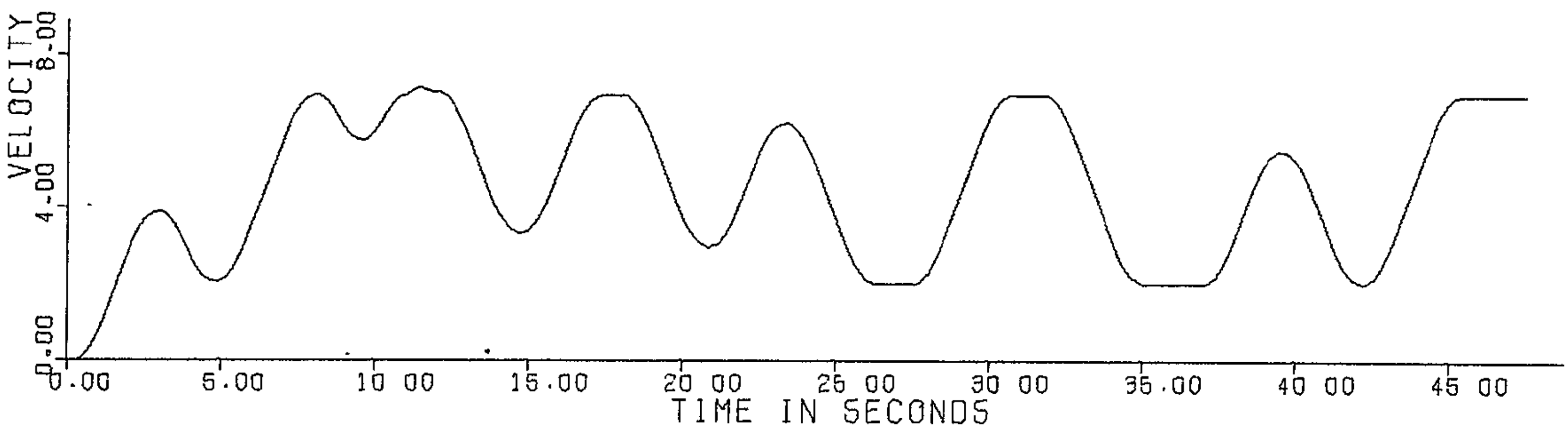


Figure 4.5. Smoothed Vehicle Dynamics Simulated at a Pedestrian Interface of Two-second Mean-Time-Between-Encounters

1) When the AMTV makes a right turn, it must yield to the pedestrians.
2) When the AMTV goes straight ahead, it must guard against over-anxious vehicles from the opposite side trying to make a left turn.
3) When the AMTV makes an unprotected left turn (without a green arrow signal), it must yield to a straight-going vehicle from the other side and also to the crossing pedestrians on its left.

These problems will not exist at intersections where protected turns (green arrows) are provided and no other vehicles or pedestrians are allowed to interrupt the AMTV. Such an intersection would be safe for AMTV operation if all the vehicles and pedestrians obey the rules. Otherwise, the AMTV must have additional sensing capability to be able to drive "defensively."

The AMTV needs a sensor that looks in its diagonal direction to guard against crossing pedestrians and fast-approaching vehicles. At an intersection with protected turns, this capability guards against emergency situations. At an intersection with any less protection, this capability is a necessity.

4.4.2 Intersections without traffic signals.

At a two-way stop intersection where the AMTV must stop, the AMTV must be equipped with sensitive distance and velocity sensors in both frontal and sideway direction. The risk is still high.

At a two-way-stop intersection where the vehicle coming from the crossing directions must stop, the AMTV confronts the same situation it would be facing at a regular signaled intersection, when it is given a green light but the turn is not protected.

At a four-way-stop intersection, the AMTV can wait and get its priority (as is currently done at JPL). All vehicles at the intersection should respect this priority. However, competitive situations may arise to which a human driver can effortlessly adjust, but for which the AMTV would need additional capability to sense the situation and make an appropriate adjustment. The sensing capability should at least include sideway sensing for distance and relative velocity between the AMTV and a potential obstacle.

In short, the AMTV should have additional sensors to detect objects and motions from both left-front and right-front directions at an intersection. Current traffic rules which provide exclusive right of way at intersections would allow safe passage of AMTV's if these rules are indeed obeyed by all vehicles and pedestrians at the intersection.

5.0 PROPOSED FURTHER STUDIES

The methodology developed and the results obtained in this study are readily extendable to further studies which are important to AMTV implementation in urban areas. Three possible areas suitable for further studies are described in the following sections.

5.1 An Urban Implementation Study

This study will first evaluate which types of urban environments are most suitable for AMTV application, and then study in detail the system control problems that can possibly be anticipated in one or two of the most suitable applications.

The candidates to be considered include city malls, large shopping centers, government complexes, universities, airports and limited-size business districts. The criteria for evaluation will include cost, demand, ease of implementation, and comparison with alternative transit systems. Advice will be sought of cognizant personnel of these facilities.

Once an urban application is selected for implementation study, concrete system-control problems can be considered. These will include route selection, guideway layout, stations configuration, intersection control and pedestrian crossing zones in addition to the scheduling and headway control problems already addressed in the present study. In conducting this proposed study, user's preference and the impact of AMTVs on regular traffic flow will be important considerations.

5.2 Large Scale AMTV Transit Systems

For a large number of vehicles, operating in a transit system of many loops which cover a wide area, the optimal operating strategies developed for a small-scale system will not suffice. A system with a number of vehicles demands a good strategy for efficient vehicle allocation and dispatch.
A system with a network of many transit loops may need to carry passengers from point to point with minimum transfer between vehicles; this capability requires an efficient strategy of vehicle routing. All this also requires sophisticated data handling and analysis.

Some of the required system control capabilities of a large-scale AMTV system are the following:

(1) Data Management: To keep track of vehicle locations and routes, passenger locations and destinations, as well as other necessary data and statistics.

(2) Communication: To transfer command/control information and other data between vehicle, station, and the system control center.

(3) Optimal route finding: To find the best routes for vehicles to serve passengers, according to an optimization algorithm.

(4) Optimal vehicle allocation and dispatch: To determine which routes need more vehicles and how the vehicles should be dispatched in order to best service the passengers.

5.3 A Transit System with Higher-Speed (15 to 20 mph) AMTVs

In order to reduce passenger transit time or, if desired, to operate in regular street lanes, an AMTV needs to have a higher cruising speed, possibly 15 to 20 mph. A system of such vehicles can conceivably be used to replace, or restrict, automobiles in central business districts and other areas which are currently congested with automobiles.

A feasibility study will be necessary to assess the safety and reliability of a transit system composed of the higher-speed AMTVs, and to evaluate the sensing and control capabilities required on the vehicle. The interaction between the AMTV and the regular traffic, either on the street or at an intersection, will also be studied.

APPENDIX A

References

Ref. 1 - Jet Propulsion Laboratory, "Preliminary Design - Automated Mixed Traffic Vehicle," JPL #1200-221 (JPL Internal Document), April 1975.

Ref. 2 - Anderson, J. E., et al (ed), "Personal Rapid Transit," University of Minnesota, 1972.

Ref. 3 - Anderson, J. E., et al (ed), "Personal Rapid Transit II," University of Minnesota, 1975.

Ref. 4 - Mennie, Don, "People Movers," IEEE Spectrum, July 1976.

Ref. 5 - Office of Technology Assessment of United States Congress, "Automated Guideway Transit," 1975.

Ref. 6 - Haight, Frank "Mathematical Theories of Traffic Flow," Academic Press: New York, 1963.

Ref. 7 - Barnett, Arnold and Daniel Kleitman, "Optimal Scheduling Policies for Some Simple Transportation Systems," Transportation Science, Vol. 7, pp 85-99, 1973.

APPENDIX B - GLOSSARY

AMTV	Automated Mixed Traffic Vehicle
Average Cycle Time	Time required for a vehicle to complete a loop, averaged over a period of time.
Central Station	The station where schedule and headway control are implemented when the controls are implemented at only one station in the loop.
Cycle-time Scheduling	The cycle time between successive departures of a vehicle from the same station, after completing a loop, is prescribed. The clock for scheduling is reset to zero every time the vehicle leaves a central station.
Even Headway	Average cycle time divided by number of vehicles.
Fixed-Route System	A system in which the vehicle cannot change its route from one route to another.
Fixed-time Scheduling	The complete schedule of each vehicle for one day's operation is prescribed. The clock for scheduling is reset only at the beginning of the day.
Headway	Gap between a vehicle and another vehicle ahead of it measured by time.
Headway Control	To measure headway between a vehicle and another vehicle ahead of it, and hold the vehicle if the headway is less than minimum allowable headway set by the system operator.
Homogeneous System	A system in which all stations have identical characteristics such as passenger arrival rates, departure rates, and driving time between stations.
Inter-station Control	The time intervals between departures of a vehicle from consecutive stations are prescribed. The clock for scheduling is reset to zero at every station.
Loop	Complete AMTV route, ending at the point of departure.
Minimum Allowable Headway	The minimum headway prescribed by the system operator to achieve maximum system efficiency.
Non-homogeneous System	A system in which all stations have different characteristics.
Prescribed Headway	The minimum allowable headway prescribed by the system operator.
Schedule Control	To measure vehicle arrival and hold the vehicle if it is ahead of the given schedule.
Variable-Route System	A system in which the vehicle can change its route from one loop to another.

APPENDIX C

CURRENT JPL AMTV SYSTEM:
EXPERIMENTAL OPERATION AND PRELIMINARY DATA*

*The contents of this appendix is obtained from JPL document #5020-30, September 30, 1976, "A Proposal For An Automated Tram System."

DESCRIPTION OF PHASE I EXPERIMENT

A. INTRODUCTION

In this section, the Phase I vehicle now operating at JPL, the route it is being operated on, the results which have been obtained to date, and a cost estimate for vehicle and components will be briefly described.

B. VEHICLE

The present vehicle has been based on a commercial six-passenger electric tram to which sensing and control components have been added to permit automated operation following a buried sense cable.

The present vehicle is shown in Fig. A-1 at one of the passenger stops on the JPL route. A speed of 7 mph, about three times the normal walking speed, has been selected for cruise mode on the straight sections of the route. Established techniques for following a buried cable were used to guide the vehicle.

Optical headway sensors seen in Fig. A-1 are used to detect pedestrians or vehicles in its path to a distance of at least 25 ft, causing the vehicle to slow. A second and independent sensor channel detects objects to ∿10 feet, commanding a stop.

C. OPERATING MODE

Basically, the vehicle operates continuously and faithfully following a guide cable and making brief stops for passengers. Since the desired speed of 7 mph is too fast for a turn, the vehicle is programmed to stop before entering each turn and move through the turn at a walking pace.

Riders are instructed to wait at one of several designated points for the vehicle to approach. Each curve entry is one of these points, but others are provided. After stopping, the vehicle waits 4 seconds and then moves on. If one or more passengers board, the vehicle will be inhibited from moving by passenger stop switches located on the canopy supports. When the passenger is seated in the vehicle, he releases his grip allowing the vehicle to move.

The same pressure switches will command the vehicle to stop at any time (not just at the programmed stop) so that the passengers can get off at will. If a pedestrian or other vehicle moves in front of the automated tram, it will be stopped by its headway sensors. A contact switch seen in Fig. A-1 serves as a backup to the headway sensors but is not activated in normal operation.

D. ROUTE

The present route is a single loop at JPL of 2000 ft total length as shown in Fig. A-2. The U-turns at each end are executed at intersections which are protected by stop signs. The intermediate intersection is also a 4-way stop.

It is desirable to extend the existing route during FY'77 as indicated on the smaller scale map of JPL in Fig. A-3 in order to obtain a longer route at minimum cost. Candidate routes which will be examined in further detail for the Phase III experiment are also indicated in Fig. A-3.

E. SAFETY

The basic question which this experiment addresses is related to the design of an adequate sensing and control system for safe driverless operation. An inherent difficulty in developing such a system is that no matter how sophisticated the system can be designed, situations which will frustrate it can be imagined. These may be called "what if" situations, and their number is limitless and constrained only by the degree of thoroughness and imagination used to compile them. However, it is difficult to evaluate in advance which are the important "what if's" and which are not: For example, to what extent even human drivers make assumptions about how interactive traffic will behave is not clear.

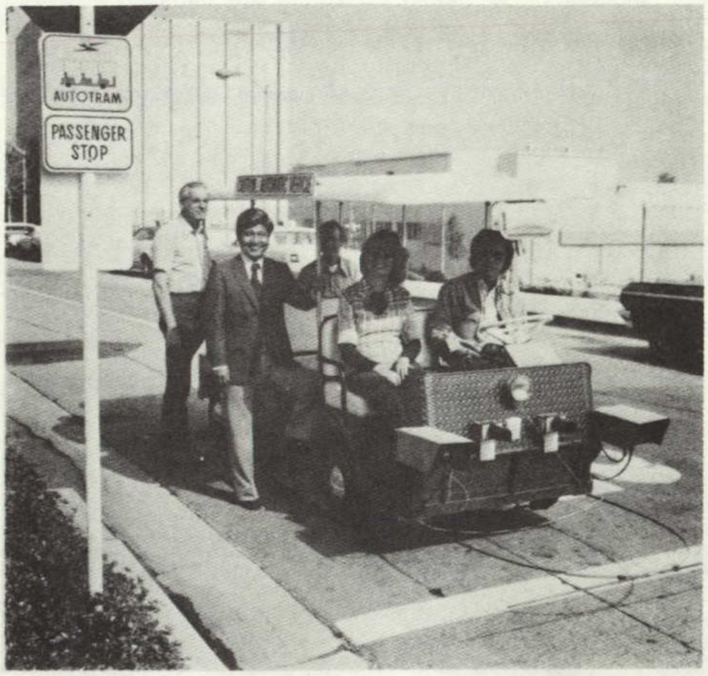


Fig. A-1. View of prototype AMTV at passenger stop point of JPL route

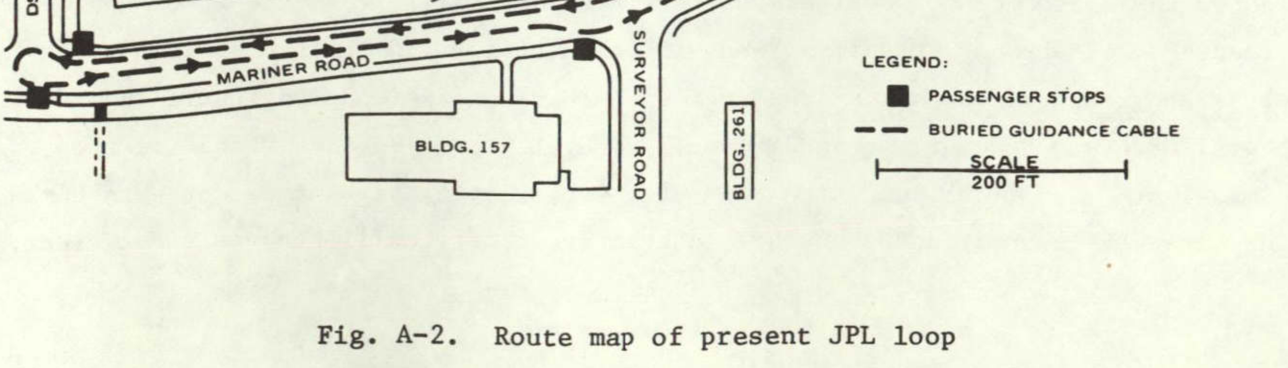


Fig. A-2. Route map of present JPL loop

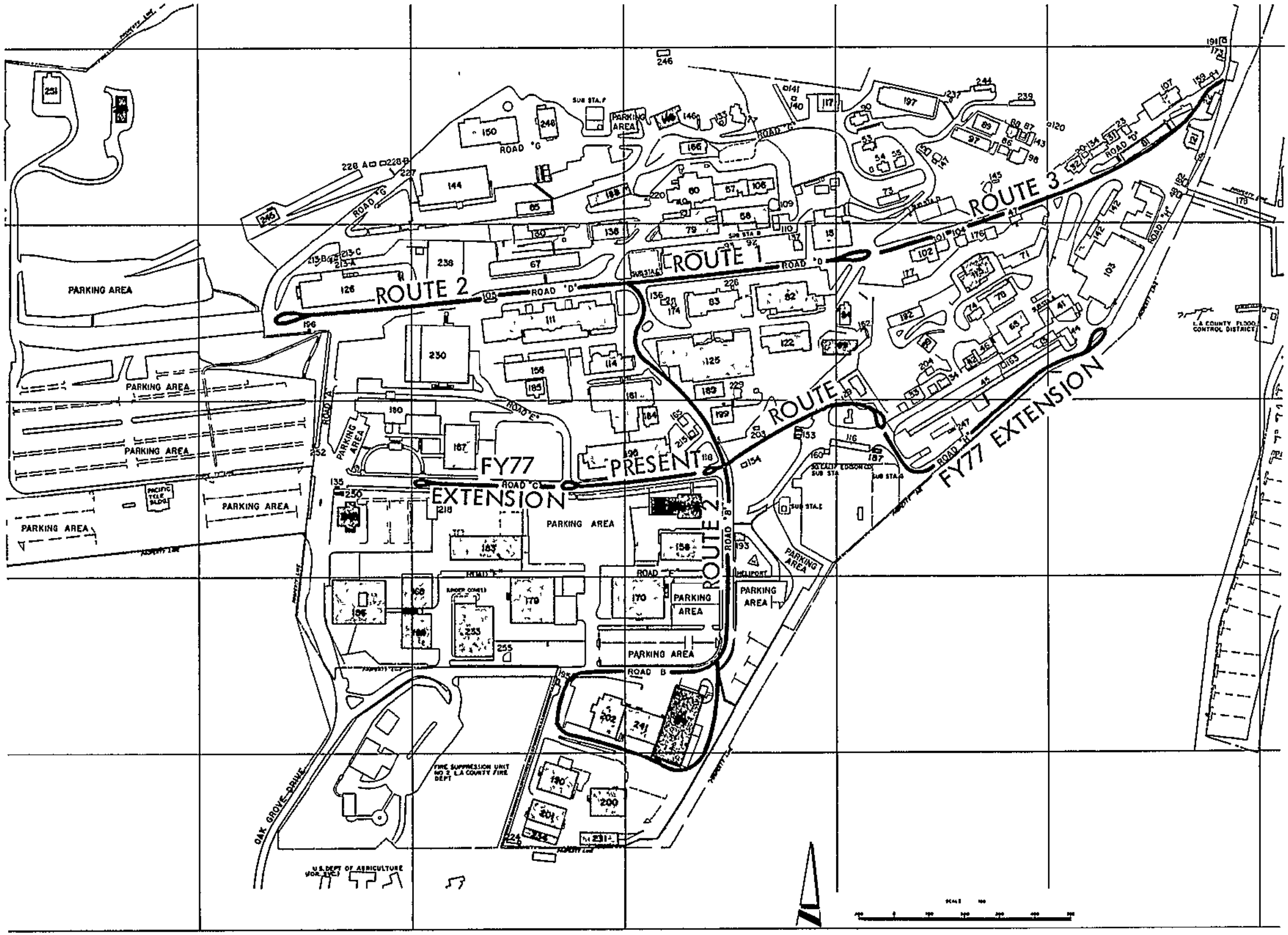


Fig. A-3. Site map showing candidate future routes

Accordingly, an observer is present at all times during this experiment, and he is an integral part of the experiment. The observer occupies a conventional driver's station. He has the same responsibilities for safe operation in the automated mode as if he were actually driving the vehicle. He also has the responsibility for anticipating problems with riders boarding and leaving the vehicle. Control reverts to manual mode on any observer input through the manual controls as in the operation of a passenger car cruise control.

The second function of the observer is to document all incidents occurring during the operation of the vehicle. Several types of incident might occur, such as

1) Near misses.
2) Instances in which the observer assumed control of the vehicle because he anticipates a problem.
3) Any panic stop, automatic or not.
4) Any unspecified problem relating to system design or safe operation.

These observations will form a quantitative data base for establishing which are the real "what if" situations that must be dealt with. The data will be used both for future improvement of the system design and for estimating its reliability when operating in a given environment.

F. RESULTS OF PRESENT EXPERIMENT

The vehicle described above has been operated with an observer on a daily basis at JPL since Febrary 1, 1976. Passengers have been invited to ride since March 31, 1976. Passengers were invited to board at indicated points. Although it was pointed out that riders could stop the vehicle anywhere with the canopy support stop switches, passengers have left the vehicle only at the programmed stops. The vehicle has been operated for 1 hour each morning and afternoon. Tests of the sensors are performed regularly as follows.

1) Stopping distance is checked before each run by the use of a blackened test target.
2) Sensor output is noted with the test target in various positions.
3) Background noise level is recorded.

These tests, designed to bring out any change or failure before running the tram, have confirmed that the sensor performance is stable. The observer tallies a number of categories of events during operation and keeps notes describing any other unusual occurrences. The data are recorded in a notebook for subsequent study.

These data are summarized in Table A-1 and the noted categories of events are described briefly below:

1) Loops Traversed

   The number of complete circuits of the 2000-ft loop route shown in Fig. A-2.

2) Blocks

   Indicates the number of times the route was obstructed, but the Autotram stopped for the obstruction. The most common obstruction by far has been illegally parked vehicles.

3) Bail Outs

   Indicates the number of times that manual intervention was required to stop the vehicle.

   a) Turns

      The most common event involved a change in direction of the guidewire. In turns towards an obstacle, the sensor sees an obstacle too late. This type of event can occur either in cruise mode with a long-radius curve or at reduced speed on a short-radius curve. It occurs primarily because the straight-ahead sensor geometry does not point along the vehicle path in a turn.

Table A-1. Preliminary data AMTV

Event	2/1/76 to 3/16/76		3/17/76 to 4/12/76		4/15/76 to 4/29/76		Total	
	Events	Loops per Event	Events	Loops per Event	Events	Loops per Event	Events	Loops per Event
1. LOOPS TRAVERSED	167		266		229		662	
2. BLOCKS (VEHICLE PARKED ON PATH)	16	10.4	16	16.6	8	28.6	40	16.5
3. BAIL-OUTS (MANUAL INTERVENTION)								
TOTAL	29	5.8	9	29.5	6	38.2	44	15.0
1. TURNING TOWARD OBSTACLE	6	27.8	4	66.5	3	76.3	13	50.9
2. U-TURN (BLIND PHASE)	8	20.8	4	66.5	2	114.5	14	47.2
3. START AT SAME TIME (PEDESTRIANS)	2	83.5	0	-	-	-	2	331
4. TRUCK OVERHANG	12	13.9	1	266	-	-	13	50.9
5. MISCELLANEOUS	1	167	0	-	1	229	2	331
4. FALSE ALARMS (SENSOR NOISE)	-	0.33	-	0.71	-	0.64	-	0.52

An excessively long time constant (~1 sec) in the present sensor-vehicle stop control is a secondary cause. The causes of this event type will be eliminated in future redesign efforts. A pedestrian crossing in front of the vehicle can cause a similar incident. Although such events have been caused deliberately by persons testing the vehicle, no such incident has occurred inadvertently during operation, and none are included in the data.

b) U-Turns

Events occurring during the U-turn at each end of the route. The present headway sensors are automatically turned off during the U-turn by a steering angle signal because their straight-ahead field is not effective. The vehicle is therefore blind during the U-turn. U-turn events are a special case of the turn event, a) above, but are categorized separately because of the special turn-off logic that is activated on the U-turn.

c) Truck Overhang

A number of events have involved trucks where the bed was too high to be seen by the sensors.

d) Start at same time

Involves a pedestrian who wished to cross in front of the stopped tram, and by chance, both start at once. When this type of event has occurred, pedestrian and bumper switch have been quite close immediately before both moved, say 1 to 2 feet.

e) False alarms refer to momentary sensor inputs which are not readily associated with a target. The usual cause is automobile reflectors located outside the normal sensed area, but passengers may not notice the event.

In all categories, the frequency of events tended to decrease during succeeding intervals. It is believed this is a result of better adjustment of the sensors. A contributing factor may be an increased familiarity of the people normally using the street with the tram.

Two uncategorized events occurred and were listed as miscellaneous in Table A-1. One involved a car traveling in the opposite direction to the tram and pulling out into the tram's path close enough so that the observer swerved the tram away as a precaution. The second event involved a car parked at an angle extending into the tram's path which the breadboard sensors did not see in time.

Some tentative conclusions can be drawn from the data regarding sensor design and system operation. All the incidents appear to be correctable by appropriate system modifications. First, the failures of the present rather rudimentary sensors can be grouped into four categories. Modifications can be suggested as follows to eliminate each type of event.

1) The sensors should be modified to scan the area toward which a turn is being made and ignore objects to the other side that will not be in the vehicle path. In addition, care should be taken in route planning with the layout of the curves.
2) A special extension of the above capability should be added for protection in a low-speed U-turn.
3) The sensor pattern should be extended vertically to see higher targets.
4) Use of a musical horn to announce start up should be investigated as a means of avoiding indecision by pedestrians and to alert passengers that the vehicle is about to move.

Second, the control lag associated with responding to a sensor stimulus should be reduced to 0.1 to 0.2 second to correspond more closely to the behavior expected from an automobile with a human driver. This will assist in eliminating the category of incidents involving turning.

More generally, it is also concluded that

1) Obstruction of the route (by parked vehicles) has been a frequent event. Means to avoid such blockages will ultimately be needed and could involve either familiarizing of the local community with the characteristics of the AMTV or providing provision for the AMTV to leave its guide cable briefly to pass around the obstruction.

2) Interference or indecision involving interaction of the AMTV and other vehicluar traffic at an intersection with boulevard stop signs has not occurred.

VEHICLE AND ROUTE COST

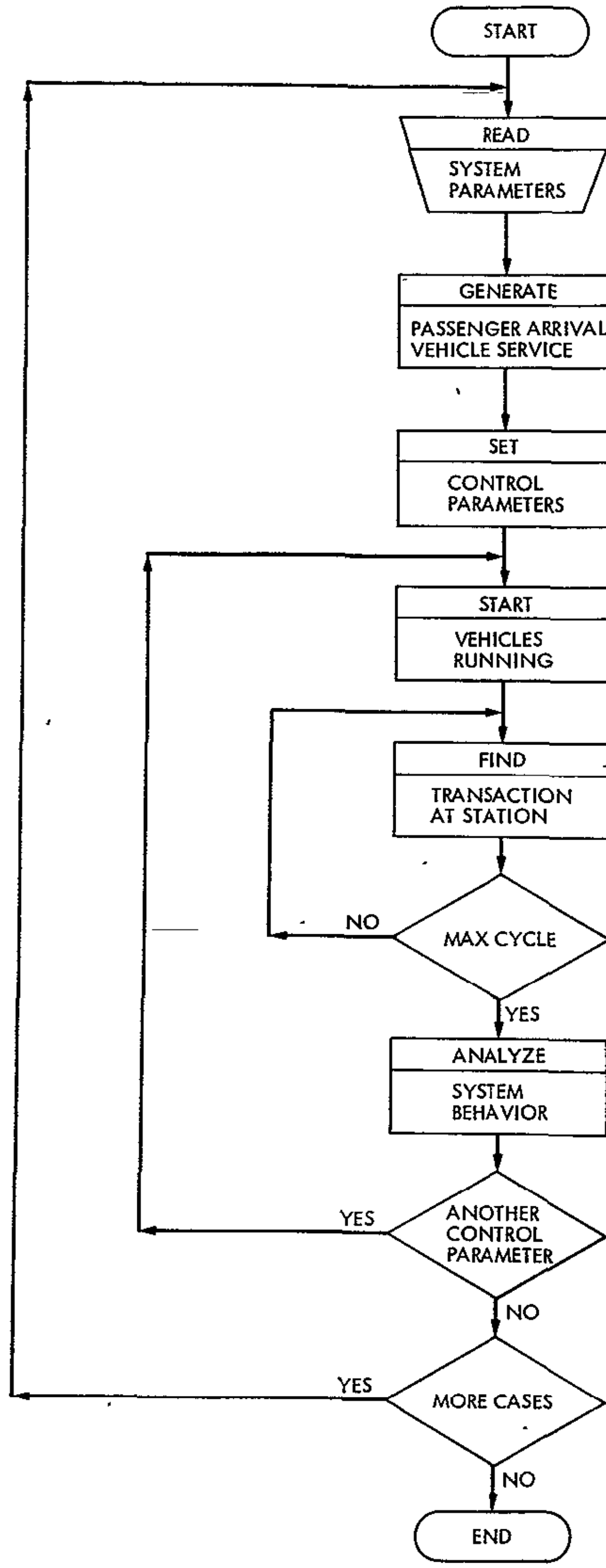
Table B-1 contains a summary of the hardware cost of the AMTV and its JPL route. The intent was to present cost figures which would be representative of the vehicle cost in production using 1976 dollars. Production runs in the 100's to 1000's appropriate for manual assembly techniques are assumed. The vehicle costs were based on information collected during the development of the present prototype vehicle in spring of 1975 and were increased by 10% to allow for inflation.

Development engineering man hours were not included, but assembly and wiring technician time was included to approximate the cost of the hardware in production. The total cost of a developmental vehicle is, of course, much larger. The total of $16522 from Table B-1 may be compared to the cost of a cable guided automated tractor purchased from production of approximately $10,000. The cable-guided tractor is a comparable vehicle except it is somewhat less sophisticated, being designed for a much slower speed, 1 to 2 mph, and not having a headway sensor. Actually, this comparison indicates that JPL's figures are somewhat high since the purchase price of the tractor from production must include an overhead for engineering, sales, and profit.

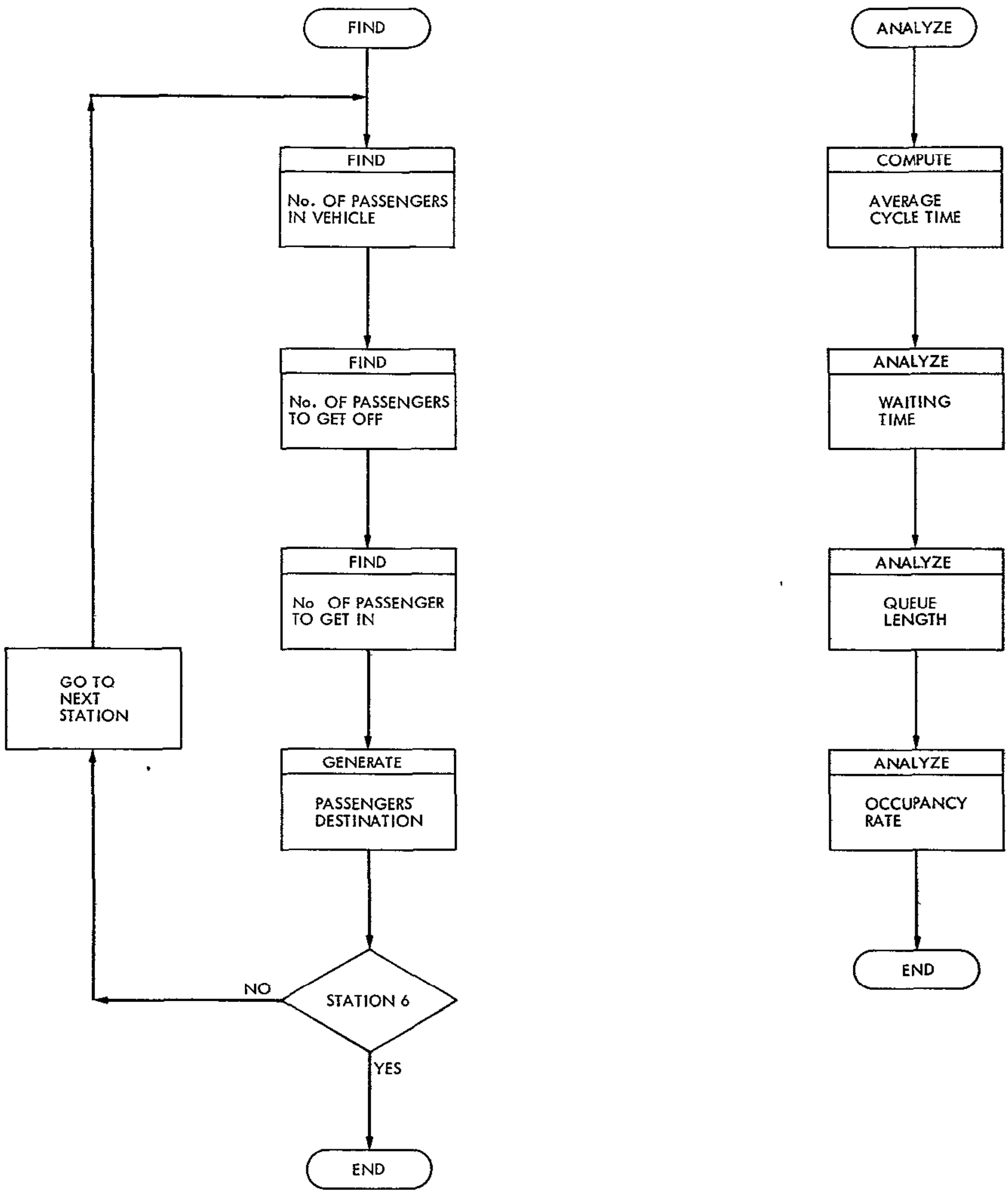
The route costs were based on actual costs for installation of the JPL 2000-ft loop and were prorated to a 1-mile length. Actual material costs are included, but actual man hours were reduced by an estimated factor to provide for a learning curve. Cost of the associated signs were included.

Table B-1. Summary of estimated hardware costs

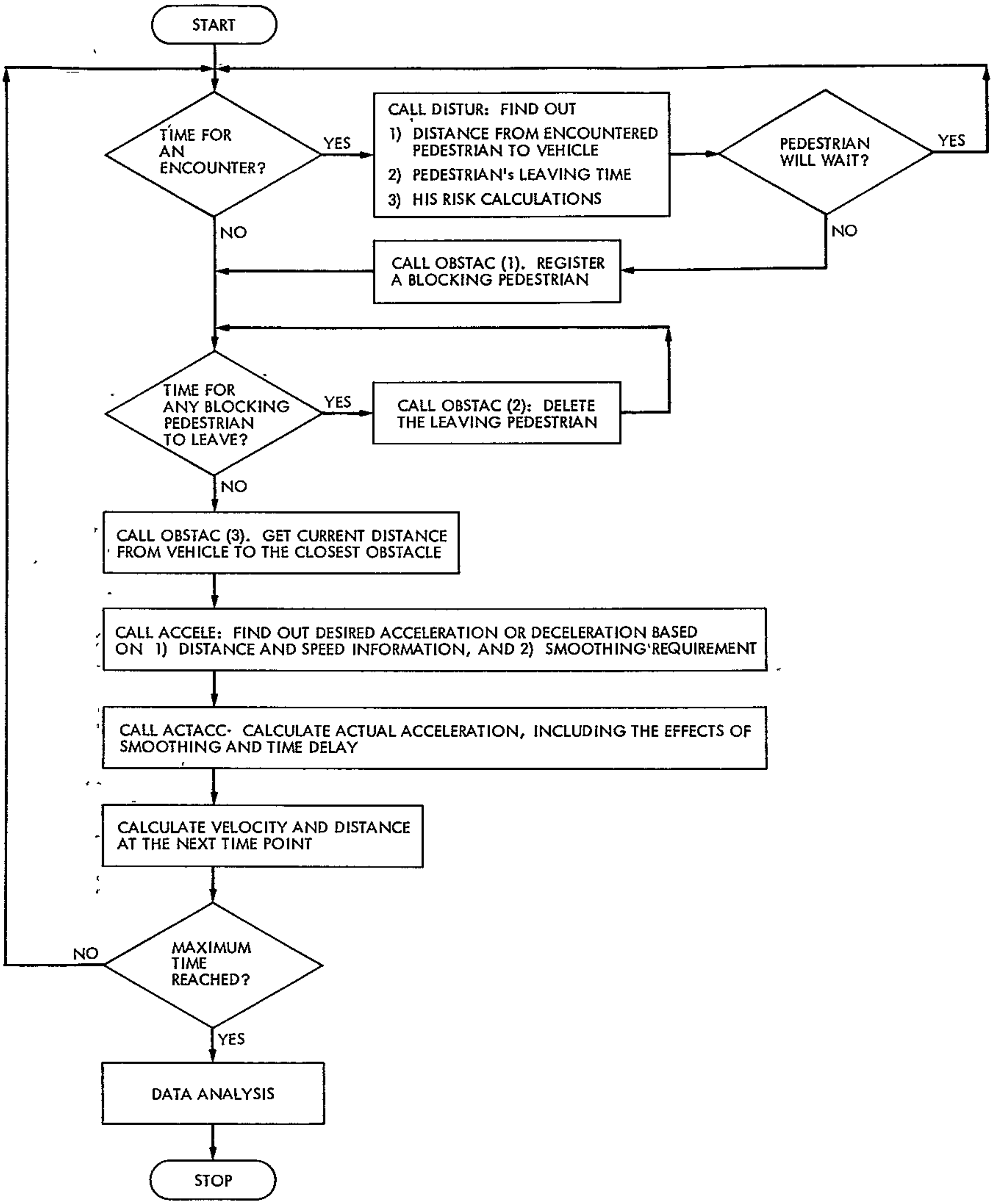
A. Vehicle				
1. Basic vehicle including SCR controller			$ 7150.00	
2. Hydraulic actuation brakes and steering				
Parts		2200		
Assembly		550		
			2750	
3. Speed control service				
Tachometer		77		
Parts Fab		220		
Assembly		110		
Electronics		220		
			627	
4. Control Electronics				
2 circuit cards		440		
Assembly		110		
			550	
5. Headway Sensor				
21 optical elements		2310		
4 circuit cards		600		
Assembly		550		
			3520	
6. Steering Sensor				
Pickup head		550		
Circuit card		165		
Assembly		110		
			825	
7. Bumper and switches		1100	1100	
	TOTAL		$16522	
B. Route costs for 1 mile of route				
1. Guideway			1 mile	
Wire			232	
Layout			290	
Saw cutting			871	
Epoxy filler			580	
Labor to place wire			928	
Signs and Placement			1742	
Magnet Placement			290	
	TOTAL			$ 4935
2. Exciter				
Box			65	
Electronics			330	
Labor to install			330	
	TOTAL			$ 731



Appendix D. Flow Chart: Vehicle Scheduling and Headway Control



Appendix D. Flow Chart: Vehicle Scheduling and Headway Control (Continued)



Appendix E. Flow Chart: Vehicle-Pedestrian Interface