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AMTV
TECHNOLOGY AND SAFETY STUDY

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16. Abstract

This report discusses technology and safety related to the implementation of an Automated Mixed Traffic Vehicle (AMTV) system. System concepts and technology status are reviewed and areas where further development is needed are identified. Failure and hazard modes are also analyzed and methods for prevention are suggested. The results presented are intended as a guide for further efforts in AMTV system design and technology development for both near-term and long-term applications.

The AMTV systems discussed include a low-speed system, and a hybrid system consisting of low-speed sections and high-speed sections operating in a semi-guideway.

Needed technology includes further development of headway sensing devices, and development of flexible, and fail-safe control hardware.

The safety analysis identified hazards that may arise in a properly functioning AMTV system, as well as hardware failure modes. Safety-related failure modes were emphasized. A risk assessment was performed in order to create a priority order and significant hazards and failure modes were summarized. Corrective measures were proposed for each hazard.

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Automated vehicle; shuttle transit; optical sensors; safety, failure modes cable follower

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PREFACE

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Many individuals have helped in conducting this study. In particular, the assistance of G. Deshpande is gratefully acknowledged. He contributed in a significant way, both by participating in all our discussions, and by reviewing this report at several stages during its preparation.

In addition, the ideas and comments of several others have been very helpful. The support and guidance of G. W. Meisenholder has been important from the beginning of the task. Many valuable comments and suggestions have been received from J. Land and W. Woods, and have been very helpful. P. Cassell has provided valuable comments and guidance related to the design of the experimental JPL AMTV. We would also like to thank W. Watkins (WE Disney Enterprises) for his suggestions and help in reviewing our safety analysis.

Finally, several stimulating technical interchanges with C. Henderson, T. Anyos, J. Wilhelm and others from SRI in connection with a parallel AMTV requirements and marketing study they are conducting were most helpful. Particularly, ideas from these discussions relating to safety and route configuration have influenced this report.

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SECTION I

SUMMARY

A. PURPOSE, SCOPE, AND APPROACH

This report discusses the technology and safety related to the implementation of an Automated Mixed Traffic Vehicle (AMTV) system. System concepts and technology status are reviewed and areas where further development is needed are identified. Failure and hazard modes are also analyzed and methods for prevention are suggested. The results are intended as a guide for further efforts in AMTV system development for both near-term and long-term applications.

The AMTV systems discussed include a low speed system, and a hybrid system which can operate at the low speed and at a higher speed within a protected right-of-way. The low speed system is a candidate for a near-term demonstration and can be used in pedestrian malls, large campuses and recreational parks. The hybrid system may have application, after further development, on urban streets, in airports or in other situations where longer distances may be involved. Examples are given in Section II, which describe a shuttle service between two shopping centers separated by many city blocks, and a tram-type system in a pedestrian mall.

The remainder of the study was conducted using the following approach: The physical elements of an AMTV system, both moving and stationary, were first described in terms of system requirements and subsystem specifications (Section III). Technology status was then evaluated and required developments were identified within this framework (Section IV). Based on the AMTV physical elements and operating concepts, a comprehensive safety analysis was conducted to examine potential hazards caused by hardware failures and by events unrelated to hardware failure. Corrective and preventive actions in terms of design modifications or operatial procedures were suggested (Section V).

B. MAJOR FINDINGS

1. Initial Demonstration

Straightforward development using current technology will make it possible to demonstrate a low speed AMTV system in three to five years. With a prudent, fail-safe design, and appropriate right-of-way protection, the AMTV system can operate safely in an environment containing pedestrians. An initial demonstration should restrict the mixed-traffic environment in order to ensure safety during the learning period.

Work needed to implement the demonstration would include the following:

(1) Optical headway sensors to provide better frontal coverage, quicker response, and the added capability of sensing in the direction of a turn.

(2) Bumper switches to provide both backup protection against collision, and a smooth, compliant surface that would minimize the chance of injury. Such a bumper switch should extend around the sides of the vehicle.

(3) Design of a suitable vehicle matched to the application, and where possible, using existing automated guideway technology.

(4) Control logic improvements to provide flexibility and added capability.

Roadside equipment may also be needed for system check-out and automatic scheduling control. The use of roadside sensors for control at crossing points should also be considered.

Further work is needed to ensure safety, including:

(1) A review of the AMTV system design to ensure hardware reliability and to apply fail-safe design principles to all vital guidance and control subsystems.

(2) Development of means to prevent the AMTV from moving prematurely while passengers are boarding; perhaps by an interlocking door mechanism.

(3) Development of effective procedures for route surveillance, system checkout, fault recovery, and maintenance.

(4) Consideration of the effect of weather (rain, mud, ice and snow) on system operation.

(5) Development of a clear definition of right of way and passenger access.

(6) Development of procedures to inform the public about the characteristics of the AMTV.

2. Urban Application

Subsequent to an initial demonstration, a hybrid AMTV system could be developed for applications involving longer distances. This system would consist of low-speed route sections for passenger pick-up and delivery, and high-speed route sections for longer-distance connection between the low-speed sections. On a low-speed section, the AMTV would behave like the initial demonstration system mentioned above. On a high-speed section, however, means must be provided to separate the AMTV pathway from pedestrians and other vehicles because of the longer stopping distance. It is not accurate to refer to this pathway isolation as a guideway, in the sense that it is a track that steers the vehicle, since the guidance and headway protection will continue to be electronic. Instead, we refer to it as a semi-guideway, because of the similarity to a true guideway, and because the AMTV would not require a continuous, unbroken, grade-separated right-of-way. At traffic intersections the AMTV could cross either using grade separations or at-grade using traffic signals and barriers coupled to the AMTV control system.

Initially, pathway protection can be accomplished by means of physical barriers such as fences and curbs. However, after public awareness of the system characteristics is developed, the needed pathway assurance may well be met by the use of accepted rules, like those governing a bikeway, together with expected advances in sensor technology. This extension would permit future use of the pathway by other vehicles. A 20 mph AMTV operating in an unrestricted mixed-traffic environment is not felt to be reasonable in the near future; research leading to new sensing technology must come first.

The low-speed section and high-speed section can be considered as modular functional elements that may be combined in various ways to configure urban applications with varying geometry. The underlying technology can be discussed by examining AMTV operation on a typical low-speed section and on a typical high-speed section, together with some consideration of the interconnection. While much of the technology developed for the initial demonstration can be extended for use in a hybrid system, still further development and new system concepts are needed for high-speed operation.

Although determination of the best speed for each mode must await further experience, the values selected for initial study are 7 mph for the low speed, and 20 mph for the high speed.

A long-range headway sensor must be developed for 20-mph operation, having a sensing range of 125 feet; the distance required to stop a 20-mph vehicle with moderate deceleration. Reliable detection of other AMTV's and automobiles at this distance is achievable by modification of the present type of optical headway sensors. This approach, however, does not ensure timely detection of smaller, dark targets due to limitations on light source power. Based on the expected capability of such a long-range sensor, a reasonable collision avoidance philosophy for an AMTV operating at 20-mph in a semi-guideway is to perform a routine programmed low-deceleration stop for another AMTV or an automobile, and to use special control logic combined with fast braking to stop for pedestrians or smaller-size obstructions which have violated the guideway barriers, and are not detected at 125 feet. Roadside sensors to detect guideway violation and signal a slower speed to the AMTV should also receive attention.

In the long-term, after community familiarity with the AMTV is established, crossing of streets with other vehicular traffic will become possible under appropriate conditions, using coupled traffic signal control or stop signs. When an AMTV must make a turn it must interact with the signals at the intersection; therefore, development of an appropriate signaling procedure will be necessary. Another valuable precaution will be a stationary sensor system capable of detecting a potentially dangerous vehicle at the intersection (such as a car about to run a red light) and signaling the AMTV to stop until the danger passes.

C. RECOMMENDATIONS

A list of items which must be developed for an initial demonstration, and others for a longer-term urban application are summarized in Table 4-1.

To ensure safe and smooth introduction of an AMTV system into public service, the system must be mature in design and free of defects. For this reason, any AMTV system design must be tested in a controlled environment before it is committed to public service. Reduction of accident risk, the elimination of bugs and the implementation of desirable design changes are important steps which should be taken before introducing the new technology to the public. In addition, the use of attendants for insuring safe and reliable operation during the initial learning phase of an AMTV demonstration should not be overlooked. The attendants should not be perceived as drivers, and perhaps do not need to be seen as uniformed employees by the public. They could be positioned either in the vehicle or at strategic roadside locations, and could perform the safety backup function with an unobtrusive box having a "stop" command button. They might also assist with fault recovery, using a key - activated manual control box. The AMTV need not have a conventional automotive driver's station.

SECTION II

INTRODUCTION

A. PURPOSE

The purpose of this report is to review the technology used in an Automated Mixed Traffic Vehicle (AMTV) system, to identify areas where further development is either required or desirable, and to conduct a safety analysis of an AMTV system. In both parts of the report the goal was to develop recommendations which could act as a guide for further development of the AMTV concept. The report addresses the problem of developing an AMTV capable of operating in an environment containing both pedestrians and vehicular traffic. Attainment of true mixed traffic capability is assumed to be the long-term goal, but it is recognized that an initial demonstration must be in a more restricted environment.

B. BACKGROUND

The AMTV concept has been described in an earlier paper (Ref. 1). Basically, it offers a cost-effective alternative to conventional busses or other transportation modes for many applications requiring frequent, low speed service, since both the cost for a driver on each vehicle and the large investment required for exclusive guideway construction can be avoided.

A feasibility demonstration of an AMTV, using what was basically a breadboard vehicle was conducted at JPL during early 1976. Results from this experiment are reported in Reference 1. Data generated by the JPL vehicle and experiment form a baseline for developing the technology and hardware sections of this report. The experiment used a wire-following steering system patterned after work of Fenton and Olson at Ohio State University (Refs. 2 and 3). Similar techniques have been used by a number of investigators, and reliable speeds of 50 mph have been demonstrated (Refs. 4 and 5). The sensors used for collision avoidance were developed at JPL, and were derived from earlier work on sensing for remote manipulation applications (Refs. 6 and 7).

Although the JPL vehicle is a small electric tram, any type of vehicle could be incorporated into a future AMTV system, with the size and type of vehicle being determined by the service requirements of the specific application. A number of guideway systems employing automated vehicles have recently been put into service. Requirements of these vehicles are quite similar to those of an AMTV, except for the provision for collision-avoidance (headway) sensing, and the steering mechanization. Experience derived from development of these guideway systems is therefore likely to be useful in further AMTV vehicle control development. Some existing guideway systems with relatively small vehicles and related reference documents are:

(1) Morgantown (Ref. 8)

(2) Airtrans, Dallas/Ft. Worth Airport (Ref. 9)

(3) Seattle/Tacoma Airport Shuttle (Ref. 10)

Another type of automated vehicle system that may offer applicable experience is the automated mail cart or automated warehousing vehicle system (Refs. 11 to 13). These systems may employ relatively complex multi-loop routing controls, but are very low-speed systems without the headway sensing capability required for higher speed service.

C. SCOPE OF STUDY

The present status of the technology needed for an AMTV was examined with respect to two stages of application, which are further described later in this section. The first example of an application is one which would be appropriate for an initial demonstration of any AMTV system, which might take place in 3-5 years time. The environment of the initial system should be relatively benign and the developments needed are fairly straightforward. The second example of an application is a more challenging one, and assumes an urban CBD type of environment. Further developments required for such an AMTV system are identified. These developments are discussed primarily in terms of today's technology, but some of the improvements or added capabilities represent fairly significant extrapolation from present experience, and may require advances in the basic technology employed. These long-range developments are identified as such in the text.

Finally, it should be recognized that an AMTV system is a new concept, and its implementation will involve many non-technical questions during the initial period when operators, users and other traffic are familiarizing themselves with the new type of service. Possible questions are:

(1) What special traffic rules or laws need to be made for the AMTV, if any?

(2) How should operation be funded; should there be fares?

(3) How will user preference features be taken into account?

(4) How will passenger security be affected by vandalism and pranksters?

(5) Can passengers be allowed to assist in case of a minor problem (such as a delivery truck parked on the route)?

Investigation of these questions is beyond the scope of this study, which is primarily concerned with the technology required to implement an AMTV system.

In the safety analysis, no preconceived constraints were defined. However, it soon became apparent that many of the issues identified were not unique to the AMTV concept or the technology required to implement it, but are also found in existing transportation systems. Therefore, in order to limit the amount of data treated in the safety analysis, the following criteria were applied:

(1) Hazards which are common to other transportation modes or activities such as earthquake, or falling objects, were not treated in detail.

(2) Social hazards, such as vandalism and criminal attack were not treated.

Identified items of this type were left in the raw data, and presented in Appendix A, for reference.

D. ORGANIZATION OF REPORT

In the remainder of this section, the two examples of AMTV application previously mentioned are described in more detail.

Section III presents general requirements appropriate to an AMTV system, independent of any specific implementation of the hardware. Definitions of the necessary AMTV subsystems are given. Such definitions are, of course, somewhat arbitrary, since the partitioning of system functions is never unique. It is felt, however, that the functions identified will be present in similar form in any AMTV system, and therefore the definitions presented have general validity. The subsystems of the present JPL AMTV were used as a baseline, and other elements were added to it to form the complete system. Following the subsystem definitions, performance specifications for each subsystem are identified to the extent now possible. These specifications are still general, but take into account conclusions drawn from the JPL experiment and from the safety analysis presented in Section V.

Section IV discusses development activities required to demonstrate an AMTV system. Technology developments necessary in order to implement a near term demonstration are recommended. Further developments and long-range research needed for an ultimate AMTV application are separately identified.

In section V, the procedures used in conducting the safety analysis are described, the results are interpreted, and suggestions are made for implementation of the results.

The Hazard Catalog and associated data developed in the safety analysis are contained in Appendix A. Similarly, a failure mode catalog is contained in Appendix B. The conclusions and recommendations of Section V were developed from the analysis of data described in Appendixes A and B.

Brief analytical models for various elements of the AMTV are presented in Appendix C.

E. AN EXAMPLE OF AN AMTV APPLICATION

This section describes a potential AMTV application in an urban environment in order to provide a baseline for developing more detailed descriptions of the AMTV and its subsystems in subsequent sections. The example selected incorporates the main features which are considered technically feasible in a future system, and illustrates the utility of the AMTV from the user point of view. The capability of operating an AMTV in the type of environment described here is felt to be a desirable developmental goal.

The application envisioned provides shopper shuttle service between two large shopping centers separated by a distance of one mile or more, as illustrated in Figure 2-1. In addition to the shuttle function, low-speed service is also provided within each shopping area. For this application, a service with high schedule frequency is envisioned, but not high passenger throughput much as would be encountered in line haul rapid transit at rush hour.

In each shopping center, the route passes through parking lot type areas as indicated in Figure 2-2, where both pedestrian and low-speed vehicular traffic is encountered. The vehicle travels at its low speed in this environment. Brief (3-4 second) stops are made either routinely or on demand at predetermined points to permit passengers to enter or leave the tram. With an appropriate (probably electric) vehicle, part of the route could pass through the interior of the shopping mall building, where the AMTV would operate in a purely pedestrian environment.

Between the two shopping centers, the route follows a semi-guideway, which is an on-grade vehicle path reserved for the AMTV by fencing or curbing. Alternatively, distinctive lane markings, together with rules similar to those presently governing bikeways may be used to define the AMTV pathway. The vehicle cruises at high speed while in the semi-guideway. The guideway protection does not extend through intersections, but rather the AMTV is coupled to conventional traffic signals in such a way that safe passage across each intersection is ensured. Fixed auxilliary devices are required to detect intrusion into the guideway by other vehicles or pedestrians, and also to ensure that a red traffic signal is not violated by vehicular cross traffic. Figure 2-3 depicts the high-speed route sections. Retractible barriers are shown in the figure to provide physical protection from cross traffic. Actuation of the barriers would be coupled with AMTV control and the traffic signals. They would be raised within the red period for cross traffic while an AMTV is crossing. Designated locations for passenger pickup are incorporated at approximately one block intervals. Turns would be made at intersections, with appropriate traffic signal coupling.

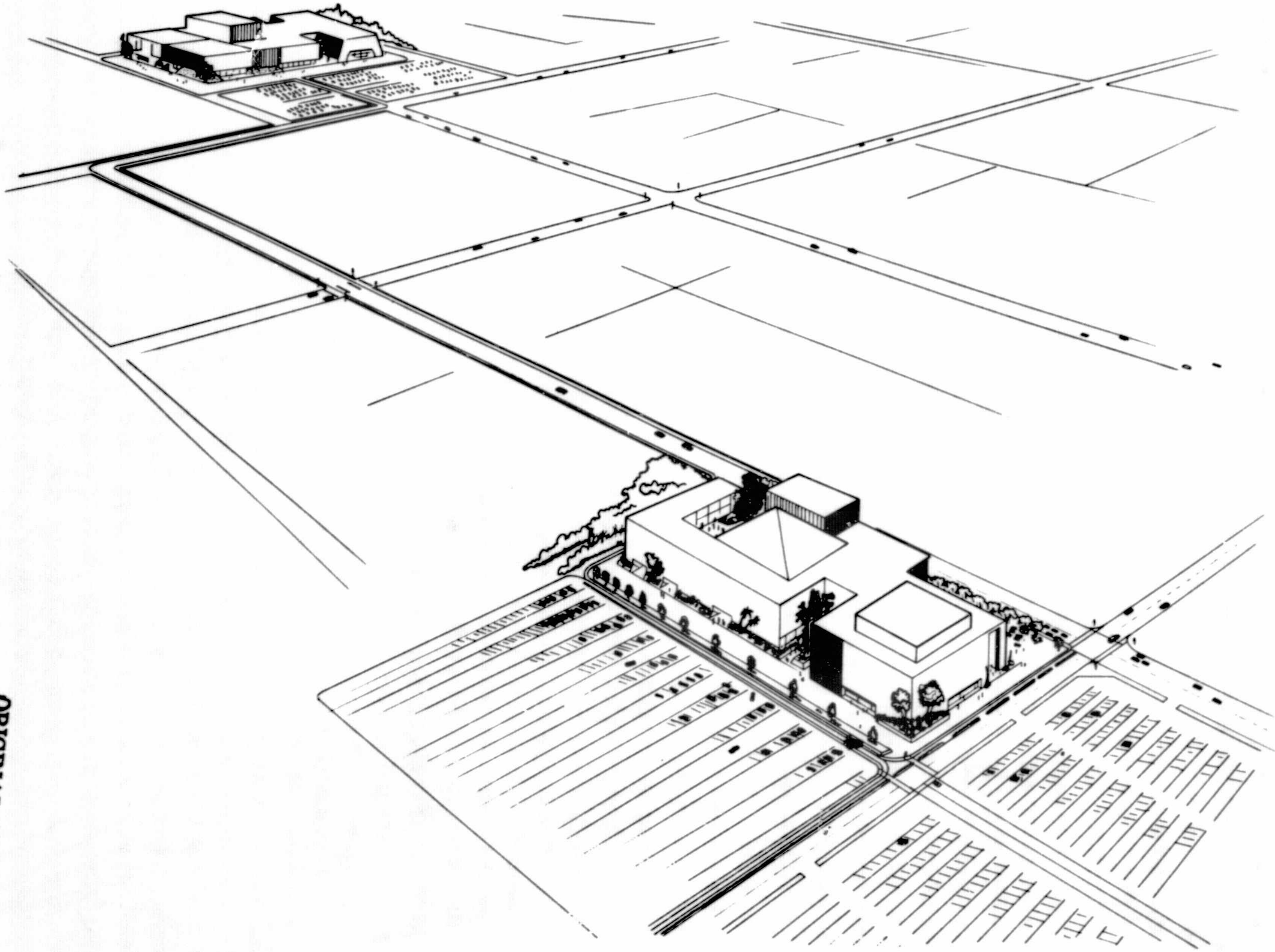


Figure 2-1. An Example of an AMTV Application---Overview

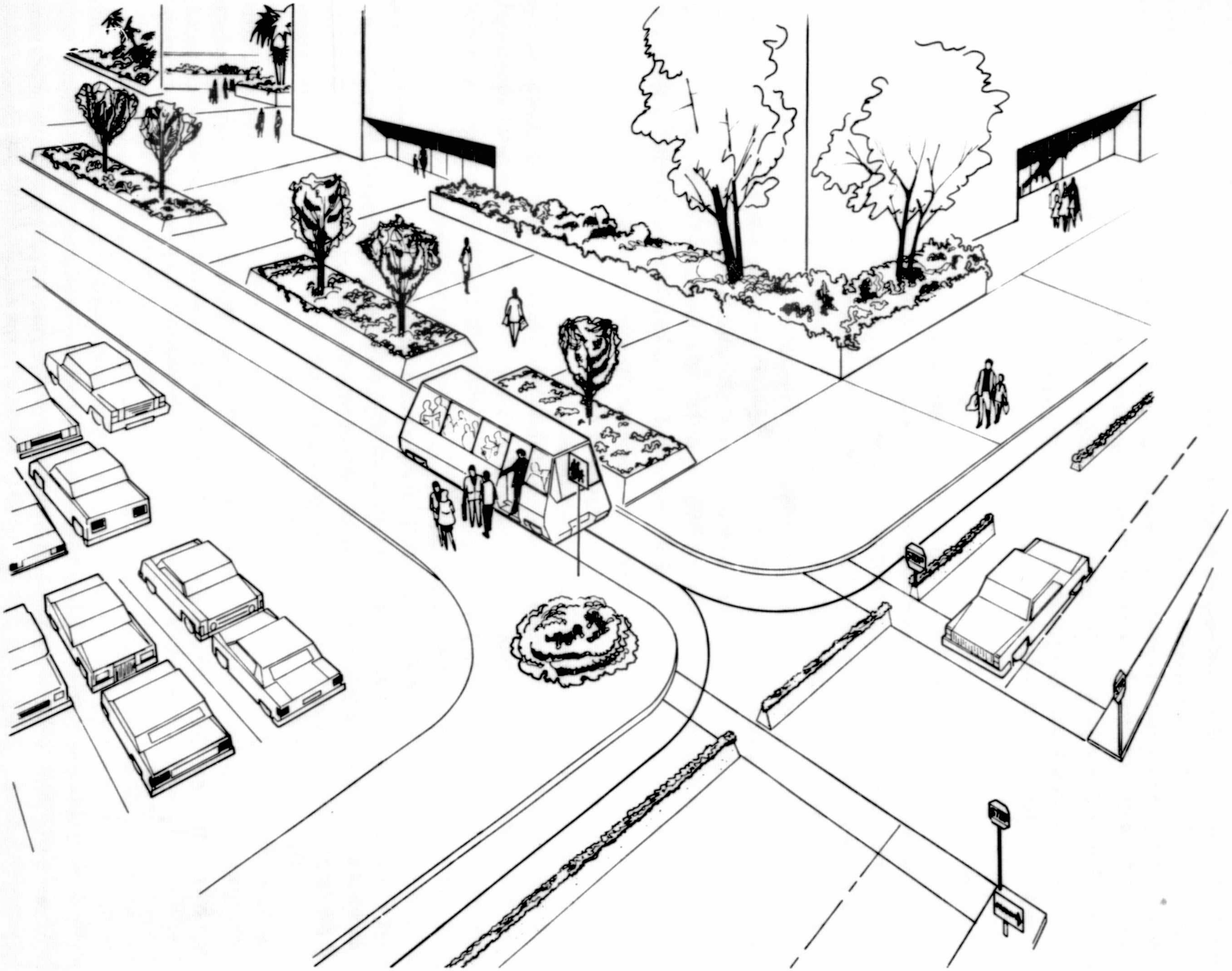


Figure 2-2. An Example of an AMTV Application---Low-Speed Route Section in Terminal Areas

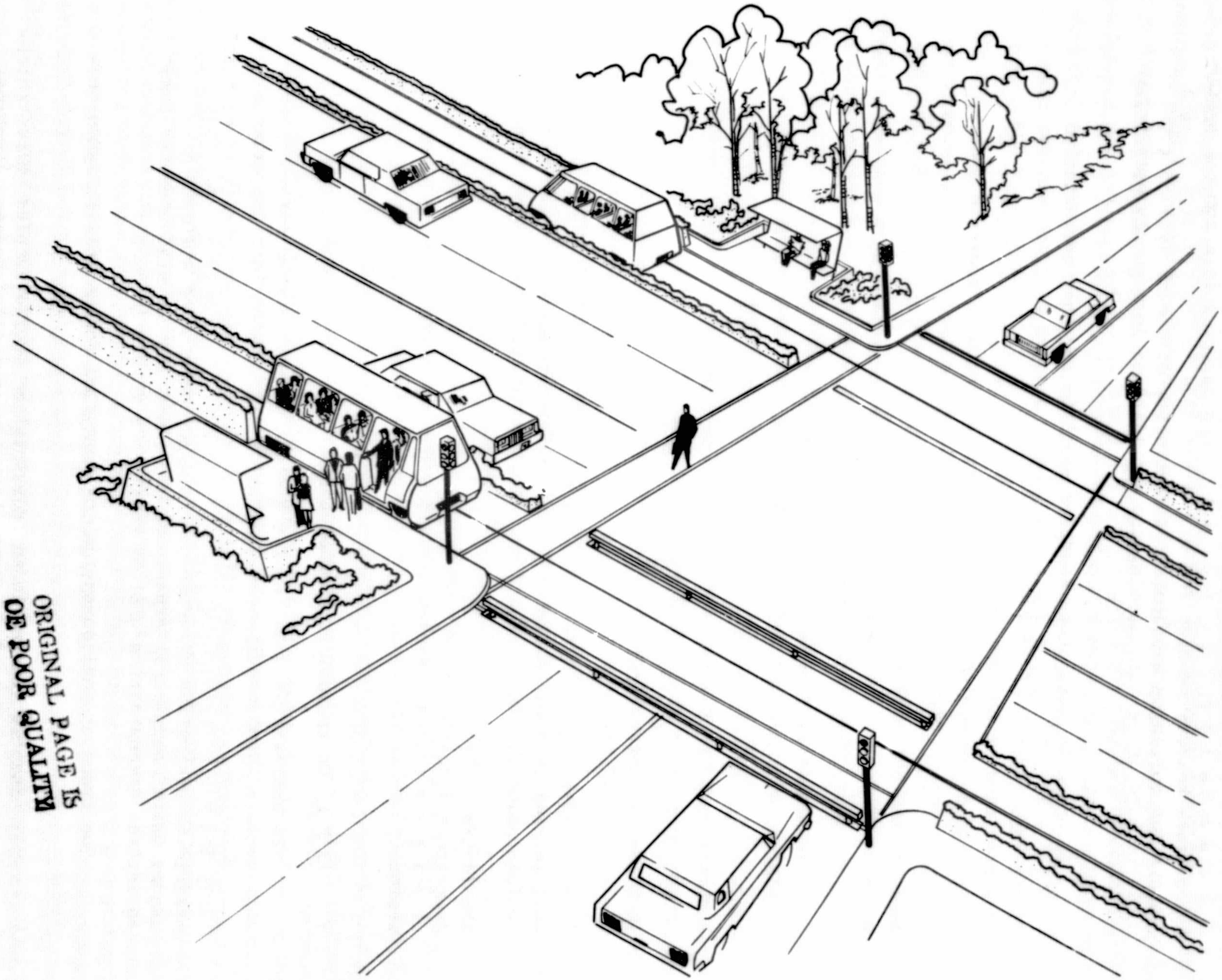


Figure 2-3. An Example of an AMTV Application---High-Speed Route Section

In general, an AMTV may have three speed modes; the high-speed and low-speed modes already mentioned and an additional 1-1/2 mph mode which will always be incorporated as a part of the basic vehicle control system. Appropriate headway sensing for each speed mode is incorporated in each vehicle for collision avoidance. A distinctly different type of AMTV could be used in certain specialized applications in a purely pedestrian environment and would operate in the 1-1/2 mph speed mode only.

In order to make these examples specific for the more detailed discussion of AMTV system design to follow, a speed of 7 mph was selected for the low speed mode, and 20 mph for the high speed mode. A speed of 7 mph, used in the JPL experiment, is a reasonable compromise, permitting an average speed comfortably faster than walking with moderate sensing requirements. A 20 mph mode would be satisfying for longer distances (> 1 mile), but presents considerably more difficult sensing requirements. However, these speeds are not fixed; their choice at this point is somewhat arbitrary. It will be necessary to accumulate much more experience with the AMTV concept before it is possible to decide on the best speeds.

It should be further emphasized that the application illustrated in Figures 2-1, 2-2 and 2-3 is hypothetical, and intended only as a framework against which the AMTV technology can be discussed. It is not intended to specify what the possible AMTV applications might be. The different speed modes and accompanying types of route environment can be used in different combinations to satisfy the requirements of applications quite different from the example described above. For instance, an inter-terminal shuttle operating on an airport apron could utilize the 20 mph semi-guideway mode, only. The type of vehicle used would differ depending on the specific requirements of the application; a 20 mph AMTV would likely be a closed bus type vehicle, while an AMTV vehicle used in a route limited to a 7 mph speed may be an open tram configuration for faster boarding. A complete AMTV system will also require a vehicle storage and maintenance area which is not shown in the figures. For the purposes of this report, it is assumed that the geographic location of the AMTV system is one not subject to heavy snowfall or icing conditions. System operation should continue during rainy weather.

F. EXAMPLE OF AN INITIAL DEMONSTRATION

The application selected for an initial AMTV system demonstration must be in a considerably more restricted environment than the example just described. During the early phase of AMTV development, it is particularly important that the exposure of the AMTV to automobile and truck traffic be controlled in order to minimize the risk of accident or injury while operational experience is gained. It is also expected that an initial demonstration will be relatively modest in scope.

Two types of environment can be suggested for an initial demonstration:

(1) Shuttle service in an industrial or public complex where vehicular traffic does exist, but with controlled access. Control-

led vehicular access implies that interacting drivers are selected in some way, for example by requiring a pass to be shown, and that traffic is more orderly and less dense than would be typical of a busy urban street. An initial application in an industrial environment also has the advantage that the interacting population can be more effectively informed of the utility, rules-of-the-road, and possible hazards of an AMTV system.

(2) A shopping mall shuttle in a pedestrian environment, as illustrated in Figure 2-4. An open court-like environment is envisioned, like that created by the conversion of a shopping center street into a mall. Alternatively, the AMTV route might encircle a parking lot or deliver passengers to the parking lot entrance, but it would not travel on streets used by the general public for vehicular traffic. The AMTV would interact only with pedestrian traffic. As shown in the figure, planters or curbings can be used to further isolate the AMTV path. The degree of isolation is a safety consideration, and is a variable that should be expected to change as public familiarity with the system increases, and as the sensing technology becomes more sophisticated.

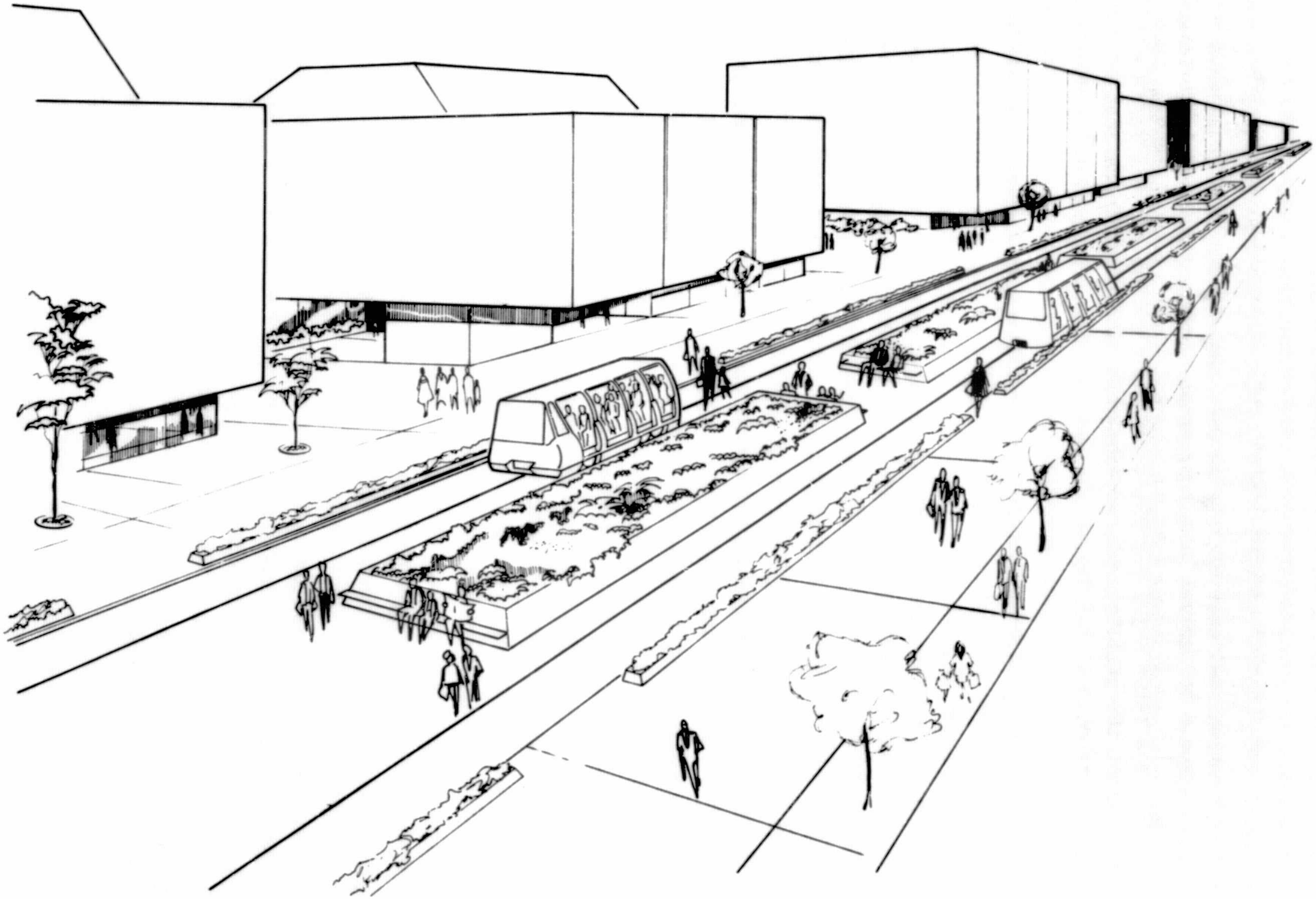


Figure 2-4. Near Term Demonstration System---Shopping Mall

SECTION III

SYSTEM AND SUBSYSTEM FUNCTIONAL REQUIREMENTS

A. INTRODUCTION

This section proposes system requirements, subsystem definitions and functional requirements for 1-1/2 mph, 7 mph, and 7/20 mph hybrid Automated Mixed Traffic Vehicle (AMTV) systems. These requirements serve as a conceptual framework within which safety can be analyzed and needed technology developments can be identified. Because system and subsystem functions mutually interact with safety considerations, the requirements stated in this section reflect an iterative process of combining the results of the safety analysis given in Section V with the system requirements developed in the early part of this section.

Requirements for the 7 mph AMTV are based on the experience gained in the development and operation of the experimental 7 mph AMTV at JPL and are largely carried over from that design (see Ref. 1). Other system requirements are developed with reference to the assumed applications given in the previous section.

B. SYSTEM REQUIREMENTS

The overall AMTV concept requires consideration of route configuration, passenger interfaces and protection, vehicle operation, regulation of the traffic environment, intersection handling, route condition, system checkout, fault recovery, storage and maintenance, and level-of-service control. The system requirements which integrate each of these aspects are briefly described below.

1. Route Configuration

The route for a 7/20 mph hybrid AMTV system consists of 7 mph intermittent-stop and 20 mph express sections. On a 7 mph section, the AMTV operates at or below 7 mph picking up and discharging passengers, and sharing the roadway with pedestrians and slowly moving vehicles. Examples of a 7 mph section include large parking facilities, shopping malls or other pedestrian areas, bikeway type lanes on city streets, traffic intersections and other gaps in a semi-guideway route section. On a 20 mph semi-guideway section, the AMTV operates at constant speed, slowing as necessary for curves, traffic signals or as it approaches a 7 mph section. It also slows down when an obstacle is detected in the pathway and will, if necessary, come to a full stop to avoid colliding with it. For safe operation, the 20 mph section right-of-way requires fences, or curbs to separate pedestrians and vehicles from the AMTV path. In a similar way, 1-1/2 mph sections may be programmed into 7 mph AMTV route segments, for example, at a U-turn.

2. Passenger Interfaces and Protection

a. AMTV Boarding. Because random boarding would cause excessive delays, marked passenger stops would be provided in a 7 mph or 7/20 mph hybrid system. A 1-1/2 mph AMTV could operate as a moving platform, allowing passengers to enter or leave at any time without stopping the vehicle. If traffic intersections are limited to pedestrians and very light vehicles (bicycles, for example), a 7 mph vehicle can be an open type tram to permit faster boarding.

Either 7 mph or 7/20 mph hybrid AMTVs will be programmed for a predetermined standing time at each passenger stop to allow sufficient time for boarding. Should boarding not be complete by the end of the standing time, sensors must be installed to sense the presence of passengers in the boarding zone and prevent the vehicle from moving off. Alternatively, manually operated entrance doors equipped with jamb interlock switches which will electrically inhibit vehicle motion until all doors are closed and locked may be used. In addition, passenger operated emergency push button switches located near the seats can be used as a back-up system.

b. Capacity. There is no technical constraint on the size and capacity of an AMTV. Therefore, accommodations can be based on the expected level of service required for the particular application. As examples, the experimental JPL AMTV has eight seats, but a 7/20 mph hybrid AMTV for shuttle service between two shopping centers may well have 20 or 30 seats. The straightforward relationship between AMTV parameters and system capacity is given in Table 3-1. Service capacity can be increased by increasing the capacity of each AMTV, adding more AMTVs to the route or by forming multi-car trains using specially designed tractors and trailers.

If desirable from an application standpoint, standing passengers may be permitted on an AMTV if they remain clear of the boarding entrances. In such cases, handgrips must be provided, and vehicle acceleration and jerk levels must be controlled to prevent throwing standing passengers off balance.

c. Passenger Protection. A 7 mph AMTV should have an enclosed body for protection of passengers in a side collision unless, as noted above, it only interacts with pedestrians and/or very light vehicles. However, for safety and passenger comfort, a 7/20 mph hybrid AMTV must have an enclosed body with manually or automatically operated quick opening doors. Emergency stop buttons should be provided for use by passengers in the event of a collision, impending collision or on-board emergency. A simple but reliable door mechanism should be used such that if the door is not securely closed, the vehicle will not move. While the vehicle is in motion, all doors will remain locked.

d. Passenger Comfort. Noise levels must be kept low and vehicle vibrations in the horizontal, vertical and longitudinal directions must be kept within acceptable limits (Ref. 14). Interior layout and seat spacing must be arranged to permit free passenger movement during boarding stops. Appropriate interior lighting should be provided.

Table 3-1. Relationship Between AMTV System Capacity Parameters. (Values For nominal speed, stops per mile and vehicles per mile are assumed. Ten second passenger stops are assumed. Note that a 30 passenger vehicle with one door would require a longer stop period, not shown).

Nominal AMTV Speed	Stops per mi	Average Speed	Travel time/mi	Vehicles per mi	Headway Interval	Line Capacity 8 passenger AMTV	Line Capacity 30 passenger AMTV
mph	-	mph	min	-	min	pass./hr	pass./hr
1.5	0	1.5	40	10	4	120	450
1.5	0	1.5	40	30	1.3	370	1380
7	15	5.0	12.0	2	6.0	80	300
7	5	6.2	9.7	6	1.6	300	1120
7	10	5.5	10.9	6	1.8	270	1000
7	15	5.0	12.0	6	2.0	240	900
7	20	4.5	13.2	6	2.2	220	820
7	15	5.0	12.0	20	0.6	800	3000
20	4	13.9	4.3	1	4.3	110	420
20	1	18.1	3.3	3	1.1	440	1640
20	2	16.2	3.7	3	1.2	400	1500
20	4	13.9	4.3	3	1.4	340	1290
20	8	10.5	5.7	3	1.9	250	950
20	4	13.9	4.3	10	.43	1120	4190

Maximum vehicle acceleration and jerk rates shall be within the range established as common practice in public transit vehicles.

3. AMTV Operation

a. Lateral Steering. An AMTV should track a fixed guidewire reliably and in a fail-safe fashion.

b. Passenger Stops. An AMTV should come to a controlled stop upon passenger request. Road-fixed devices should also be available to command the same controlled stop. In more advanced systems, persons at a designated boarding area may call for service. In such a case, a call button either on the AMTV or at the passenger stop area could cause the preset stop maneuver to be executed.

c. Headway Sensing. The AMTV must be able to sense obstacles in its path, such as pedestrians, vehicles or potentially damaging objects, and perform a controlled stop to avoid collision.

d. Collisions with Small Objects. If the AMTV bumper contacts an object undetected by the headway sensors (such as a rock or small animal), the emergency braking system will be activated to bring the AMTV to a locked-wheel stop. The brakes will remain set until the path is cleared. Procedures for restarting the AMTV must be developed.

e. Intersection Control. If an AMTV route passes through or turns at an intersection, the intersection must be equipped with four-way stop signs or traffic signals which are coupled with the AMTV control system. In the latter case, the right-of-way of an AMTV within the intersection must be fully protected by the traffic signal.

4. Route Constraints

a. Grades and Roughness. Normal grades found in typical city streets (± 10%) and moderate dips, bumps and roughness of the road surface should be acceptable. The vehicle design must be compatible with the actual route surface to be used.

b. Weather Conditions. AMTV operation in rain or on wet surfaces should be allowable.

c. Curves. The number of curves along an AMTV route should be minimized and curve radii should be compatible with headway sensor design. Where slowdown is necessary to permit safe negotiation of a turn or curve, a positive signal must be provided to the AMTV by the guidewire or a roadway marker.

d. Metal Covers and Gratings. The AMTV guidewire must be continuous, and its function involves a.c. magnetic fields. Therefore, the location of large steel objects such as manhole covers, gratings or rails in the road surface must be compatible with guidewire placement. Guide field distortion was found negligible for 7 mph travel with the guidewire 3 inches from the edge of a manhole cover; however, continuing the pathway across such a metal plate presents a problem.

5. Fault Detection and Recovery

Any system fault, whether of a vehicle or of a fixed element, must be signalled in a timely way to system operating personnel. Provisions shall be made for manually steering or towing a failed AMTV to clear the path of succeeding AMTVs or other traffic. Each AMTV should contain a prominently posted placard giving instructions on how to deal with the more likely emergency conditions. A system emergency plan should be developed to deal with serious accidents.

6. Maintenance and Storage

Facilities for off-line storage of vehicles, and procedures for routine maintenance and repair of AMTVs should be provided.

7. Scheduling Control

A dispatching system, preferably automatic, is required to maintain uniform AMTV vehicle spacing throughout the route and to execute established level-of-service policies. The dispatching system will accommodate daily and hourly variations in passenger demands to provide consistent service at a reasonable system load factor.

8. Safety Provisions

The system shall be designed such that any single failure cannot cause an unsafe condition. This provision may be met by applying fail-safe design practices, including the use of redundancy. Where redundancy is used, confirmation that each redundant element is operating properly must be provided. Steering, braking, headway sensing and motor control systems are critical functions which must have these provisions.

C. SUBSYSTEM DEFINITIONS

A complete AMTV system contains both vehicles and fixed elements. This section defines both the subsystems associated with the vehicle and those which are stationary elements. Their interrelationships are depicted in Figure 3-1. The subsystem definitions fulfill the overall system requirements discussed above.

1. Vehicle Subsystems

a. Headway Sensing Subsystem. The headway sensing subsystem contains an array of long and short range proximity sensors that can detect obstacles far enough ahead of the AMTV to permit a controlled

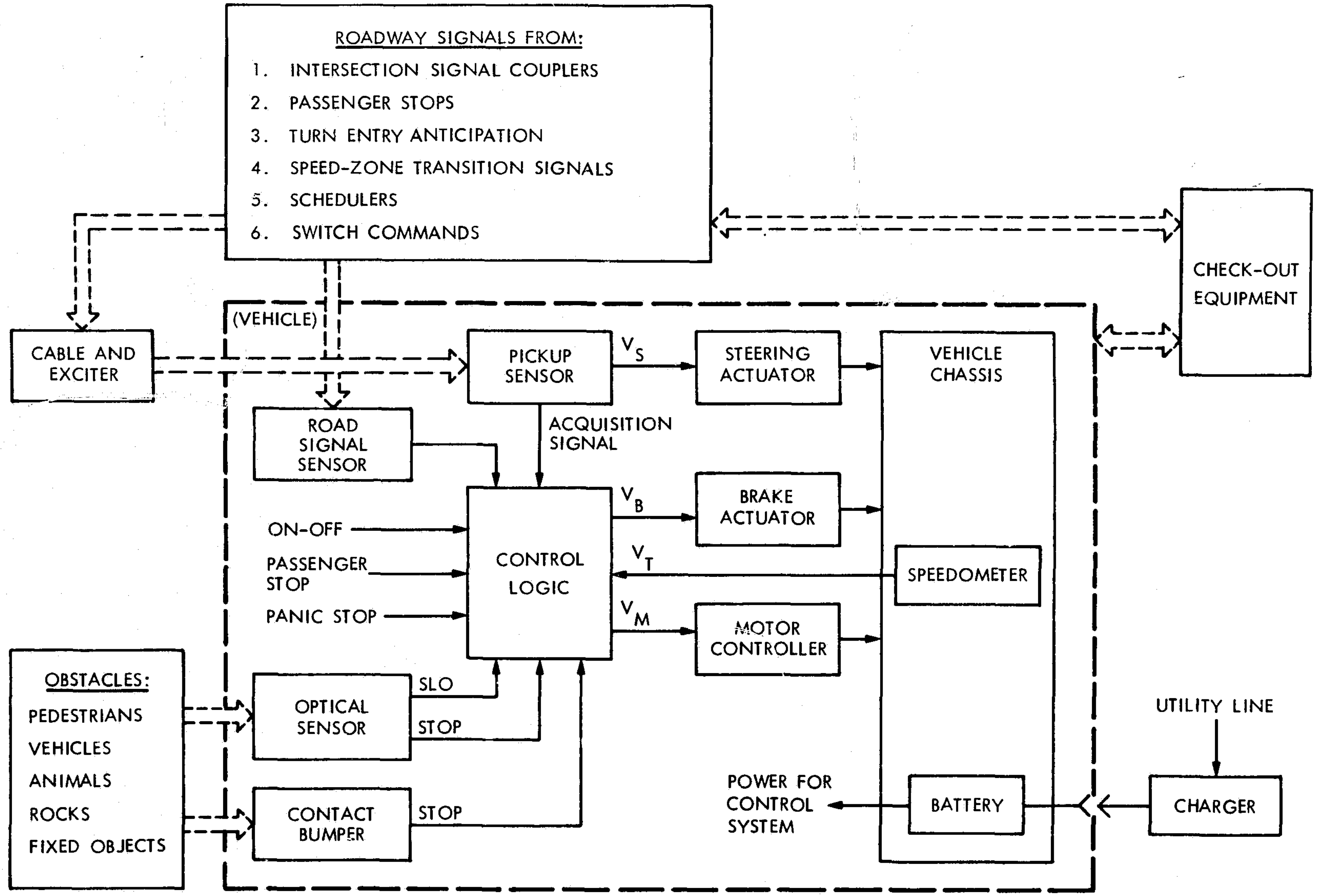


Figure 3-1. AMTV System Block Diagram

stop, as well as front and side bumper switches that actuate on contact with obstacles which have escaped detection by the proximity sensors. The contact switches trigger a locked-wheel stop.

b. Steering Subsystem. The steering subsystem contains a set of electromagnetic detectors that receive and resolve lateral error signals from the electrically excited guide cable installed in the pavement, plus the control actuators which operate the steering control linkage to maintain the vehicle on course.

c. Control Logic Subsystem. The control logic subsystem consists of the electronics and associated logic to receive inputs from various sensors (headway, steering, tachometer, etc.) and on-board switches and generate appropriate command signals for drive motor control and braking subsystems.

d. Drive Motor Control Subsystem. The drive motor control subsystem uses command signals from the signal processor subsystem to control the traction motor torque.

e. Braking Control Subsystem. The braking control subsystem contains actuators and drive electronics necessary to apply the hydraulically actuated service brakes in accordance with signals generated by the signal processor subsystem.

f. Vehicle Chassis Subsystem. The vehicle chassis subsystem consists of the basic chassis, body, suspension, braking system, propulsion (drive motor and battery), and other components that are normally a part of a conventional manually-controlled or AGT electric vehicle.

g. "Passenger Interface" Subsystem. The passenger interface subsystem consists of safety and operations related devices necessary to permit AMTV operations with passengers. Items such as passenger stop switches, emergency stop buttons, automatic door operations, boarding threshold switches, seat switches, etc., are included.

2. Stationary Subsystems

a. Route Subsystem. The route subsystem includes the guidewire installation, electric exciters, signalling system for routine stops and turns or curves and traffic separators (fence, curb or painted lines).

b. Intersection Coupling Subsystem. The intersection coupling subsystem includes all mechanisms involved in safely meshing AMTVs with pedestrian and other vehicular traffic at intersections. Stop signs, traffic signal timing modification devices, signal-to-guidewire couplers and errant vehicle detectors (to sense possible traffic signal violators) are mechanisms that might be used singly or in combination at intersections.

c. Passenger Stop Subsystem. The passenger stations may include sign posts, marked boarding lanes, benches, overhead cover or call buttons to signal the AMTV system that passengers are waiting to board.

d. Maintenance and Storage Subsystem. The maintenance and storage garage consists of a protected facility with proper equipment for off-line storage, repair, and routine maintenance of vehicles.

e. Dispatching and Fault Detection Subsystem. The monitoring and fault detection subsystem includes equipment for monitoring system operation, and for detecting and responding to system breakdowns. Included also are fault recovery and emergency response procedures. The dispatching subsystem consists of equipment for automatic control of vehicle schedules, route spacing and load factors.

f. Check-out Subsystem. Consists of equipment and procedures to confirm the correct functioning of system hardware before putting an AMTV into daily service.

D. SUBSYSTEM SPECIFICATIONS

This section outlines the design requirements for the above subsystems, and gives some important numerical parameters involved in their design.

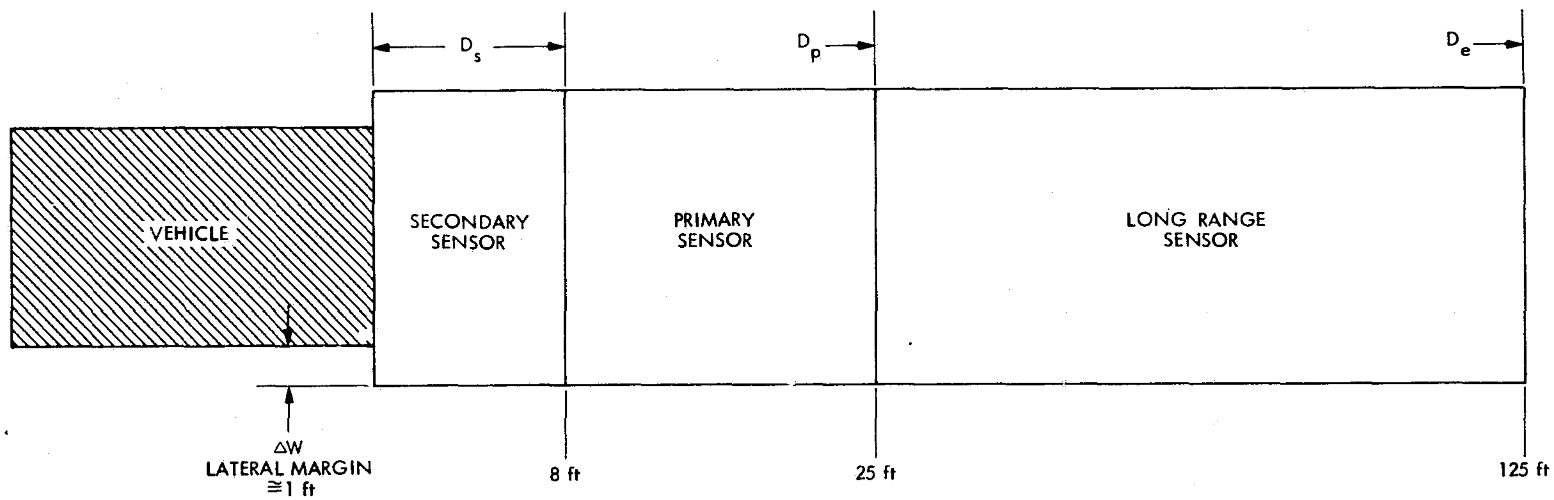
1. Vehicle Subsystems

a. Headway Sensing. Although a number of other sensing concepts are possible, optical sensors have been used on the JPL AMTV for headway sensing. Their capability can be extended for use in a 7/20 mph hybrid vehicle and the system can be simplified for use in a 1-1/2 mph AMTV. A 7 mph vehicle requires primary (25 ft) and secondary (8 ft) sensors. For a 1-1/2 mph AMTV, secondary sensors alone are sufficient. The sensing range of a 7/20 mph hybrid vehicle must extend to 125 ft, necessitating a third set of sensors, called the long range sensors.

The diagram of Figure 3-2 illustrates ideal sensing patterns for each of the sensor elements. The rectangular areas shown in the figure for each sensor element indicate the area within which the sensor must detect an obstacle. Acceptable margins for each area are also indicated. The actual individual detector beam areas are elliptical, so design compromises must be made to approach the ideal field pattern. Further discussions of long-range sensor characteristics, beam definition and sensor articulation for extended lateral coverage in curves are contained in Section IV.

The one-foot lateral margin requirement (ΔW) shown in Figure 3-2 is defined such that the sensing system must detect low reflectivity target from one foot left of the vehicle to one foot right of the vehicle, and be insensitive, or blind, to retroreflective surface which is at least two feet away from either side of the vehicle.

The headway sensor also has longitudinal margin requirements. The detection window for the primary system is defined such that low reflectivity target within 25 feet must be detected and retroreflective target more than 40 feet away must not be detected. For the secondary



ΔW { ≥1 ft FOR BLACK DIFFUSE TARGET; ≤2 ft FOR RETROREFLECTOR

D_s { ≥8 ft FOR BLACK DIFFUSE TARGET; ≤12 ft FOR RETROREFLECTOR

D_p { ≥25 ft FOR BLACK DIFFUSE TARGET; ≤40 ft FOR RETROREFLECTOR

D_e { ≥125 ft FOR BLACK DIFFUSE TARGET; ≤200 ft FOR RETRO REFLECTOR

Figure 3-2. Optical Headway Sensor Coverage Diagram headway sensing system, the detector must respond to a low reflectivity target within 8 feet and must not respond to a specular or retroreflective target more than 12 feet away. The corresponding figures for the long-range sensor are 125 ft and 200 ft.

A contact-bumper switch will activate the emergency braking system on contact to perform a locked-wheel stop. Such a braking system will stop a 7 mph vehicle within three feet on dry surface, and a 20 mph vehicle within 18 ft. It is possible, by means of a cats-whisker type switch extending in front of the vehicle, to perform an emergency stop without colliding with the obstacle at speeds up to 7 mph. A design trade-off which should receive further attention involves the choice between a cats-whisker type emergency contact switch, and a well-padded physical bumper design into which the contact switch is incorporated. The padded bumper-switch option is the only practical approach for a 20 mph system. Although a locked-wheel stop is undesirable, there appears to be no other acceptable strategy in the event that an obstacle contacts the front of a moving AMTV.

The headway sensing system design must contain fail-safe or self-check features. Failure of the system should cause the vehicle to make a controlled stop.

b. Steering. The cable-following steering technique has been demonstrated at higher speeds on larger vehicles than are anticipated for AMTV applications (see Refs. 4 and 5). The vehicle should respond to a lateral error signal within acceptable steady-state displacement error bounds, and without excessive overshoot or hunting characteristics. The route curvature radii should be made as large as possible and standardized where practicable, to optimize headway sensor function in a curve. Vehicle speed within a turn or curve should be limited to prevent nominal lateral accelerations in excess of 0.05 g in order to avoid discomfort to passengers in the event that the guidewire installation is inaccurate. The guidewire should be placed within approximately 1/2 inch of the true line, and transition radii can be helpful at the entrance to curves, even at 7 mph.

c. Control Logic. The function of the control logic is to accept and process all vehicle sensor and manual override signals and to deliver appropriate commands to the vehicle drive-motor controller and brakes.

The basic functions of the control logic are listed in Table 3-2. Lower numbered inputs take precedence in case of more than one input. In addition to the automatic functions shown in the table, the control logic is required to perform function switching from automatic to manual mode operation if any manual override command is made. The table illustrates that each of the inputs may originate from more than one source.

The table defines the overall control logic function for a 7/20 mph hybrid AMTV. Logic functions for a 7 mph AMTV or for a 1-1/2 mph vehicle are given by an appropriate subset of the total list. Specifically, a 7 mph AMTV requires only the first 4 commands, plus the seventh.

Table 3-2. General Control Logic Functions for an AMTV

Command	Source	Function
1. Panic Stop	A. Red buttons B. Contact bumper	Apply full brakes and hold. Auto mode input cancels.
2. Stop	A. Secondary sensor B. Loss of cable C. Passenger Stop	Slow to stop at controlled rate and hold
3. Timed Stop	Programmed stops	Slow to stop at controlled rate - pause for passenger boarding
4. Slow - 2	A. Primary sensor B. Steering angle input C. Road-fixed speed zone signal	Accelerate or decelerate at controlled rate to 2 mph and hold speed.
5. Cruise - 7	A. Long-range sensor B. Road-fixed speed-zone signal	Accelerate or decelerate at controlled rate to 7 mph and hold speed
6. Cruise - 20	Enabling road-fixed sensor input	Accelerate at controlled rate to 20 mph speed
7. Auto	A. Auto mode key switch B. Steering acquisition signal (both inputs required)	Activates logic; accelerate at controlled rate to 7 mph and hold speed

A 1-1/2 mph vehicle only needs the first three commands, and the seventh, which now causes the vehicle to cruise at 1-1/2 mph.

The control logic subsystem also determines the acceleration and deceleration rates and the rate of change of acceleration (jerk) which are transmitted as commands to the drive motor controller. These rates are a compromise, chosen to ensure a safe stopping distance and to minimize discomfort to the passengers. Since standing passengers might be permitted, the rates must be consistent with common practice in other transit vehicles that allow standing passengers. Typical rates for other transit systems are given in Table 3-3. Although the possibility of using higher rates has been discussed, published data are insufficient to make a conclusive suggestion (Ref. 14a).

Table 3-3. Typical Acceleration/Deceleration and Jerk Specifications for Other Transit Systems

Vehicle	Max. Normal Longitudinal Acc/Decel.		Max. Emergency Deceleration		Normal Longitudinal Jerk		Emergency Jerk	
	g	f/s^2	g	f/s^2	g/s	f/s^3	g/s	f/s^3
Morgantown	.137	4.5	.330	10.5	.130	4.2	.320	10.5
AIRTRANS	.116	3.8	.280	9.0	.080	2.5	-	-
BART	.152	4.8	.152	4.8	-	-	-	-

Based on the values given in Table 3-3 the longitudinal acceleration, and jerk rates suggested for an AMTV are as follows:

(1) Normal Accel./Decel. . . . . 0.16 g or 5 fps^2

(2) Emergency Deceleration . . . . . . 0.33 g or 10.5 fps^2

(3) Normal Jerk . . . . 0.16 g/s or 5 fps^3

(4) Emergency Jerk . . . . 0.33 g/s or 10.5 fps^3

Here, the term "emergency" applies to a stop commanded by the control logic (a more complex logic than given in Table 3-1), in response to an abnormal sensor input. The contact bumper would command an instantaneous locked-wheel stop.

Stopping distance as a function of the acceleration and jerk rate chosen are given in Appendix C. Stopping distance from a constant speed, and a worst case stopping distance, which occurs with the vehicle still accelerating but nearly at the maximum speed, are given in Figure C-1.

d. Drive Motor Controls. The drive motor current is regulated to control vehicle acceleration and slow down the vehicle before hydraulic braking is applied (dynamic or regenerative braking).

Motor overcurrent and overspeed protection should also be provided. The sensors for these protective circuits should be separate from those used in the main control system to provide backup protection in the event that a failure in the motor armature or field, or a failure in speed control circuitry occurs.

e. Braking. While dynamic braking provides redundancy, and can even be programmed to absorb most of the energy, friction brakes are the primary braking system.

The friction braking system must be designed in a fail-safe manner such that with loss of on-board power, the brakes will operate automatically to bring the vehicle to a safe stop. Spring-applied, power released parking brakes can provide this backup function. The brake controller should employ redundant systems with a dual master brake cylinder as in passenger automobiles. The integrity of each system and the switchover function should be tested daily as part of the vehicle checkout. The braking system should also contain an automatic anti-rollback function. Since no AMTV installation will require vehicle backing while the vehicle is in service, the anti-rollback function will be operative at all times in the auto mode.

f. Vehicle Chassis. The principal vehicle configurational and safety features were discussed above as part of the system requirements. Other operational requirements are listed below.

(1) Roof - Overhead protection should be provided on any AMTV that does not operate exclusively indoors. A hard roof is preferred, but a cloth canopy type roof may be acceptable for tram type vehicles.

(2) Interior Lighting - Interior lighting should be provided as appropriate to the application.

(3) Ride Quality - The ride quality of an AMTV should be consistent with those of a conventional low speed transit vehicle.

(4) Interior Noise and Vibration - Interior noise and vibration levels should be consistent with standards of conventional transit vehicles.

(5) Cleaning and Maintenance - Interior and exterior surfaces of the vehicle should be clean in design and constructed of

durable waterproof materials to permit rapid and frequent cleaning by maintenance personnel. Equipment compartments should be easily accessible for service and repair.

(6) Operational Range - The vehicle should operate continuously without battery recharge for at least four hours of service. Greater endurance is desirable, depending on application. A battery charge state instrument should be installed in a visible location to indicate to operating personnel when battery recharge is required. Depending on the economics of the application, it may be desirable to include battery-pack quick-change provisions in the design of the vehicle. Alternatively, where combustion fumes or added power plant noise can be tolerated, a hybrid powerplant (battery and heat engine in combination) may be installed.

g. Passenger Interface System

(1) Seating Configuration - Seating for enclosed vehicles should face forward or to the interior. Aisles should be of sufficient width to allow at least one passenger to move freely to or from the entrance doors. Seating for open tram type vehicles for 1-1/2, and in some cases, 7 mph AMTVs may face forward or to the outside.

(2) Doors - Folding or sliding type doors are appropriate for enclosed vehicles. Doors should be placed on one or both sides of the vehicle depending on the application, and should be wide enough to permit free passage. It may be desirable to have several doors, one per seat, for rapid boarding. Doors should fit flush to the exterior of the vehicle or be faired at the leading and trailing edges to minimize injury to a pedestrian who may be standing too close to a moving vehicle. Door handles, if used, should be flush and of a design which will avoid entrapping the hand of a boarding passenger if, for any reason, the vehicle moves before boarding is completed. Release switches might be placed on the closing edges of doors to open the door in the event a small object is caught as the door closes. An inhibit switch will prevent the vehicle from moving until all doors are completely closed. All doors will remain locked while the vehicle is in motion.

(3) Interior and Exterior Signing - Emergency instructions should be provided on an interior placard, as well as cautionary signs (i.e., "No Smoking," "Watch Step," etc.) and route information signs. Exterior signs should be limited to route designations and any boarding instructions that may be necessary (i.e., "Entrance," "Exit," etc.).

(4) Front and Side Bumpers - Pedestrian Protection - All AMTVs should have soft bumpers equipped with emergency switches at the front and sides of the vehicle. The front should be designed to provide a smooth padded bumper effect that

will deflect pedestrians or small fixed objects to the side with minimum probability of injury. The sides of the vehicle should be clean and free of protuberances.

(5) Sounding Signal - An audible signal may be sounded to warn pedestrians of an approaching AMTV. The signal may be sounded continuously or be triggered by vehicle headway sensors. The signal should not be harsh in character or excessively loud.

2. Stationary Subsystems

The stationary subsystems include the guidewire system, right-of-way protection, intersection control, curve and turn control, stop control, operational monitoring and fault control, and scheduling control subsystems, plus the associated checkout and maintenance functions necessary for assuring reliable and safe operation of the AMTV.

a Route Subsystem

1) Right-of-Way Guard Fencing. The right-of-way of 7/20 mph hybrid AMTV systems will be protected on the street side of 20 mph sections by a low protective rail or curb strong enough to physically deflect an automobile in a glancing impact. Fencing will be required on the sidewalk side of the right-of-way to prevent pedestrians and small animals from straying into the right-of-way area. At intersections, the right-of-way will be marked on the pavement but will otherwise be unprotected. For 1-1/2 mph and 7 mph AMTVs the right-of-way will be marked on the pavement but fences will not be required to prevent entry into the right-of-way.

2) Lateral Control. The steering system reference for AMTVs is provided by an uninterrupted buried wire cable or a train of emplaced markers located nominally along the center of the right-of-way throughout the entire route. Suitable pickups on the vehicle will detect lateral deviations of the vehicle from the center of the right-of-way and provide corrective signals to the steering system. Any interruptions in the cable or train of markers should cause the vehicle steering system to hold steering angle while the braking system makes a programmed stop.

The vehicle sensor for the acquisition signal should be carefully designed to accept a definite lateral excursion by the vehicle, ($\sim\pm8$ in.). Road fixed marker signals must function correctly over a wider excursion. Lateral clearance between the AMTV path and any curbs or fixed structures alongside it must accommodate the same lateral excursion, although a properly functioning AMTV will track the wire within a much closer tolerance ($\sim\pm$ 1 in). If a spur or switching point is included in the route, techniques for switching must be incorporated, for example each spur will be coded or only the proper sidetrack guidewire will be excited - the unwanted sidetrack guidewire excitation will be removed either manually or automatically. Existing technology used in warehousing systems is applicable.

3) Longitudinal Control. Provisions must be made for transmitting speed zone, turn anticipation and stop commands from the roadway to the vehicle. These commands will signal the entrances and exits of curves where speed must be reduced and will identify passenger pickup points and stop signs for traffic control. These types of signals will be time invariant, as opposed to route or spur switching and traffic control signals which vary with time and will be handled by other means.

b. Intersection Coupling. Time varying signals which are coupled to the traffic signals must be transmitted from the roadway to the AMTV. Whether the AMTV preempts other vehicular traffic at intersections or not, the AMTV and normal traffic signalling system must be integrated and interlocked in such a way that adequate stopping distance is provided to the AMTV and that at no time can an AMTV and cross traffic be admitted to the intersection at the same time. Turning traffic will not be permitted during the AMTV crossing periods at intersections. Where stop sign intersection control is used, four-way stop signs are needed. The AMTV will then respond to the intersection as it does to a programmed passenger stop; stopping for a fixed period of time, and then proceeding. In the event that the AMTV route itself includes crossings, switch points and merging, appropriate coupling for speed control must be incorporated to permit safe crossing and merging.

c. Passenger Stations. Because boarding areas for 7/20 mph hybrid AMTVs could possibly be located in a 20 mph section of the route, special protective measures must be taken to prevent entrance to the guideway by animals or small children, since the normal semi-guideway protective fencing must be removed to permit boarding. For 7 mph or 1-1/2 mph AMTV systems, boarding areas should be clearly marked with boarding call switches mounted on posts for systems which do not automatically stop at all boarding stations. Consideration may also be given to overhead protection and lighting at boarding stations.

d. Maintenance Areas and Storage Garage. A garage area must be provided for storage of vehicles not in service. Facilities for routine maintenance should be housed in conjunction with the garage; where necessary spare part inventories consistent with the level of field repair will also be stored. System maintenance and operations personnel will be headquartered at the garage area which may serve also as the operations center.

e. Dispatching and Fault Detection. Provision should be made to maintain a consistent level of service at all times by monitoring spacing of AMTVs on the route continuously and automatically. If bunching of vehicles occurs, this condition should be detected and corrected by selectively delaying vehicles at a central dispatching station. Means must be provided to signal operating personnel about the occurrence of an anomaly on the system. In a simple system, monitoring of the time between vehicles at a central stop may suffice. In more sophisticated systems, some form of communication system may be required.

f. Checkout Provisions. Each AMTV must be checked out daily before entering service. Special attention will be given to safety related items such as headway sensors, steering, and braking systems. Some of the vehicle checkout may be performed automatically using on-board vehicle self-check features built into microprocessor control logic. Additional functional checks may require dynamic tests of the braking and steering systems using fixtures or test stands installed at the garage. The function of redundant switchover systems in the vehicle must be individually checked to ensure that all multiple redundant paths of critical systems are operable and that the switchover logic properly detects and performs the switching function in the event of an in-service failure.

Tests of the stationary system elements should also be performed on a daily basis. To perform this checkout, it is expected that maintenance personnel will drive an AMTV through the route exercising each signal and observing each speedup and slowdown function in accordance with a procedure developed for the particular installation.

SECTION IV

REQUIRED TECHNOLOGY DEVELOPMENTS

A. INTRODUCTION

The purpose of this section is to examine the technology required for the AMTV, and to identify those areas which need further development in order to achieve a fully operational AMTV system. The discussion follows the AMTV system description outlined in Section III. Performance of the present AMTV mechanization is compared to the requirements set forth there where possible, and approaches toward making the desired improvements are recommended.

The conclusions have been derived partly from the JPL AMTV Phase I experiment conducted during February through June of 1976 (see Ref. 1). Extrapolations related to the 20 mph mode and other refinements which were not a part of the earlier experiment have been made.

B. RECOMMENDATIONS FOR AN INITIAL APPLICATION

Efforts needed for implementation of a near-term demonstration are listed below.

(1) Optical Headway Sensor Performance Improvement - The performance of the optical headway sensors should be made to conform with the specifications given in Section III. Improvements in beam definition and response time constant are required.

(2) Sensor Beam Pointing Control - Provision for directing the sensor beam in the direction of a turn is needed. This capability must be provided in a way that is commensurate with the requirements of the route. For example, a simple straight-ahead route with U-turns performed in an area separated from other traffic would not require additional sensor capability. In general, provision must be made for sensing in a standardized long radius curve and in a U-turn.

(3) Bumper and Emergency Stop Switch Combination - The bumper must provide the dual function of protecting the AMTV in the event of a failure of the optical sensor system, and minimizing the risk of injury to a pedestrian under the same circumstances. Some form of emergency stop-on-contact capability must be provided over the entire frontal area of the vehicle, (including windshield area) and also along the sides for protection during a turn.

(4) Fail-Safe Design - It is important that an operational AMTV, even in the early demonstration stages, be made as reliable as possible. Further, its design should be fail-safe, either by inherent design or by the application of redundancy in critical components.

(5) Microprocessor Based Control Logic - Although it is not a significant cost driver, the flexibility and added capability of a microprocessor control and logic system will be a valuable asset to a developmental system.

(6) Safety Measures for Passenger Boarding - Doors or a perimeter sensing system must be provided to inhibit the vehicle from starting while passengers are in the process of boarding or leaving the AMTV.

(7) Safety and Fault Recovery Plan - A general Safety and Fault Recovery guideline must be developed for typical applications as well as unique procedures for specific applications.

(8) Vehicle Operational Range - If battery powered vehicles are used (an attractive alternative for environmental reasons), provisions must be made for simple and rapid change of battery modules, appropriate to the specific application.

C. STATUS OF AMTV TECHNOLOGY

The required performance of each subsystem element, and approaches for achieving it are discussed below in further detail. Required performance is discussed with reference to the examples of applications illustrated in Section II-F. The items discussed are summarized in Table 4-1. An estimate of where each task falls along the line between straight-forward engineering and long-range research is given in the columns labelled "Type of Effort". Here, the term "Engineering" implies that there is some applicable experience, "Development" implies that the approach appears to be fairly straight-forward, but involves some new advances, and "R&D" implies that basically new technology is needed, and it is not clear what the best approach is to solving the problem. The columns labelled "Need" identify which of the two described applications require the results of the task, or whether the task is aimed at an increase in system capability.

1. Headway Sensing System

Headway sensing is a key element of an AMTV, and refinement of this system should receive top priority in future hardware development. The headway sensing system has a number of independently functioning parts which together protect the AMTV from collision. A set of optical sensors provide overlapping coverage for basic straight-ahead collision avoidance. A separate set is required for protection during a U-turn maneuver. Both are backed up by a combination compliant bumper and contact switch.

Table 4-1. Listing of Needed AMTV Technology Developments

Subsystem, Item	Need			Type of Effort		
	Initial Demonstration	Urban Application	Added Capability	Engineering	Development	Long term R&D
A. VEHICLE						
1. Headway Sensors						
a) Long-range sensor		X			X	
b) Response time	X			X		
c) Noise optimization		X			X	
d) Beam definition	X			X		
e) Vertical extension of coverage	X			X		
f) Turn coupling	X				X	
g) U-turn sensing	X			X		
h) Contact bumper design	X			X		
i) Contact bumper vertical extension	X			X		
2. Steering						
3. Control logic						
a) Microprocessor implementation			X	X		
4. Drive Motor Control						
a) Reduce time constant	X			X		

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Table 4-1. Listing of Needed AMTV Technology Developments (Continuation 1)

Subsystem, Item	Need			Type of Effort		
	Initial Demonstration	Urban Application	Added Capability	Engineering	Development	Long term R&D
5. Braking						
a) 4 wheel proportional	X			X		
b) Parking brake	X			X		
6. Vehicle chassis						
a) 8-12 hr. endurance			X	X		
7. Passenger Interface						
a) Early Startup Protection	X			X		
b) Audible signals			X	X		
B. FIXED ELEMENTS						
1. Route						
Discrete marker study			X		X	
Guide wire installation automation			X		X	
2. Intersection Coupling						
a. Design		X		X		
b. Right turn capability		X			X	
c. Left turn capability		X			X	

Table 4-1. Listing of Needed AMTV Technology Developments (Continuation 2)

Subsystem, Item	Need			Type of Effort		
	Initial Demonstration	Urban Application	Added Capability	Engineering	Development	Long term R&D
d. Protection against signal violation		X			X	
e. Guideway intrusion protection		X			X	
3. Vehicle checkout						
a. Implement		X		X		
4. Scheduling		X		X		
5. Monitoring, Fault recovery, accident plan	X			X		
6. Maintenance and storage	X			X		
C. <u>OTHER ITEMS</u>						
1. Fail safe and reliable design	X			X		
2. Long-Term Technology development						
a. Headway sensor alternatives			X			X
b. Automated passing capability			X			X

In the JPL AMTV, the basic sensors are optical devices, consisting of an array of four primary (25 ft) sensors, which together generate a beam about 6 in. thick vertically and somewhat wider than the vehicle, and two similar but smaller fan beam secondary (8 ft) sensors. These are simple fixed devices without scanning elements or precision optics (see Refs. 6 and 7). Although the present sensing performance has been adequate for the breadboard feasibility demonstration, it would not be adequate in an operational situation. The signal-to-noise ratio for a black target is marginal, and the interrelated time constant of the sensor outputs (1/2 sec) is excessive. Beam definition, both laterally and down-track, also needs improvement.

Fabrication and evaluation of an improved set of sensors is planned. This set is an array of 7 sensor elements, each element performing both the primary and secondary sensor function. One element of this set has been built and tested in the laboratory. Its beam definition has been found to be satisfactory and sufficient signal to noise ratio to obtain a 0.1 sec time response has been obtained. Evaluation of this system will continue with tests on the present vehicle.

Additional specific developments which must be made to improve the various sensors are described below.

a. Long Range (20 mph) Sensor. Sensing elements to detect vehicles or other large objects at a distance of 125 ft must be developed for vehicle operation at 20 mph. Since no past work has been specifically aimed at these requirements, this is a new development task. Light source power constraints will limit the capability to detect small black targets using an extension of the present primary sensor approach. However, reliable detection of other AMTVs or automobiles in a semi-guideway is straightforward. Therefore, reasonable performance goals for a development task are to achieve;

(1) Reliable detection and emergency stop for a pedestrian or similar size object in a guideway.

(2) Reliable detection for a programmed stop (normal deceleration) for another AMTV or automobile in the guideway.

In this context, emergency stop means to stop the vehicle using maximum braking effort. Stopping in this mode would be an abnormal event because the guideway security will have been violated to necessitate the stop.

Other improvements required in order to achieve these goals are, optimized signal-to-noise design of the sensors, and improved optical design for beam definition at 125 ft range.

b. Primary Sensors. The primary sensors carry the main headway sensing burden. They must operate without the degree of control over the operational environment that can be provided by the 20 mph semi-guideway. Except for the different range requirements, the two sensor types are functionally equivalent. They must detect any object in the path of the vehicle large enough to be a hazard to the vehicle, or a pedestrian or another vehicle.

The following items should receive attention. The specific ideas presented apply to both the primary and the long-range (20 mph) sensor systems.

(1) Detector Noise and Response Time Optimization - Detection of a black target at 25 ft and discrimination against a distant, fully sunlit, white background are conflicting requirements. Optimization of the detector channel for best S/N performance is needed. Detector response time is inherently coupled with noise, and should be considered as a part of the tradeoff. It is felt that a detector response time of 0.1 sec is necessary to obtain an overall vehicle response time of 0.2 sec, e.g., a value which approximates the expected response time of a human driver.

(2) Beam Definition - The headway sensors must detect any object in an area approximately 1 ft wider than the vehicle on each side. The sensed area must be precisely defined laterally to permit unimpeded passing of parked cars. The need for good beam definition arises because of the extreme difference in reflectivity between a black diffuse target and a retroreflective lens such as an automobile tail-light or reflector. The sensor beam will always be larger for retroreflective targets, because much more light is returned to the detector by a retroreflector.

Two approaches are possible for achieving the required beam definition. The one to be investigated next involves the use of an array of several sensing elements, each one a narrow well defined (6 in. laterally) beam. The other involves the development of special (perhaps aspheric) optics designed to cover the required area with one or two sensor packages. A cost tradeoff exists between the two approaches which should ultimately be examined. It involves the use of more costly optics in the one case versus a multitude of simple sensing elements in the other.

(3) Vertical Extension of Headway Sensing Area - The present sensors cover only a plane near the road surface (1 ft high). Ultimately, either extension to cover the total height of the vehicle will be needed, or because the probability of encountering an overhead obstacle is low, such an occurrence may be treated as an emergency stop situation covered by a bumper switch.

(4) Sensor Pointing During Turns - The most frequently encountered shortcoming of the simple straight-ahead sensor beam of the breadboard AMTV involved lateral coverage during turns. With a sensor beam 1 ft wider than the vehicle, and extending 25 ft ahead, calculations indicate that a turn with a radius of curvature of 300 ft or less will compromise the headway

protection on the inside of the turn. Either coupling of the sensor beam with steering angle, or some means of switching in or out special sensor elements directed at a slight angle to the vehicle centerline are possible solutions. In addition, a means to signal the vehicle in advance of a turn appears to be needed, not only for lateral sensor coverage, but possibly also for speed control. In developing a simple mechanization of turn-coupled headway sensing, it will be advantageous to limit route turn radii to one or a few standardized values.

Figure 4-1 illustrates the order of magnitude of path curvature allowable for a straight-ahead sensor pattern which is wider by distance ΔW on each side than the vehicle. The curves are computed for different values of ΔW, and relate curve radius R to the distance D from the front of the AMTV to an obstacle on the inside of the turn in a position that would just be grazed by the vehicle, when it would first be detected by the sensor. The curves can be interpreted as giving the minimum turn radius that will not compromise the straight-ahead sensor, as a function of sensor range. Note that the typical radii are much longer than the minimum radius of curvature permitted by lateral acceleration (60 ft at 7 mph for an 0.05 g lateral acceleration).

c. Secondary Sensors. Except for beam definition, the secondary sensors used on the JPL experimental vehicle provided satisfactory performance.

In addition to the straight-ahead sensing requirement, the secondary sensing system of an operational AMTV must also provide warning of collision during a minimum radius turn (U-turn), a function not incorporated in the JPL experimental AMTV. Such a turn is performed at low speed, and is a separate problem from the cruise-speed turn problem discussed above. In a U-turn, the velocity vector of the front of the vehicle is rotated by an angle of 45 deg or more with respect to the centerline. Suitable short range sensors looking to the side, (and even toward the rear for passing traffic) are needed and can be incorporated as part of the secondary sensing channel. These can be activated by steering angle, but road-fixed signals to anticipate the U-turn may also be desirable.

d. Contact Bumper-Switch. The final element of the headway sensing system is a mechanical switch-bumper combination which applies maximum braking if actuated by contact with an obstacle. A fiberglass "Whisker-pole" arrangement was used in the JPL experimental AMTV to provide the switch function only. However, it is desirable to actuate the switch in conjunction with a compliant but durable bumper structure to provide both pedestrian as well as passenger protection in the event of a collision.

The contact switch function must also be extended to cover the full height of the vehicle in the event of an overhanging obstacle, perhaps by a combination of the switch mechanism with a replaceable windshield.

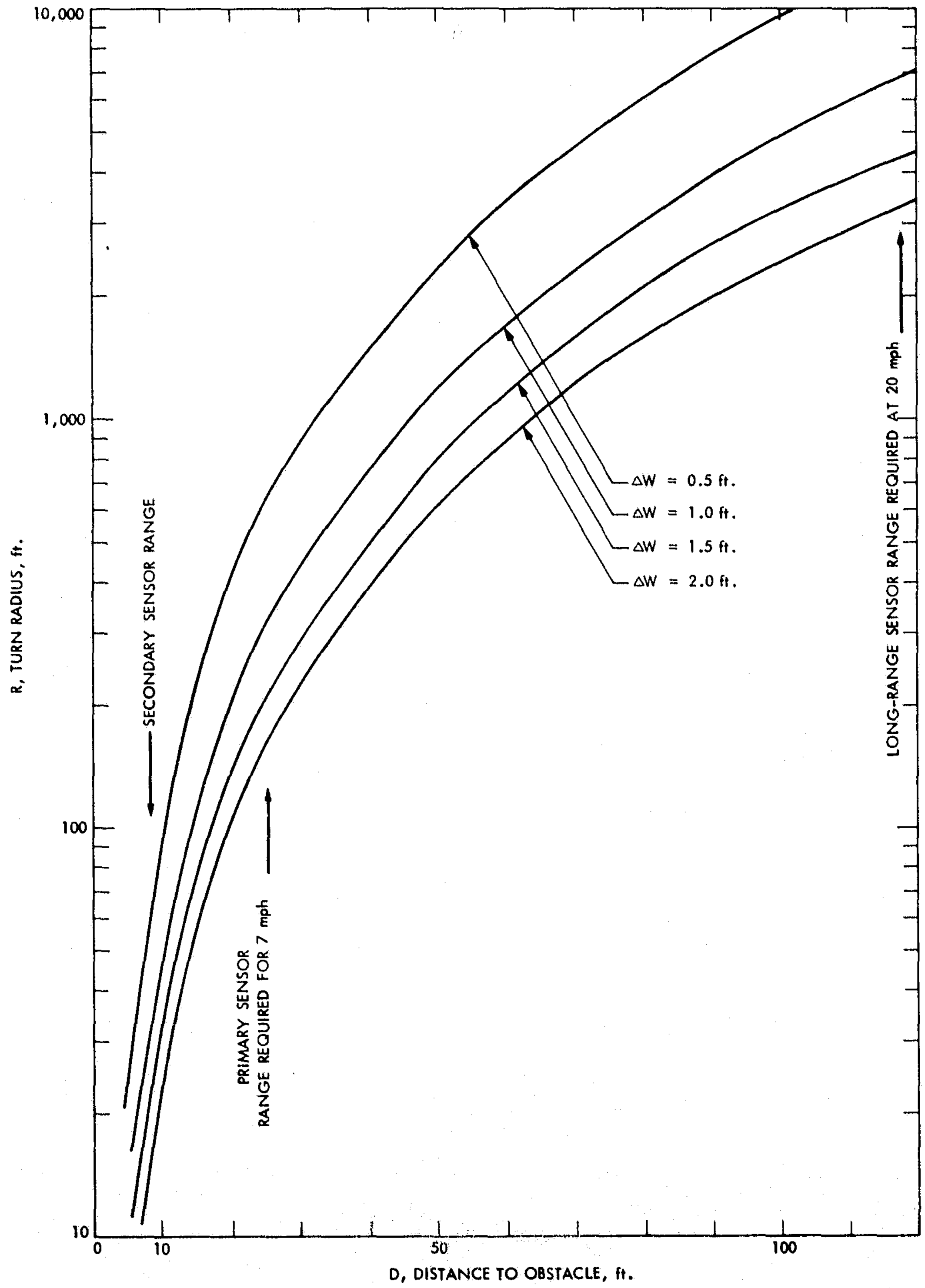

Figure 4-1. Minimum Turn Radius For Correct Sensor Function as a Function of Target Distance for Different Sensor Width Margin ΔW

e. Long-Term Developments. Although an infrared proximity sensor has been used for the headway sensing function, other approaches should also be evaluated. The development of a sensing device that can reach to 125 ft, return position and velocity data for the closest target, and also scan a swath to either side of the vehicle is technically feasible, although much too costly at the present time to permit use on an AMTV. Development of this type of capability, in a simple, low-cost device is a reasonable expectation from today's rapidly developing electronic technology, and would permit raising the cruise speed of an AMTV from the present 7 mph while relaxing the requirement for complete guideway protection.

2. Steering System

The hydraulic steering servo used on the JPL experimental AMTV is of conventional design and has proven to be precise and reliable. Its design is described in Reference 18. Little improvement appears to be required except to enhance its reliability by the application of fail-safe design principles.

3. Control Logic

The present hard-wired controller processes a number of discrete on-off inputs while producing smoothly varying speed signals for drive motor and braking control. A fixed parameter ramp generator supplies the speed profile program and passive networks limit the rate of change of acceleration/deceleration (jerk) commands. While its performance is satisfactory, logic modifications or changes in parameters have been awkward to make.

Development of a microprocessor controller is a desirable future task to provide greater control flexibility, added sensor signal processing capability, internal redundancy and self-check ability, and an ease of function modification which will be of particular benefit during the development and evaluation of the vehicle. Also, the microprocessor will provide added capability, for example, to select differing deceleration profiles depending on target distance and closure rates as indicated by times of switching between high-speed, primary and secondary sensor channels. Individual vehicles could also be programmed to follow different routes using a coded road fixed signal rather than requiring roadside equipment to effect switching between routes. The microprocessor can be useful in automating prestart checkout procedures, and can be used for certain housekeeping functions such as route loading (based on seat occupancy count), battery state of charge monitoring, etc. The microprocessor can supervise on-board redundant systems and provide switchover signals in the event a failure is detected.

4. Drive Motor Control

The present JPL experimental AMTV is equipped with an SCR controller which provides both traction motor control and dynamic braking. Switching between forward power and braking involves inherent delays in the present controller, which can be as great as 1/2 sec. Either separate modulatable hydraulic service brakes should be used with dynamic braking reserved only for redundant use, or an improved controller design is needed. This task involves straight-forward engineering and should take advantage of existing designs wherever possible.

5. Hydraulic Service Brakes

Hydraulically actuated mechanical service brakes are required, either as the primary braking system or alternatively, as a dynamic braking backup system and for a holding brake. A four wheel modulatable service braking system is needed. Proportional control can provide a smooth transition between dynamic and friction braking while the vehicle is brought to a full stop, yet still permit instantaneous application of all wheel brakes for an emergency stop.

As a part of the braking system, spring applied, power released parking brakes must also be incorporated to protect against internal power failure due to battery depletion or malfunction. Many of the required braking system features are common to other automated guideway transit systems but will require careful engineering and performance verification. Maximum use should be made of technology from other automated vehicle systems.

6. Vehicle Powerplant

The JPL AMTV is battery powered, which provides excellent controllability but limited range. Ideally, an AMTV should operate continuously over a full day without any refuelling, recharging or other service. Increasing the number of batteries will provide marginal range performance for a 7 mph AMTV but is likely to be insufficient for a 7/20 mph hybrid AMTV. Alternatives include the following:

(1) A short mid-shift or mid-day high-rate recharge in which the vehicle is removed from service for an hour or two during a slack load period.

(2) Battery exchange using quick change mechanisms and special garage handling systems to permit a one-man rapid battery pack exchange.

(3) A heat engine-battery hybrid vehicle in which the heat engine provides all sustaining energy.

(4) A heat engine only powerplant which requires refuelling only and can easily operate over a full day without attention.

All of the alternatives suffer limitations. A mid-shift recharge service procedure will require significant maintenance personnel time to service a large fleet of vehicles. A battery exchange system to accomplish the same purpose will require a large inventory of batteries to supply the fleet with quick replacements. A hybrid power plant provides an attractive alternative in that it possesses the controllability features of the all electric vehicle with the range performance of a heat engine only vehicle. Both the heat engine-only and hybrid power plants suffer the drawbacks associated with pollutant emissions and flammable fuels.

Considerable work on electric and hybrid vehicles throughout the country is being sponsored by the Department of Energy, and many of the results should be applicable to an AMTV.

7. Passenger Interfaces

Means for preventing the AMTV from starting up before passengers are clear of the doors or entrances need to be developed. On a closed vehicle, the doors with their associated protective systems provide this function.

In an open vehicle, protective systems must not only ensure that the boarding process is complete, but that limbs and packages are within the perimeter of the vehicle. An additional beam-break type of perimeter sensor coupled to the secondary sensor channel should be investigated as a solution to the passenger containment problem in tram type vehicles.

Audible signaling devices also may play a part in assuring that passengers are prepared for automatic vehicle startup and that pedestrians are provided with an audible warning of an approaching vehicle. A tone preceding startup and possibly another type of tone, musical rather than a warning horn, to indicate the presence of an AMTV to pedestrians should be investigated for these purposes. In general, such devices must be tested in an operational environment to evaluate their effectiveness.

D. STATIONARY SYSTEM ELEMENTS

While many of the stationary systems required for AMTV operation have parallels in other transit system concepts, their use in an AMTV system is a primary function in contrast to the backup function they typically provide in driver-controlled systems.

1. System and Route Design

While route layout will usually be dictated by the constraints of particular applications, some general procedures should be developed for the design and to establish both the economic and practical feasibility of AMTV installations. Included in these should be considerations of,

(1) Geographical variation of passenger demand within service area.

(2) Unique hazards related to the operational environment, (i.e., weather) fault recovery provisions, and fencing and curbing requirements.

(3) Maintenance garage and operational personnel requirements.

(4) Number of boarding areas needed and facilities required at each boarding point.

(5) AMTV related intersection control and route turn or switching limitations.

(6) Minimum curve radii, allowable curve speeds and curve radii standardization.

(7) System installation and operational costs.

2. Guide Cable Installation

The wire following steering technology has been proven through numerous applications, and its use on early AMTV systems is highly probable. Limitations of guide wire installations include placement over reinforcing bar, buried or surface rail tracks, manhole covers and drainage gratings. These can normally be avoided by the design of the route, removal or relocation of metallic objects, aided by the use of a phase sensitive wire following technique. A more severe hazard to a guide wire installation is ground motion which can result in cable breakage. Early demonstration system installations should be located in areas where frequent ground freezing does not occur to minimize the risk of wire breakage due to this cause.

The speed and accuracy of the cable installation could be significantly improved by development of equipment and procedures to mark the road surface rapidly and accurately for saw cutting, perhaps using a manually driven AMTV; and development of a specialized device or tool to apply backfill material.

In addition, further work is needed to integrate longitudinal control information with the lateral guide cable either through individually excited sections of cable or by coded markers placed on the road surface at the time of cable installation. An initial study is underway at JPL to investigate an alternate method of providing steering references by using discrete markers placed at regular intervals in the road surface. In this approach, certain types of longitudinal control information could be integrated with the lateral reference by the use of coding in the placement of the markers. The results of this study will be described in a separate report.

3. Longitudinal Control

Individual sections of an AMTV route must convey slowdown, speedup and programmed stop signals to the AMTV. On-board equipment will detect the presence of longitudinal control information and activate the motor-controller. At boarding points and signal controlled intersections, the on-board sensing systems will command computed deceleration profiles based on fixed markers which will bring the AMTV to a near stop, after which it might continue to creep at a very low speed until final stopping is accomplished by another marker signal.

Proper vehicle speed information for individual sections of the route can be provided by road-fixed coded markers or by changes in excitation frequency or modulation of the cable. For example, when a "go" signal is received from an intersection traffic control signal, either the cable frequency or modulation of the intersection entrance section might be changed to provide the speed command through and beyond the intersection. Redundant information could be provided by coded markers.

4. Intersection Coupling

Development of effective means of coupling the AMTV system with traffic signals will be necessary. To date, no work has been done on this subject. Two modes are envisioned; (1) AMTV travel through a signal controlled intersection can be adapted to a conventional fixed timing sequence or, (2) the AMTV may exert priority control over the normal signal timing system. In either case, there must be an electrical interface between the traffic control signal and the AMTV longitudinal control system to ensure that the AMTV will not attempt to enter an intersection which is admitting cross traffic. In general, traffic along the direction of the AMTV will be allowed to flow during AMTV passage through the intersection. An electrical tie from the traffic signal to the AMTV system will cause the intersection entrance section or marker to command the AMTV to stop on a "yellow" signal whose timing is appropriately adjusted to ensure that an oncoming AMTV can stop before entering the intersection. All intersections through which an AMTV route passes must either be signal controlled or must have stop signs for cross traffic.

5. Turn Capability

Closely related to signal coupling at intersections is the capability for an AMTV to safely execute turns in a mixed traffic environment at intersections. A right turn can be implemented in a straight-forward manner, but achievement of left turn capability is more complex. Possible alternatives for left turn capability include:

(1) Introduction of an All Red Period in the Normal Signal Cycle - The success of this method will depend on assuring that the AMTV lane is clear of stopped vehicles ahead of the AMTV when the AMTV receives the clear signal.

(2) Special AMTV Left Turn Lane and Signal - The need for lane changes by the AMTV in order to enter the left turn lane is a drawback to this method.

6. Guideway and Intersection Protection

Roadside sensors may be required to (1) detect a car on a cross street which is likely to run a red light (errant vehicle), and (2) detect intrusion into the semi-guideway. While a guideway intrusion detector may be conceptually simple, an errant vehicle detector could prove more difficult to devise. Such sensing capabilities do not presently exist in the required form. If needed, the capability will have to be developed.

7. Scheduling and Dispatching

Appropriate procedures and devices for dispatching and spacing multiple AMTVs on a single lane need to be developed. Conceptually, automatic methods can be devised in which AMTVs are added to or withdrawn from service (dispatched) on the basis of occupancy sensors, and which do not require real time communications from each vehicle to a central dispatching area. Similarly, spacing (scheduling) of AMTVs on the route can be accomplished by selectively delaying the departure of each AMTV from a central dispatching station. The details of such concepts need to be worked out and the need or lack of need for real-time communications to each AMTV must still be established.

8. Vehicle Checkout

As part of a complete AMTV system, procedures and equipment for checkout of each vehicle before it enters service will be required, and must be developed. Checkout can be automatic, manual or a combination of both. Performance tests of the headway sensing, steering and braking systems are vital (see specific items in the Hazard and Failure Mode Analysis Section). Perhaps a more difficult task is the checkout of system stationary elements such as longitudinal control markers including signal couplers, curve and turn slowdown markers, etc. The function of each of these should be checked out at least daily.

E. CONTINUING DEVELOPMENTS

1. Fail-Safe and Reliable Design

As part of the development process involved in setting up an operational AMTV system, detailed engineering of each vehicle and stationary subsystem must be performed to incorporate fail-safe design principles and to achieve reliable operation. This process is not really a development activity; existing technology and hardware is available and will guide the design in most cases, but many problems unique to the AMTV concept must be addressed. The analysis in Section V is an initial step in this process.

2. Long-Term Research and Development

Two specific areas deserve priority as long term Research and Development tasks.

(1) Headway Sensors - Alternative sensor approaches, including active scanning devices using laser sources should be examined for applicability. Optical methods, radar and ultrasonic devices should all be evaluated. Opportunity for improvement by the combination of sensor types should also be considered; for example an optical scanner for precise beam definition plus an ultrasonic device or doppler radar for relative velocity determination.

(2) Blockage - JPL experimental AMTV experience showed that blockage of the route by other parked vehicles was a frequent occurrence. Service and delivery vehicles were the most common offenders, and would be expected in any urban area. Therefore, a capability for an automated vehicle to recognize a route blockage, maneuver around it at minimum speed, and reacquire the cable after passing would be a valuable asset. Mechanization of such a maneuver would be conceptually simple, through a microprocessor controller having prestored passing paths in memory. However, safely executing even a simple maneuver like this in a complex and unpredictable operational environment presents a very challenging problem. Therefore, the attainment of this capability must be regarded as a long range goal. In the meantime, it will be necessary to avert the blockage problem by making rules to keep the AMTV path clear, and subsequently enforcing them, a task that the AMTV passengers could help with.

SECTION V

SAFETY ANALYSIS

The demand for safety in transportation systems has always had a strong influence on their development and use. Public vehicles such as the AMTV must be perceived by their users as safe, and in practice this has meant significantly safer than a private auto. Achievement of such levels of safety in a new type of system is a challenging goal. The safety analysis described in the following pages is intended as a first step toward reaching that goal. The methodology described in Reference 15 has been used as a guideline.

The safety analysis was undertaken without preconceived assumptions or limitations. However, due to the volume of data generated, the scope was subsequently limited in order to concentrate on items unique to the AMTV system concept. The AMTV system was assumed to follow the system description found in Section III of this report, and the block diagram shown in Figure 3-1 was used as a guideline. However, no assumptions were made regarding implementation of the elements in the block diagram.

It should be noted that many of the system and subsystem requirements described in Section III have been conditioned by the results of this safety analysis. The safety analysis proceeded in parallel with the technology portion of this study and influenced the requirements given there.

A. OBJECTIVE

The goal of this safety analysis was to perform a systematic, step-by-step examination which would attempt to identify all possible hazards, and identify one or more approaches toward eliminating each hazard. A separate examination of each hazard was then made to determine its severity and to establish priorities for implementing corrective actions.

B. DEFINITIONS

1. Safety

Freedom from those conditions that can cause injury or death, or damage to property.

2. Hazard

Any condition that can potentially cause injury or death or damage to equipment or property.

3. Failure

A condition resulting in the inability of the system to perform the designated function. A failure may or may not constitute a hazard.

4. Fail-Safe

A characteristic of a system which ensures that any malfunction affecting safety will cause the system to revert to a state that is known to be safe.

C. METHODOLOGY

The analysis was performed in two parts. Part 1 was the Hazard Modes, Effects and Prevention Analysis (HMEPA). It included all hazards which were related to operation of a properly functioning AMTV system. The origin of these hazards tended to be people related, involving actions of either passengers on the AMTV, pedestrians, or vehicles which interact with the AMTV. Part 2 was the Failure Modes and Effects Analysis (FMEA). It involved failures of the AMTV hardware and the hazards resulting from such failures. Established techniques for conducting failure mode analyses which have been used in space mission development were used (Ref. 16). Of course, every failure does not necessarily constitute a hazard. In this analysis, the safety implications of hardware failures were emphasized, but it should be recognized that any failure results in a loss or degradation of service. For this reason, high reliability, or the absence of failures is also an important goal.

By its nature, the first steps in the safety analysis tend to be qualitative and intuitive. A list called a hazard catalog, which is made as complete as possible, was first compiled, based on experience and on an understanding of the function of the system. Subsequently, the effect to be expected if each hazard is activated and the probability of such activation are estimated in order to determine severity. Tentative corrective actions are also identified at this stage. The complete hazard catalog is presented for reference as Appendix A and the failure mode catalog is contained in Appendix B. In order to condense the volume of information to a more manageable level after compiling the two catalogs, two criteria were used to select significant hazards for further consideration.

(1) The hazard severity estimate

(2) A judgement that the hazard was unique to the operation of the AMTV system, rather than one which other transportation modes or the general public are also subjected to.

The significant hazards thus selected are presented in tabular form in Table 5-2, and are discussed in the Findings and Recommendations Section E. below.

D. PROCEDURE

A flow plan for the Hazard and Failure modes analysis is presented in Figure 5-1. Each block in the diagram, briefly described below, represents one step in the process.

1. Identify Hazard Categories and Failure Categories

The initial step in the safety analysis is to establish broad hazard categories and to develop a fault tree structure for the failure mode analysis. The categories are kept general and comprehensive to help avoid unintentional omissions. The elimination of irrelevant or less important hazards is done later.

2. Identify Hardware Failure Modes

One hazard category is system hardware failure. The first step in performing the failure modes and effects analysis (FMEA) is to identify all hardware failure modes. This process is also intuitive, but is aided considerably by the system block diagram found in Figure 3-1 and fault tree diagrams such as Figure B-2. An effort is made to be comprehensive in order to prevent inadvertent omissions. Again, the list is subsequently sorted during the following risk assessment step.

3. Identify Failure Effects

The probable consequence of each failure is identified. This is actually done in parallel with the failure identification step.

4. Generate Initial Preventative Actions

If it is possible to identify a tentative fix for the failure, it is done in the initial preventive action block. This information is used as a source of ideas later when more detailed preventative actions are developed. Each failure effect is assessed later to evaluate the possible hazard resulting from it.

5. Identify Hazard Modes

The hazard categories not related to hardware are studied using a process analogous to that just described, called the Hazard Modes, Effects, and Prevention Analysis (HMEPA).

6. Identify Hazard Effects

Having identified all the hazard causes for each hazard category, the probable hazard effects are then identified. If a hazard prevention

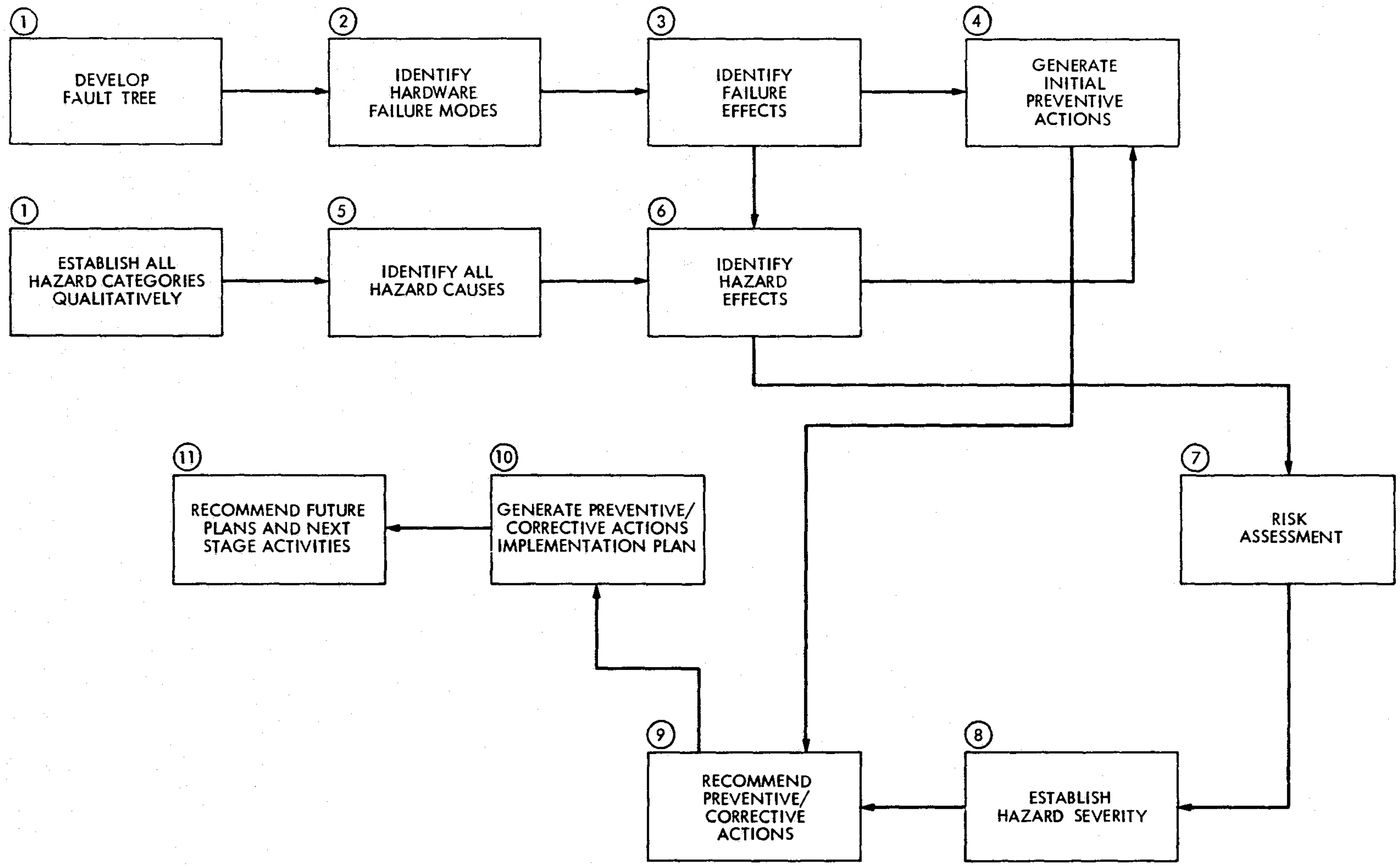

Figure 5-1. AMTV Safety Analysis Work Flow Plan

technique is known at this time, it is also recorded for later reference as part of 4 above.

7. Risk Assessment

A risk Assessment was conducted in order to identify in a reasonably systematic way the irrelevant or minor hazards and to identify the more important hazard areas for further elaboration. The risk assessment was achieved by assigning intuitive ratings to hazard severity (S), probability of occurrence (P), and control cost (C). The ratings were obtained by having each member of the study team independently assess each item, and then averaging their judgements, expressed in numerical form as defined in Table 5-1. The resulting assessment ratings are included in the hazard catalog in Appendix A and B. The risk ratings assigned range from 4 (catastrophic) to 1 (negligible) for hazard severity (S), from 4 (high) to 1 (almost never) for probability of occurrence (P), and from 4 (none) to 1 (high) for control cost. If the identified hazard was felt to be beyond the scope of this study, it was categorized as "not applicable" (N/A) and not considered further.

Table 5-1. Risk Assessment Table

Elements	Values				
	4	3	2	1	N/A
Hazard Severity (S)	Catastrophic	Critical	Marginal	Negligible	Beyond the Scope of This Study
Probability of Occurrence (P)	High	Moderate	Low	Almost Never	
Control Cost (C)	None	Low	Moderate	High	

8. Identify Significant Hazards

Important hazards which should receive early attention in future AMTV development were identified by applying the following criteria.

(1) All hazards for which $S + P \geq 6$ are considered to be significant hazards.

(2) All hazards for which $S + P \leq 4$ are deleted from further consideration.

(3) All Hazards for which $S + P = 5$ are individually assessed; specifically, all $C = 2$ and $S = 3$ are considered to be significant hazards.

This process was necessary in order to reduce the size of the hazard list to a more reasonable length before further examination of the important hazards. Note that the risk assessment process creates a priority order for the hazard catalog, which, although not explicitly presented, can guide future investigation.

9. Recommend Corrective Actions

Once the significant hazards were established, a more thorough examination was made in order to generate recommendations for preventive actions for these significant hazards. Information contained in the initial preventive actions column was re-evaluated with an ultimate goal of achieving a truly "fail-safe" design. Once recommendations were developed, they were listed in tabular form as part of Tables 5-2 and 5-3 on the following pages to complete this study.

Further steps were identified in the flow chart but were not carried out as part of this study. Using the present recommendations, a plan for implementing these actions should be drawn. Plans for future safety analysis activity were also identified as an item in the flow chart. A safety analysis such as this is open ended in nature, as it can accept newly identified hazards at step 1 or 2 as they are recognized, and the entire process can be iterated in order to refine the priority ordering and ideas for corrective actions.

E. FINDINGS AND RECOMMENDATIONS

In any initial demonstration of a new concept such as the AMTV there will inevitably be hardware bugs and unforeseen safety problems. Such events could lead to serious problems in an AMTV system if not closely monitored. The frequency of these events will decrease with experience. Those using the AMTV and pedestrians that interact with it will gradually become more familiar with it, and its operation will become smoother as a result. Without using standby "drivers" or "operators" with manual vehicle controls, it will be very desirable to provide good coverage of important points on the route during the initial learning period by attendants either at the roadside or on the vehicle. Each attendant should have means for stopping the vehicle and subsequent manual override, if that should become necessary, using a key. Appropriate use of attendants during the critical experimental phase of a demonstration could shift a significant load away from foresight and prediction of future system behavior into real-time monitoring and correction, a much easier task. For example, the question of whether or not an AMTV can safely negotiate cross traffic (vehicles or pedestrians) can be answered empirically by allowing an attendant at the site in question to override automatic control if that becomes necessary to ensure safety. Empirical answers may well be the only ones possible in the subjective area of AMTV interactions with other traffic.

1. Significant Hazards and Recommendations

Seven types of events have been singled out as significant hazards for which preventive actions must be developed. These concerns are as follows:

(1) Collision with another Vehicle - If physical interaction between an AMTV and another vehicle is possible a significant hazard results, and the probability of collision must be reduced to the lowest possible level because of the probability of serious injury in such an event. This item is discussed in the context that vehicles can interact with the AMTV. It is recognized that physical separation is also a preventive action, and that in any early demonstration, vehicle interaction should be avoided or sharply limited.

(2) Collision with pedestrian.

(3) AMTV moves while passengers are boarding.

(4) Objects overhanging AMTV Route or missed by optical sensors.

(5) Objects beneath the headway sensor range.

(6) Objects protruding from the vehicle.

(7) Ice and Snow on Surface - This item is included, even though our initial assumption was to limit application to an ice-free region.

The details of these findings and recommendations are contained in Table 5-2 following. The left column of the table lists the areas of concern. The middle two columns suggest two types of corrective actions, either by means of design or by procedure. Remarks, references and notes are included in the right column.

2. Significant Failures and Recommendations

Six types of failure have been found to result in significant hazards. Any one of these six significant hazard types can be thought of as a single point failure possibility. The results and suggested corrective actions are presented in Table 5-3. The format is identical to that used for the significant hazard modes. Each subsystem level failure mode identified can result from various specific circuit-level failures. The significant failure modes are as follows:

(1) Brakes fail due to control failure or hydraulic system failure

(2) Headway sensors fail "off".

(3) Steering control failures due to control or hydraulic system malfunction. Those failures producing a hardover response are considered significant failures; passive or steering centered failures are not.

(4) Speed control fails due to control failure or propulsion failure. The result is an overspeed or a rollback condition.

(5) Road fixed stop or slow sensor fails.

(6) Vehicle chassis fails, for example a flat tire.

Table 5-2. Summary of Hazard Analysis and Recommendations

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
1. Collision with vehicle			
A) En route collision. Side swipe is most probable.	a) Provide physical protection for AMTV path such as low curb, or chain-link fence.	a) Create rules similar to bike-way right-of-way laws; use painted lanes	
	b) Provide all-around bumper and body enclosure on AMTV to minimize damage in minor collision	b) Inform the public about the AMTV and its characteristics.	
	c) Provide distinctive signal lights on AMTV or audible warning signal		
	d) Provide side looking proximity sensing coupled to steering or warning signals		

Table 5-2. Summary of Hazard Analysis and Recommendations (Continuation 1)

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
B) Collision by cross-traffic at inter-section	a) Provide grade separation for AMTV b) Provide fixed roadside sensing capability to sup-plement the on-vehicle headway sensors. The primary capability sought should be detection of vehicles likely to violate a red signal c) Provide all-around bumper and AMTV body design to min-imize damage and injury in the event of any collision	a) Limit cross-traffic vehicle speed thru intersection if appropriate	a) Existing traffic laws, if obeyed, cover this event b) A critical hazard, though very improbable

Table 5-2. Summary of Hazard Analysis and Recommendations (Continuation 2)

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
	d) Program AMTV to move into intersection at 2 mph for 1 length to signal intent to cross. Then accelerate to 7 mph e) Provide special audible or visual signals while crossing		
C) Collision at intersection where AMTV turns	a) Grade separation at intersection b) special audible and visual signals as in 1) B) f) above c) Provide conventional automotive turn signals on AMTV, coupled to control system.	a) Left turn by AMTV requires an all way red period for other traffic	a) Safe left turns by an AMTV at a signalized intersection poses a difficult and subtle problem. Further study and experiment is needed

Table 5-2. Summary of Hazard Analysis and Recommendations (Continuation 3)

Significant Hazard	Recommended Preventive Actions: Design	Recommended Preventive Actions: Procedure	Notes
	d) Roadside sensors as 1) B) b) above e) Provide traffic islands for right turn		
D) Vehicle moves into path of AMTV too close for AMTV to stop	All items noted under A, enroute collision, would be effective		Contact bumper will minimize damage or injury
2. Collision with pedestrian. Pedestrian moves into path too close, or into side of moving vehicle	a) Provide bumper incorporating emergency wheels-locked stop switch. Surface should be smooth, padded to minimize injury, and must extend around sides of vehicle	a) Create rules or environment for pedestrians which discourage walking within AMTV path	a) Not a critical hazard; serious injury not likely.

Table 5-2. Summary of Hazard Analysis and Recommendations (Continuation 4)

Significant Hazard	Recommended Preventive Actions: Design	Recommended Preventive Actions: Procedure	Notes
	b) Develop control capability based on existing headway sensing components to detect a late intrusion into path, and react with stronger braking	b) Familiarize public with AMTV characteristics	
	c) Develop audible signal, especially for start up		
3. AMTV moves while passengers boarding or getting off	a) Provide doors interlocked with AMTV control	a) Provide instructions for boarding at stop and on vehicle	a) Probability of occurrence is high
	b) Provide sensors capable of detecting objects close to side of vehicle		
	c) Provide treadle or hand-actuated pressure switches to hold vehicle during boarding. Location should invite their use instinctively without specific instructions.		

Table 5-2. Summary of Hazard Analysis and Recommendations (Continuation 5)

Significant Hazard	Recommended Preventive Actions: Design	Recommended Preventive Actions: Procedure	Notes
4. Overhanging objects such as tree limbs in path of AMTV	a) Extend contact bumper vertically. Allows damage to a replaceable bumper panel, such as an expendable windshield switch. b) Extend optical headway sensor coverage vertically c) An effective bumper-switch combination can protect passengers and vehicle. An emergency stop results	a) Maintain regular surveillance of route for obstructions b) Establish rules to prevent movable objects such as overhanging truck loads from intruding on AMTV path. (No standing or parking signs might suffice) c) Provide means for passengers to stop vehicle. A controlled stop may be better than a wheels-locked stop because there would be less inhibition about its use	a) An overhanging obstruction is an anomolous condition b) The possibility of an obstruction being missed by a properly functioning headway sensor falls into this category. A clean mirror or piece of glass would be an example. An unlikely occurence

Table 5-2. Summary of Hazard Analysis and Recommendations (Continuation 6)

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
		d) Provide means for passengers to report obstructions in a timely way	
5. Small object on road surface below effective sensor coverage	a) Design contact bumper switch to cover any object large enough to cause damage to AMTV	a) Maintain regular surveillance of route for obstructions	a) Downward vertical curve can increase this hazard. Refer to Figure 4-1.
	b) Provide strong bumper to minimize probability of damage, and to deflect object from AMTV path		
6. Object protruding from AMTV (could be part of chassis)	a) Side bumper idea presented in 2) a)	a) Prohibit carry-on of protruding objects	
	b) Use closed vehicle design such that object protrusion is impossible		

Table 5-2. Summary of Hazard Analysis and Recommendations (Continuation 7)

Significant Hazard	Recommended Preventive Actions: Design	Recommended Preventive Actions: Procedure	Notes
7. Ice/snow on route or severe weather	a) Use snow tires or studded tires b) Design system so that a lower speed could be used if dictated by road conditions	a) Provide monitoring function capable of anticipating conditions that will degrade performance, and taking appropriate action to ensure safety	a) System description has excluded this hazard by excluding AMTV operation in ice/snow environment. However, further investigation of this subject should be made

Table 5-3. Summary of Failure Mode Analysis and Recommendations

Significant Hazard	Recommended Corrective Action: Design	Recommended Corrective Action: Procedure	Notes
1. Brakes fail. AMTV will not stop as commanded	a) Provide spring applied, power released parking brake such that in case of power loss, spring will apply brake b) Provide 4 wheel braking with dual (redundant) brake system similar to normal automotive practice c) Provide dynamic braking capability for redundancy. Dynamic braking can be service mode to save wear on mechanical brakes d) Provide low hydraulic pressure sensor which will command AMTV to stop e) Provide accumulator to maintain hydraulic pressure if pump stops	a) Provide for daily checkout procedure before placing vehicle in service b) Provide scheduled maintenance plan	a) Existing technology used in automated guideway vehicle design is applicable and should be used

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 1)

Significant Hazard	Recommended Corrective Action		Notes
	Design	Procedure	
	f) Provide functional redundancy in logic electronics for backup		
2. Headway sensors fail			
A) Optical sensors fail such that obstacle not detected.	a) Develop an in-service self-check capability to detect outage of light source b) Design sensor so that loss of power creates a "yes" output. (see present design) c) Provide redundancy in sensor design such that a single component failure results in degraded performance rather than functional failure of sensor system. Means to detect component failure must be provided.	a) Provide daily checkout procedure b) Establish maintenance plan	

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 2)

Significant Hazard	Recommended Corrective Action		Notes
	Design	Procedure	
B) Mud or dirt on sensor lens; sunlight blinding of sensor	a) Provide appropriate lens hood to protect lens b) Optoelectronic design should provide "yes" output if detector saturated, such as by solar blinding c) Examine proposed route geometry for possibility of solar blinding and eliminate possibility	a) Provide daily checkout procedure. b) Establish maintenance procedures	
C) Contact bumper switch fails.	a) Provide redundancy by having independent sections of bumper switch area. b) Design bumper to minimize likelihood of damage or injury even with failure c) Use power source for sensors that is independent from propulsion battery.	a) Provide instructions for passengers as guidelines for use of operational stop switches, and emergency stop buttons.	

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 3)

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
	d) Provide emergency stop switches for passengers.		
3. Steering Fails			
A) Sensor fails hard over. Severe lurch can occur. AMTV will stop, but can stray from designated path by several feet.	a) Provide lateral accelerometer to limit sudden steering input. b) Provide redundant sensors with appropriate selection logic. c) Provide detection for this condition which applies maximum braking. d) Limit steering actuator slewing rate to the minimum value sufficient for safe and stable steering function.	a) Provide daily checkout procedure before putting vehicle in service. b) Provide plan for regular maintenance	a) Existing technology used in cable-following automated vehicles is applicable and should be used. b) The hardover steering response can be caused by a number of component failure modes. Failures resulting in centered steering are

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 4)

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
A) (contd)			not considered significant hazards because they will result in the vehicle stopping within the designated lane upon loss of cable acquisition
B) Actuator fails hard-over. Effect same as above	a) Provide electrical limiting such that normal operation cannot drive steering angle to mechanical stop. Provide mechanical limit switches which dump hydraulic pressure suddenly upon activation b) Provide spring centering of steering angle under power-off condition.	a) Same as above	

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 5)

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
C) Acquisition signal fails "on". Vehicle could move without steering control from cable.	a) Provide redundant acquisition signal sensor. Require both signals before allowing AMTV to move.	a) Same as above	a) Requires second independent failure to activate any hazard.
D) Guide cable excitation out of tolerance. Possible degradation of steering function while acquisition signal still present.	a) Provide redundant monitoring capability to keep cable excitation within acceptable limits; out of tolerance condition should cause shutdown and signal for immediate maintenance.	a) Regular maintenance plan.	

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 6)

Significant Hazard	Recommended Preventive Actions: Design	Recommended Preventive Actions: Procedure	Notes
4. Speed control fails			
A) Control logic fails, so that speed command not consistent with existing inputs.	a) Provide redundant logic function. Redundancy needed only for those circuits which could result in an overspeed condition if not obeyed. b) Independent power source preferred c) Provide battery level sensor to stop vehicle before propulsion power is lost.	a) Daily checkout procedure b) Regular maintenance plan. c) Recovery plan needed for anomalous condition to enable vehicle to be returned safely for maintenance	a) Existing technology for automated vehicles is applicable and should be used.

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 7)

Significant Hazard	Recommended Preventive Actions		Notes
	Design	Procedure	
B) Motor control fails on. Overspeed condition results.	a) Provide independent speed sensor to detect overspeed condition and apply brakes. b) Provide circuit within control electronics to compare measured AMTV speed with commanded speed, and stop vehicle if out of limits value is detected	Same as above.	a) Tachometer failure is possible failure mode b) Underspeed condition does not result in a hazard except in case of rollback, 4C below
C) Motor control fails off. Rollback condition results.	a) See B)b) above b) Provide independent rollback detector which applies parking brake.	Same as above	

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 8)

Significant Hazard	Recommended Preventive Actions: Design	Recommended Preventive Actions: Procedure	Notes
5) Road fixed stop (or slow) sensor fails. Could result in collision if it occurs at an intersection. Failure of a road-fixed slow signal control results in an overspeed condition.	a) Provide fail safe or redundant design for those components which couple AMTV motion with a traffic signal b) Provide redundancy thru control of excitation of a segment of guide cable which is interlocked with signal. c) Designation of different speed segments of route must be redundant or fail-safe (Faster speed requires explicit enabling input such as a guide cable modulation to be present) d) Design stop sensors to function over wider lateral excursion of steering than allowed by acquisition detectors	a) Same as above	A critical failure if stop signal is associated with traffic signal coupling, or is at a traffic stop sign.

Table 5-3. Summary of Failure Mode Analysis and Recommendations (Continuation 9)

Significant Hazard	Recommended Preventive Actions: Design	Recommended Preventive Actions: Procedure	Notes
6. Flat tire or other chassis failure. AMTV will try to proceed, resulting in further damage and possibility of second failure	a) Develop sensor based on accelerometers which respond to abnormal bumps or tilts.	a) Daily checkout b) Maintenance plan c) Instructions to passengers on AMTV giving guidelines or stopping vehicle d) Provide system surveillance, perhaps at one point on route.	Existing technology applies.

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APPENDIX A
SAFETY ANALYSIS DATA

HAZARD MODES, EFFECTS, AND PREVENTION ANALYSIS (HMEPA)

HAZARD CATALOG

NOTE

This Hazard Modes, Effects, and Prevention Analysis (HMEPA) deals with those hazards involving interactions between humans, other vehicles, procedures, and environments. It is assumed that the AMTV is operating properly; hazards originating from hardware failure are covered under the Failure Modes and Effects Analysis (FMEA).

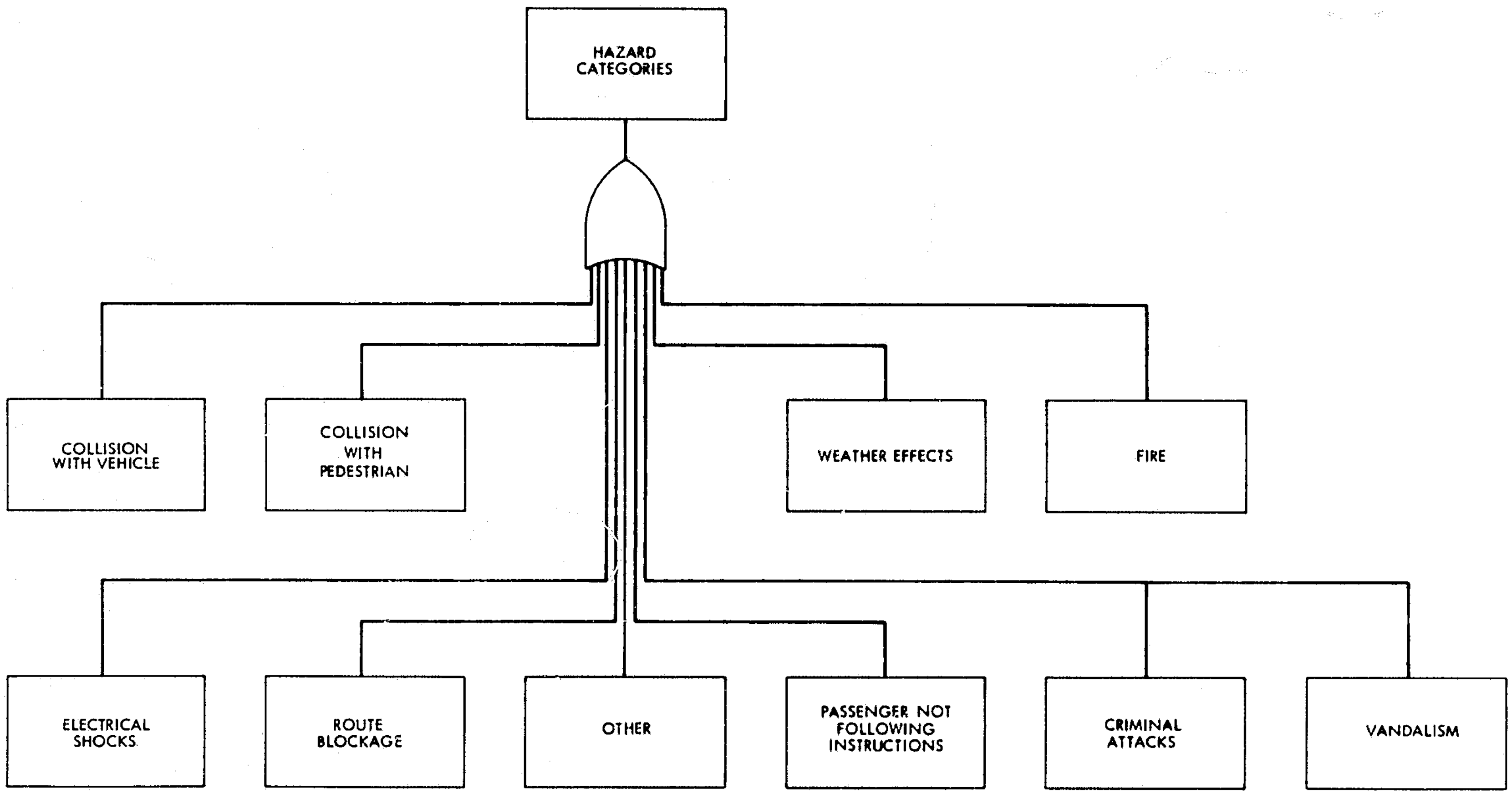


Figure A-1. Hazard Categories

Appendix A. AMTV Hazard Catalog

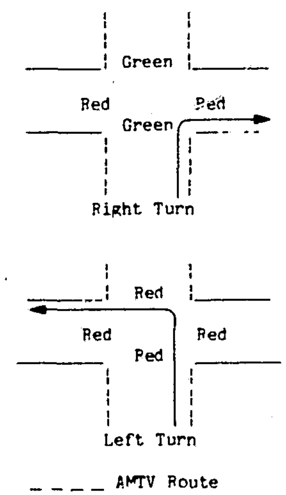
Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
A. Collision with vehicle	1. Vehicle collides with AMTV on route	Sideswipe is most probable. Both AMTV and passenger could receive considerable damages and injuries.	4 2 2	a. Provide right-of-way for AMTV over other vehicles. b. Provide all around bumper to minimize damage in the event of a minor bump. c. Install a signal light to indicate that AMTV is approaching.
	2. Vehicle moves into AMTV path too close	AMTV at the present time does not have the capability to detect approaching objects outside of its lane. AMTV unable to stop before collision. Serious injury not likely.	3 2 2	a. Sensitize the "all around bumper" mentioned above such that any object within six inches from it will cause it to stop or slow the vehicle. b. Indicate AMTV route with double yellow lines or curbing such that vehicles will not try to edge into that lane.
	3. Cross traffic collision	Critical hazard. Both AMTV and passengers could receive considerable damages and injuries.	4 2 3	It has been suggested that AMTV should make a certain amount of noise. a. Provide grade separation. b. Provide roadside sensors for warning of right-of-way violation. c. Fail-safe signal coupling required. d. Provide warning lights.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
	4. Left/right turn collision	This could result in any of the above three hazard conditions.	4 2 3	a. AMTV must have direction indicators to tell other vehicles that it is going to make a turn. b. AMTV may trigger intersection signals to be all red for sufficient duration before making a safe turn. c. AMTV might not start the left turn from the left-most lane, therefore it is very important that vehicle behind AMTV are warned by signal lights. d. AMTV path best be located adjacent to pedestrian sidewalks. Make the right turn similar to an automobile along the right curb and only on green light. Make the left turn by first having all four signals turn red and then enter the intersection to make a left turn.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
				NOTES



Ref: HMEPA A.4

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
	5. Vehicle backs into AMTV (AMTV may be already stopped)	Vehicle exiting from driveway could hit AMTV broadside. Vehicles backing into parallel parking could run into AMTV; AMTV does not backup.	2 2 3	Public education as well as some public relations will reduce this risk as well as the ones (1 thru 4) above.
A. Collision with pedestrian	1. Pedestrian or cyclist enters path too close for AMTV to stop	Pedestrian/cyclist could be injured if walked or strayed into side of moving AMTV.	2 2 2	a. Education of the public is needed. b. Make AMTV physically smooth and padded so it won't inflict injury other than knocking a person off balance. c. Incorporate emergency stop switches in bumper. d. Develop special logic to detect anomalous condition from heading sensor inputs and command quick stop.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
B. Fire; <u>Environ-mentally Caused</u>	1. Excessive heat on flammable materials	Seat material, etc., could catch fire from concentrated heat source.	1 1 2	Use non-flammable materials only.
	2. Burning fire on AMTV route	Fire could be intentionally set or could be from other cause, such as a burning tree.	3 1 1	AMTV sensors will not be able to detect this unless solid material is there. Educate the public to the existing emergency stop switch.
	3. Lightning strikes	Occurrences of lightning strikes are conceivable.		
Fire; <u>People Generated</u>	4. Passenger smoking	Passenger smoking might be both irritating other passengers and causing burns and fires to AMTV.	2 3 1	a. Prohibit smoking on AMTV. b. Use non-flammable material.
	5. Passenger carrying on explosive luggage	An accident from the carry-on explosive can incur great damage.	N/A	Prohibit carry-on of explosives.
	6. Intentionally Set	Passenger could intentionally set AMTV on fire. AMTV could be destroyed from such an act.	N/A	Promote good public relations during early stages. Ask for community co-operation. Advocate passenger policing system.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
C. Weather effects	1. Rain water damaging AMTV	Rain water could damage the AMTV and its electronics.	2 3 2	AMTV has to be designed to suit the weather of the local area.
	2. Sensor failing operation in fog	Optical sensors could be insensitive in fog and other low visibility conditions.	3 1 2	This mode has to be further studied to isolate the limitations of sensor capabilities. Present design requires visibility of 25-ft. Dense fog will produce a sensor response, and a slow command.
	3. Contact bumper interferred by EMI from overhead power lines	Low overhead power line could produce EMI to alter the sensitivity (or pick up noise signals and affect contact bumper performance.	1 1 1	Any interference signal would fail the bumper in stopped condition.
	4. Mud, dirt, etc., obscure sensor vision	Optical sensors will degrade.	4 3 2	a. Require regular maintenance procedure. b. Provide appropriate protective lens hood.
	5. Ice/snow on route	AMTV could slide if traveling on ice/ snow. Collision can result.	4 2 3	a. Use snow tires at locales where ice/snow exists. b. Heating of AMTV path also suggested. Need further study on this.
	6. Severe weather conditions	Hailstorm, heavy snow, flooding, earthquake, high wind, extreme cold weather, etc., can all degrade performance or cause system failure.	N/A	Design AMTV to suit local weather conditions. Provide procedure to avoid operating in hazardous environment.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
D. Vandalism	1. Hot wire AMTV	AMTV performance would be unpredictable and damages and injuries could results.	2 2 2 (N/A)	Design components such that no easy accessibility was available. Tires be placed behind locked chassis doors.
	2. Brake line cut	AMTV will be endangered.	3 2 2 (N/A)	Have brake line not accessible. Provide brake line pressure detection technique. Low pressure, AMTV will stop.
	3. Put blinders on sensors	AMTV will probably not move. But if blinders were of low emissivity, sensors could be inactivated.	2 2 2 (N/A)	Simulate this mode and obtain information on effects. Public cooperation needed for prevention.
	4. Unscrew the seat from AMTV	Passenger could be injured from unanchored seat.	2 2 2 (N/A)	Regular maintenance. Seat fastening locations inaccessible from outside of vehicle.
	5. Time bomb AMTV	Could be very serious, but probability of occurrence is no greater than an average public location	N/A	Promote public relations and provide reliable service.
	6. Intentional diversion of AMTV from route	Degrade system operation; cause possible collision.	2 2 2 (N/A)	AMTV will stop when guide-wire is lost. Eliminate manual override devices on AMTV. Instead, require key. See also manually operating for fun.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
	7. Guidewire disruption	Breaking of guidewire will cause system to stop.	2 2 2 (N/A)	Exciter should have means to realize when a segment of guidewire is disrupted and activate warning.
	8. Manually operating for fun	Result unpredictable.	2 2 2 (N/A)	All the manual mode operating parts, such as joy stick, accelerator, etc., should be on a plug-in unit which is manually carried by serviceman. The plug-in connector has a locked cover to prevent tampering.
	9. Let air out of tire	AMTV could tilt and cause deroutement. Vehicle will stop from loss of guide cable, but nevertheless collision could result.	2 2 2 (N/A)	Make tires hard to get to by having a cover. The use of dual chamber tires will hold pressure, even if the outer chamber fails.
	10. Hijacking by adding guide-wire	Could lead vehicle to undesirable location. Could cause unpredictable damage.	2 1 3 (N/A)	a. Do not reveal what frequency the guide cable carries. b. Make control signal more complex than single frequency.
	11. Additional stops induced	Would delay trip and make usage of system less attractive.	2 1 1 (N/A)	a. Make stop markers more complex than a single magnet. b. System surveillance function.

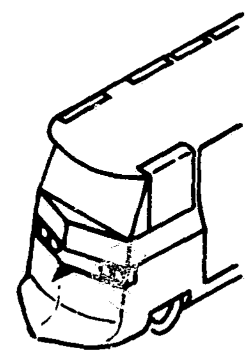
Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
E. Electric shock	1. Electrostatic charge from friction between seat and clothing materials	Passenger could get a shock.	1 1 1 (N/A)	Use seat material which will not collect charge.
	2. Passenger hand stop switch exposed	Passenger receiving shock from stop switch.	1 1 1 (N/A)	Improbable injury to passenger. Voltage on switch is is 5 volts.
	3. Battery shorted to AMTV body	Heat or spilled electrolyte could cause injury	1 1 1 (N/A)	One side of the battery is connected to the AMTV frame, using a small wire. Should the other terminal of the battery be connected to the frame the wire would melt. The purpose of the battery being connected to the frame is for EMI reduction to the electronics.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
F. Passage interference (Route blockage)	1. Overhanging objects above optical sensor range	AMTV could collide with an overhang tree limb, sign, etc. Damage and injury might result.	4 3 2	a. Maintain routing surveillance to assure that all overhangs are at least a certain height margin away b. Extend contact bumper vertically to full AMTV height to detect this.
	2. Objects on route below sensor range	A big rock or fallen tree limb could could cause vehicle damage and passenger injury.	3 2 2	a. Sensor range should be expanded to include vertical plane as well as the horizontal. b. Design the lower front part of AMTV to a snow plow shape so that it will be able to push the object on route along the way rather than run over it. c. Design (b) above into a center-pointed shape so that object on route will be pushed to the side and not be run over. d. Assume b) and c) above do not have sharp edges.
	3. Hole in pavement or excavation	AMTV may be damaged and passenger injured.	2 3 2	a. Route maintenance function. b. Procedure for notification of AMTV personnel if hole must be dug. c. Develop sensor to detect holes. d. Include inspection for holes as part of daily route checkout.

Appendix A. AMTV Hazard Catalog



Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
	4. Parked vehicles partially blocking AMTV path	Collision sensors will detect this and prevent problem, but it will break the system down and cause poor service.	1 4 2	Post signs prohibiting stopping. Public education program during early stages.
	5. Object close to side of AMTV	Boarding or deboarding passenger could be crushed between AMTV and object.	1 2 2	Safety panel on side of AMTV to cause stop. Extension of bumper sensitization idea is applicable.
	6. Protruding object from AMTV	Pedestrian or deboarding passenger could get knocked down or clothing caught.	3 2 2	Same as above. Also prohibit carry on object protruding to the outside of AMTV periphery. Enclosed AMTV will eliminate this problem.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
G. Passenger not following instruction	1. Passenger boarding from the wrong side of AMTV	Passenger might be injured since AMTV would be moving and could not be stopped from the street side.	3 2 2	Public Education. Make street side inaccessible. On future enclosed vehicles, have doors that open only when stopped and on the proper side.
	2. Passenger boarding/leaving AMTV without pressing stopping switch	Passenger might be injured by fall since the AMTV will be moving.	2 2 2	a. Request the public to follow instructions. Have signs posted both on vehicle and at scheduled stop location to explain boarding and departing instructions. Clearly indicate the location of stopping switch. b. Provide treadles on doors so it is difficult or impossible to leave AMTV without stopping it.
	3. Passenger breaking other safety regulations	Safety regulations were made to protect passengers. If broken, consequences are most likely that some one will not be properly protected and possibly be injured.	2 2 2	Public education and safety promotion needed. Minimize regulations and rules to follow by properly designing AMTV to exclude hazard possibilities.
	4. Passenger injured by other vehicle during boarding	Severe injury possible.	N/A	Flash red light when stopped like school buses. Do not allow vehicle to pass on the boarding/deboarding side of AMTV
	5. Passenger not being careful	a. Passenger bumps head on roof by not stooping. b. Passenger trips while getting on/off of AMTV. c. Passenger falling due to lurching/emergency stopping. d. Passenger getting caught in door.	N/A	Design AMTV to prevent these hazards from existing.

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
H. Passenger vulner-ability to muggers	1. Robbery	The aged and the handicapped could be especially vulnerable to this mode. Consequence of occurrence could also affect the community's acceptance.	N/A	The lack of attendant or possibly other passengers creates a need for some means to ask for assistance. Further study as to route, schedule (whether to provide service during late evening hours), street lighting, etc., needed.
	2. Kidnap	Consequence of single occurrence could affect the acceptance of the system by the public.	N/A	Further study needed. It has been suggested that the inside of AMTV be highly visible from the outside by means of good lighting, windows, etc. Lockable compartments and alarm button are other suggestions. Utilize practices and tech-nology from AGT systems.

C-2

Appendix A. AMTV Hazard Catalog

Hazard Categories	Hazard Modes	Hazard Effects	Risk S P C	Preliminary Prevention/Remark
I. Other	Motor power not able to overtake gravity on an incline during initial starting	On an incline, with the vehicle initially at a stop, the vehicle will roll backward at the instant the brake is released and the motor power is applied.	4 2 1	A study must be performed to assure that the motor will within a fraction of a second from the release of the brake be able to overtake the gravitational force on AMTV and proceed to climb. Rollback protection is required in the event of inadequancy of propulsion.
	Radiation from infra-red sensor light source	Eye damage if radiation level high.	3 1 3	Examine design for compliance with ANSI Z-136 at each design iteration.

APPENDIX B

SAFETY ANALYSIS DATA

FAILURE MODES AND EFFECTS ANALYSIS

FAILURE INDUCED HAZARD CATALOG

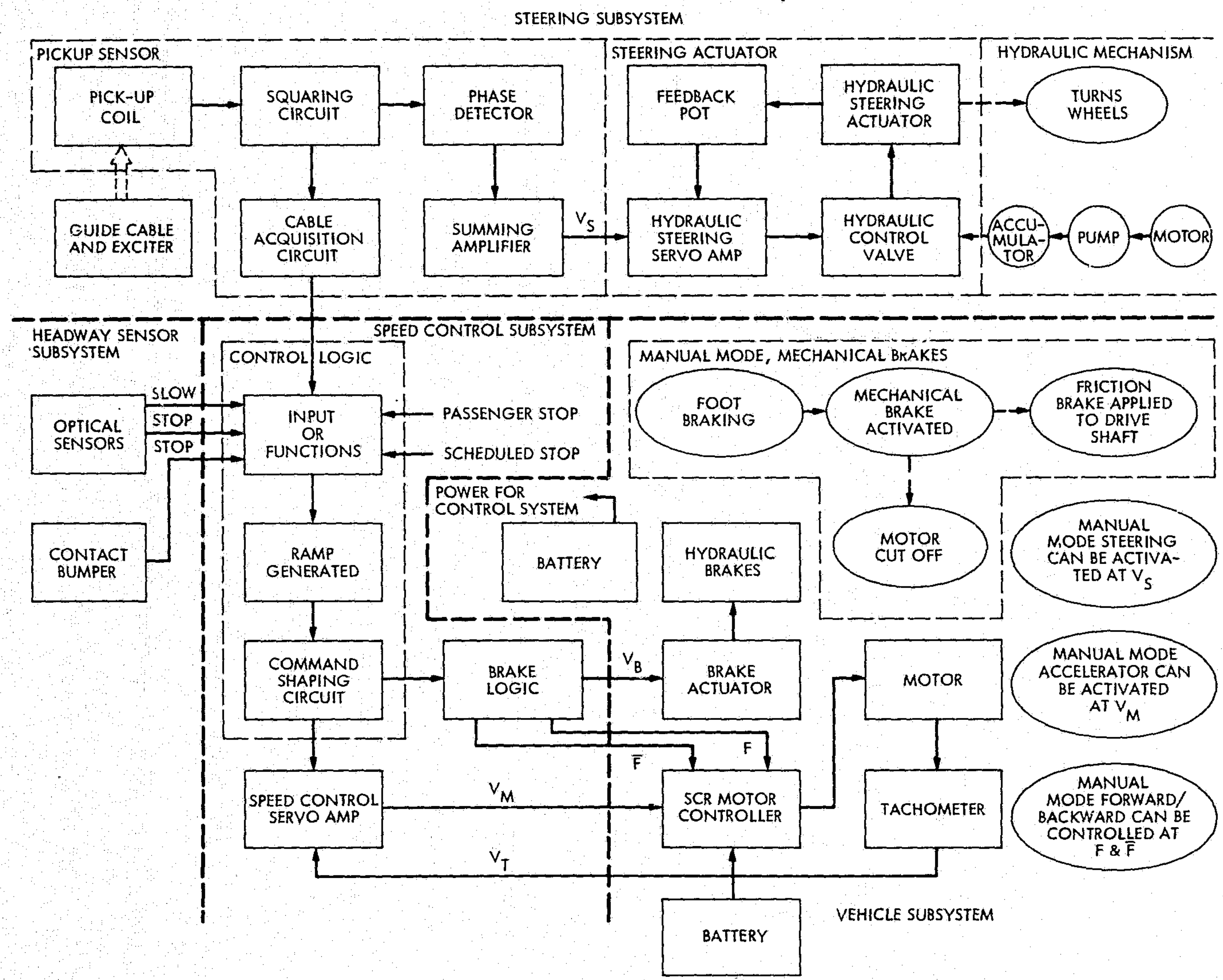


Figure B-1. AMTV Block Diagram and Subsystem Breakdown

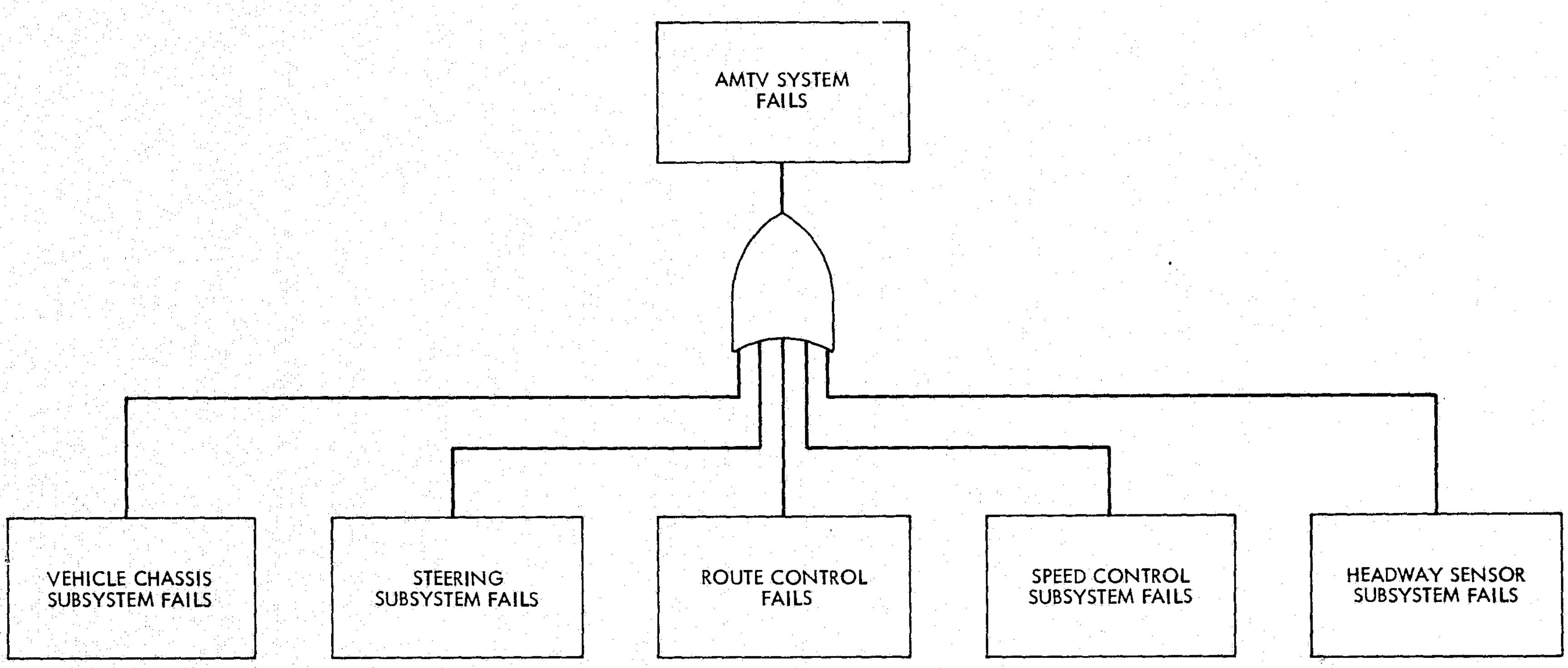


Figure B-2. AMTV System Fault Tree

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I. VEHICLE SUBSYSTEM FAILS					
I.A TACHOMETER FAILS	Servo-Tek Model No. SB-740A-2. DC generator type with rotating armature and two brushes. Typical ratings: 10V, 5mA. Tach tracks motor and feeds signals back to speed control servo amp.	1. Output open (no output voltage)	When tach gives no (low) signal, vehicle accelerates; high signal decelerates.	4 3 3	a) A fail-safe design is needed to eliminate hazard effects. b) Modify design by adding a comparator to compare command voltage V_C with tach signal V_T. If $V_T<V_C$, signal vehicle to stop. This comparator can also control over speed by stopping the vehicle when $V_T>V_C$ (max), where V_C (max) is the command voltage for maximum speed. c) Alternate independent overspeed prevention system should be investigated. Utilize existing technology being used by other vehicle systems.
		2. Output short (no output voltage)	Same as above	4 3 3	Same as above
		3. No input (broken or slipping tach shaft) = low output.	Same as above	4 3 3	Same as above

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I.B BATTERY MALFUNCTIONS	6 x 6 volt batteries 250 amp-hr life, 200 amp max, 60 amps level cruising ave. 100 amp.	1. Completely discharged	Dead battery will affect every part of vehicle operation. Steering out of control, brakes will not work, etc.	2 4 2	a) The addition of a battery state of charge detector. Do not allow AMTV to start new route loop if battery state is too low. The evaluation of a longer battery lifetime is needed. Brakes should be redesigned to be fail-safe such that the brake will apply if power lost. b) Provide separate uninterruptible power supply (UPS) for critical control functions. Low voltage tolerance of control system is also needed.
		2. Shorting or exploding	Shorting and exploding can cause fire and other injuries.	2 1 2	
		3. Leaking	Leaking can cause burns or hardware damage	2 1 2	
		4. Low ambient temperature	Low temp will make battery state of charge prediction a more difficult problem.	2 1 2	

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I.C. MOTOR FAILS	DC Series motor, 2HP, 36V 2800 rpm, GE model 48JB-503 D. Motor tracked by tach and controlled by SCR motor controller	1. Motor open	Loss of motor drive capability will degrade vehicle stopping ability.	2 1 2	Comparator mentioned in I.A is needed here to stop the vehicle when $V_T > V_C(\max)$.
		2. Motor shorted	Motor might overheat and cause burning.	2 1 2	An overcurrent protection or thermal overload is needed.
		3. Motor-tach separation	See I.A with no (low) tach signal, vehicle will accelerate	4 1 2	Comparator mentioned in I.A applies here.
		4. Motor disengaged from drive shaft	If this mode occurs when the vehicle is on a slope, the motor tach, and electronics could all be functioning properly, yet the vehicle will be out of control.	4 1 2	A speed detection system not tied to the motor must be added to the vehicle to provide a fail-safe design. The utilization of existing technology is desirable.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I.D SCR MOTOR CON- TROLLER FAILS	GE C-155 Model 100. Controls the amount of current supplied to motor by varying the frequency of square-wave pulses. Has dual direction capability, ie, forward and re- verse directions.	1. Output too high	Motor will overspeed which in turn will turn tach at a faster rate.	3 2 2	Comparator mentioned in I.A is needed here to stop the vehicle when $V_T > V_C(max)$.
		2. Output low or grounded	Low motor input. Rollback condition results.	1 2 2	Underspeed comparator in I.A will stop vehicle.
		3. Output erratic	Motor power applica- tion variable. Ride might be less com- fortable.	2 2 2	If amplitude exceeds high and low limits, comparator will stop vehicle.
		4. Degradation or loss or bi-direc- tion capability	Dynamic braking could be degraded. Motor forward drive capa- bility could be de- graded also.	4 2 2	Undesirable event. Further investigation needed, although not a single point failure. Need to have capability to switch from the detection of this failure mode to using redundant braking con- trolled by the under/ overspeed comparator.
		5. Output stuck on high regardless of input command	Vehicle will continue increasing speed.	3 2 2	a) Comparator should detect this failure mode. b) Independent overspeed detection.
		6. V_M input (from speed control) re- mains on high	Vehicle will continue to travel at a con- stant speed.	3 2 2	Fix should be implemented at previous stage, speed control servo amp.
		7. V input (from speed control) shorted to ground (low)	This is same as last stage speed control servo amp tran- sistor C-E Short. This occurrence fails motor power.	1 2 2	No action required, since vehicle will not move. Utilization of existing technology is desirable.

Appendix B. Failure Induced Hazard Catalog

Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I.E BRAKE ACTUATOR FAILS	1. Leaks	Loss of hydraulic pressure	2 3 3	No sure way to prevent this from happening except by regular maintenance and checkout.
	2. Fails on (stuck on)	Loss of hydraulic braking capability, however vehicle would not go anyhow.	1 1 2	The hydraulic brake fluid is not compatible with the hydraulic system fluid: the two are separated by a floating piston. There is no provision to check the brake fluid! Need a reservoir with sensor & detect fluid level. Present vehicle has two wheel hydraulic brakes. Future vehicles should have 4 wheel brakes with dual hydraulic brake system & an indicator to tell if one system is defective.
	3. Fails off	Loss of hydraulic braking capability.	4 1 2	

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I.F VEHICLE CHASSIS FAILURE	Tram consists of tires. axle, and frame.	1. Flat tire	Vehicle operation with flat tire(s) will be unpredictable and therefore hazard-ous	3 2 2	a) Use dual chamber tires. Even if outer ruptures, tire will still hold pressure. b) Road clearance detector. c) System surveillance at one point on route. d) Regular maintenance e) Daily checkout
		2. Axle and frame malfunction	Occurrence most un-likely although effect could be significant.	3 1 1	Axle conservatively rated.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I.G HYDRAULIC BRAKES MALFUNCTION	Two brake shoes forced against brake drum via hydraulic brake cylinder	1. Hydraulic brake cylinder leaks	Hydraulic fluid loss will cause degradation.	2 3 3	See remarks in I.E. Periodic maintenance and checkout procedure should be generated to eliminate this mode.
		2. Hydraulic brake cylinder jams	Brake could get stuck.	2 1 1	Same as above.
		3. Worn brake shoes	Braking will be degraded.	2 1 1	Same as above.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
I.H. MANUAL OPERATIONS FAIL	Operation of vehicle can be manually controlled thru various manual mode attachments including braking, steering, accelerator, and forward/backward control.	Any of manual mode operations fail.	a) Unpredictable. Could compromise ability to return vehicle for service in the event of other failure.	2 2 3	Same as above.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
II. STEERING SUBSYSTEM FAILS					
II.A GUIDE CABLE AND EXCITER FAIL	Guide cable is a buried wire permanently installed in a saw cut in road pavement. A signal of a little less than 10 KHz will be transmitted through cable by an exciter.	1. Cable broken	Vehicle will not operate without detection of this signal.	2 2 3	a) Monitoring circuit at exciter should detect out of tolerance current and shut down, if found. b) Acquisition signal detection on vehicle needs periodic check for accuracy. c) Use of dual guide cable system with automatic switch over is a redundant solution.
		2. Cable shorted	Same as above	2 2 3	Same as above
		3. Exciter outputs no signal	Same as above	2 2 2	Same as above
		4. Exciter outputs improperly (high signal, noise, etc.)	The behavior of vehicle under this failure mode is that steering will become erratic.	2 3 3	
		5. Metal plate over guide cable	Guide cable field will be disrupted.	2 3 3	a) A maintenance function b) Experimental tests needed. c) Provide two steering sensors - one at front, one at rear of vehicle.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
II.B PICK-UP SENSOR FAILS	Pickup sensor of 18 side-by-side vertical-axis coils location at same height above road and at right angle to guide cable. These signals are shaped, pulse detected, and summed. Output of this sensor goes into steering servo amp to command steering actuator. There are two additional horizontal coils included as reference signals.	1. One or more coils and/or associated circuits fail	Summing amp when detecting one signal less will ignore that missing signal. Vehicle will behave as if defective channel is not there. When failure occurs with large off center bias (ie, several coils failed from one side), vehicle will not be able to function properly at a curve.	3 3 2	a) Loss of one channel will shift vehicle center off course by one inch. Acquisition signal will stop if cable lost. A possible dual (redundant) system will increase reliability. b) Periodic checkout per written procedure needed to detect coil anomalies. c) Also, if failure of coils is enough to shift vehicle off axis far enough, scheduled stop sensor (buried magnet) would be missed and vehicle will miss its stop.
		2. Pickup sensor fails while centered	Vehicle proceeds ahead until acquisition signal ceases.	3 2 3	Another failure required before hazard occurs.
		3. Pickup sensor fails when off center	Vehicle turns suddenly before it can be stopped	4 2 3	Serious problem. Needs independent accelerometer input to limit lateral acceleration.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
II.C STEERING ACTUATOR FAILS	The steering servo amp accepts an input V_s (± 5 Vdc) from the pick up sensor and drives the spool in the control valve to feed hydraulic pressure to the appropriate side of the actuator. Actuator will steer the wheels movement tracked and picked up via a feedback pot.	1. Hydraulic steering servo amp input/output fail.	Position of the feedback pot not tracked, steering capability degraded or possible loss. Hydraulic control valve not receiving proper signal to operate steering actuator.	3 2 2	Redundancy needed.
		2. Feedback pot opens/shorts	Will drive steering to one limit.	4 3 3	Same as above.
		3. Hydraulic control valve malfunctions	Steering capability loss. Open winding will cause steering to drift to one limit.	4 2 3	Same as above. Rate of drift will depend upon mechanical zero adjustment of valve.
		4. Hydraulic steering actuator malfunctions	Steering capability loss	4 2 2	

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
II.D HYDRAULIC MECHANISM FAILS	Supplying pressure to the hydraulic system are motor, pump, and accumulator.	A failure in either the motor or the pump, or a leak in the lines	Eventual loss of steering as well as the hydraulic braking capabilities.	4 3 3	a) For steering, need a means to stop vehicle if hydraulic pressure falls below a certain limit. For hydraulic braking, a means such that the loss of hydraulic pressure the brake will be engaged, be generated. The present brake system is connected by a floating piston to the hydraulic system (due to incompatibility of brake seals with hydraulic fluid). A leak in the brake system would not show up even if the hydraulic system were fail safe. b) Addition of low pressure sensor needed to stop vehicle. c) Utilization of existing fail-safe technology desired. d) Hydraulic fluid level indicator warning light to alert to loss of fluid.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
III. SPEED CONTROL SUBSYSTEM FAILS					
III.A CONTROL LOGIC FAILS	Speed commands (slow, stop, start, etc.) will be combined to provide a set of ramp-shaped voltages which will direct the speed control servo either to activate SCR to a certain pulse rate or the brake logic to apply brake or reverse motor field (dynamic braking).	Inputs and outputs of many of the IC's in the control logic could be shorted to ground, tied to power supply, open, or short.	All input OR gates, except the passenger stop, will produce a logical 1 if an open circuit occurs between the gate and the sensor; ie, if a pri-headway sensor line opens up the logic will receive a slow command. A short circuit would disable the signal input.	4 2 3	To generate a corrective action for the control logic failure modes will require significant design effort. A convenient location to eliminate vehicle misbehavior is at the speed control, SCR, motor, tach loop. The addition of that comparator discussed in I.A, I.C, and I.D will stop the vehicle regardless of command errors made in the proceeding stages.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
III.B SPEED CONTROL SERVO AMP FAILS	Speed control servo amp accepts command from the control logic and feedback from the control supplies the motor, via SCR controller, power in the form of pulses. The rate of these pulses determines the amount of power supplied.	Last stage servo amp transistor C-E short will cause failure.	Full power on will keep vehicle full speed ahead. When $V_T > V_C$ vehicle would have full dynamic braking.	3 2 2	Another comparator is needed to compare output of speed control servo amp with the input command to assure their consistency. This is similar to that mentioned in Section I. With full power limits might not be exceeded, but vehicle would not obey command. Therefore, the comparator above should be made to stop the vehicle and call for help.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
III.C BRAKE LOGIC FAILS	Brake logic accepts command from control logic and signals the brake actuator to apply the hydraulic brake or commands the SCR to reverse the motor current flow to apply dynamic braking.	1. Fails to receive input command	Commanded braking will not result. Vehicle could possibly be out of control.	4 2 2	An investigation into using the input OR's to provide some redundancy is needed. The redundancy does not have to be two indentical paths, but rather dual signal lengths.
		2. Outputs to brake actuator or SCR controller malfunctions (opens, grounds, shorts)	Possible improper command transmission, hence vehicle not functioning properly (predictably).	4 2 2	Need further investigation to what happens if failure occurs and how to correct this deficiency.

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	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
III.D SCHEDULED STOP CONTROL FAILS	Scheduled stop detection is by means of sensing coil picking up signal from a buried permanent magnet.	1. A piece of metal laying over the buried magnet	Magnet field will be interrupted and the sensor will not pick up any signal.	4 2 3	For future sophistication, have a build-in distance interpretation capability via a mileage reader and compare with a pre-programmed info.
		2. A piece of unplanned magnet on the ground surface	Unplanned stop could be initiated by this magnet.	1 2 2	a) Not safety related.
		3. Sensor fails off	Scheduled stop will not be executed. Could possibly miss a stop sign.	4 2 3	a) System checkout procedure necessary. b) Redundant function needed for intersection control as this is critical hazard.
		4. Sensor fails on	Vehicle stops immediately; not a safety concern.	1 2 2	Same as above.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
IV. HEADWAY SENSOR SUB-SYSTEM FAILS					
IV. A OPTICAL SENSORS FAIL	Designed sense obstacles in time for a smooth stop. Primary and secondary sensor channels will provide distant (25ft) and close range (8ft) object detection respectively. The two sensor channels are pulsed at two different frequencies ($1KH_Z$ and $1.05KH_Z$) and self compared when reflected signal is received. GaAs LED and Si detector pairs are used to detect the difusely reflected light.	1. Primary fails off.	Vehicle will not slow down upon distant object detection.	4 3 2	a) Self check sensor by reflecting a test beam from the source into the detector periodically b) Use redundant sensor elements c) Examine individual element function in daily checkout. d) Stop for test target
		2. Secondary fails off.	Vehicle will continue at 2mph and not stop until contact bumper strikes the object.	3 2 3	Same as above
		3. Primary fails on.	Vehicle will revert to 2mph automatically.	2 3 2	Not a hazard
		4. Secondary fails on.	Vehicle will stop itself.	1 2 2	Not a hazard
		5. Threshold drifts up or down.	Vehicle will either fail to slow down or reduce speed falsely.	3 3 2	This is both a design margin tolerance problem as well as time degradaation problem. See items under IV. A1 above
		6. Aim error (from improper mounting or dislocating after mounting).	Will fail to detect object or detect "false alarm" from incorrect direction.	3 2 2	Periodic checkout required. Tests under IV. A1 above will check

Appendix B. Failure Induced Hazard Catalog

Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
	7. Blinded by direct sunlight.	a) The signal to noise ratio becomes unacceptable for sensor operation. This is equivalent to threshold drift. b) Saturation of detector will reduce signal gain to zero.	3 2 2	a) Investigate on a sunshade cover needed. b) Correlate route sections & time to avoid this mode. c) Design saturation detection circuit to yield "yes" output
	8. Blinded by approaching auto head lights.	Same as above.	3 3 2	Need to investigate further.
	9. Interferred by sensors signals emitted from approaching AMTV.	Picking up false signal from that emitted (not reflected) vehicle will slow down.	2 3 2	Limit signal divergence range. Limit detector field of view. Plan route with sufficient spacing.
	10. Insufficient headway sensing range for 20mph (needs 125ft).	20mph vehicle will not be able to stop with the existing design.	3 3 2	Need to add a third pair of sensors to detect long range object. For example, use high-speed to detect at 125ft & primary to detect at 25ft.
	11. Any of the optics like the lenses and the filters break, misalign, etc.	Aiming error, threshold level can both change see (5) & (6) effects.	3 2 2	Daily preoperation performance check will detect this mode.

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	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
IV.B CONTACT BUMPER FAILS	The contact bumper consists of a horizontal rod mounted on a suspended resilient semi-loop and two micro switches one on each side of the rod-to-loop contact. The contact bumper is 10 inches above the ground and extends 3 feet to the front of the vehicle. Any object in contact with the horizontal rod will activate one of the 2 micro switches and stop the vehicle immediately.	1. Contact switches fail inoperative	Loss of optical sensor backup	3 2 2	Modified the contact switch installation such that each complement the other, instead each working independently of the other as they are now. The contact switches could be push-pull switches such that if one switch fails and the contact is made on that side, the pulling effect of the other side will act as the redundancy.
		2. Contact switches fail on	Vehicle will be abruptly stopped.	3 2 2	Routine checkout needed. Regular checkout and inspection could avoid this occurrence.
		3. The rod or the semi-loop or its mounting break loose	The contact bumper might be made inactive or stop the vehicle.	2 2 2	Set up so that normal indication to proceed requires continuity and bias power on.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
V. ROUTE CONTROL					
V.A INTERSECTION SIGNAL INTERFACING FAILS	The movement of the vehicle will be linked to the intersection signal lights such that safe passage is ensured. The four-way signals have all to be red when the vehicle is making a turn.	1. Signal path opens	The signal light will not be able to receive a command, therefore might conflict with vehicle movement.	4 2 2	Design the signal path such that an open circuit will be alerted.
		2. Fails with erratic transmission	The vehicle movement will not match signal light.	4 2 3	Further study is needed.
		3. Jams light on red or green	Impede normal flow of traffic. Endanger vehicle movement when signal conflicts.	4 3 3	A detector can be installed to check that signal varies at least once during, say, one minute; otherwise a warning signal will be generated.
		4. Fails to make all lights red	Endangers vehicle.	4 3 2	Further study is needed

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
V.B. ROUTE SELECTION FAILS	When the vehicle approaches a junction where route will split into two, the vehicle must possess the capability to choose which route to take. This can be achieved by either using different cable frequencies or energize only one of the numerous cable to lead the vehicle toward that route.	1. Fails to choose	Vehicle must be made to cease motion when failure to choose occurs.	4 3 2	Must avoid vehicle from taking the wrong route when failure of choice occurs.
		2. Chooses the wrong route	Vehicle must be prevented from taking the wrong route both for convenience and safety reasons.	4 3 2	More work needs to be done. There ought to be capability for the central control to detect that a vehicle is stuck at a certain location. This capability ought to be developed and can be implemented with the localized signal source concept such that when one location sends a vehicle to the next, it tells the center that it has done it and the center ought to anticipate its arrival at the location within a certain duration. Failure to receive a confirmation of arrival from the next location will indicate that the vehicle is stuck between the two locations.

Appendix B. Failure Induced Hazard Catalog

	Description	Failure Modes	Failure Effects	Risk S P C	Preliminary Prevention or Remarks
V.C ROUTE SPEED CONTROL FAILS	Along the route, there are stretches that the vehicle travels at 20mph, 7mph, 2mph (approaching scheduled stop), or fully stopped. The present design does not have all these capabil-ities, but will have to be incorporated.	1. Fails off	The vehicle will continue to travel at the existing speed regardless of what the command signal says.	4 3 2	More work is needed. Also see III.D scheduled stop failure.
		2. Fails on	Vehicle will change to the next lower speed and proceed.	1 3 2	Not a safety concern.

APPENDIX C

ANALYTICAL MODELS OF AMTV

This appendix discusses analytical models for:

(1) Determining speed control parameters, including jerk, acceleration, deceleration and speed profile, to satisfy stopping distance requirement and passenger safety/comfort requirement.

(2) Determining steering control parameters, including proportional constant, slew rate, and geometry of the guide-wire layout.

(3) Analyzing vehicle/pedestrian interactions as they relate to system performance.

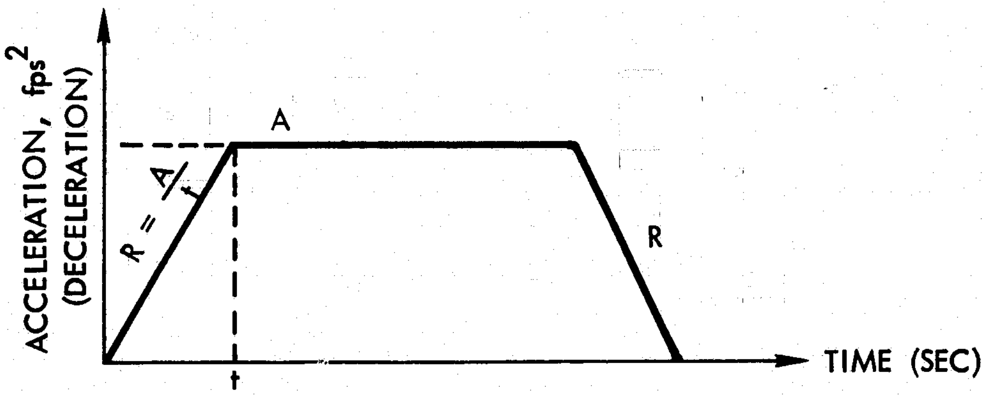
(4) Defining schedules of vehicles and their headways for operational efficiency.

All these models have been developed previously to analyze the operation of a 7-mph AMTV system. (Ref 17, 18). Major results from the previous analyses which have helped to clarify the AMTV operational characteristics and system requirements are summarized in this appendix. Also indicated is the possibility of extending these models for use in analyzing AMTV operations at higher speeds. In particular, this appendix presents in Figure C-1 a set of new curves that can help to determine the best deceleration and jerk rates for a 20-mph AMTV to stop safely and smoothly.

A. VEHICLE MODELS

1. Speed Control Model

Assume that an AMTV uses constant acceleration and deceleration rates with magnitude A ft/sec^2, constant jerk rate at R ft/sec^3, and maximum velocity V fps. The time-profile of acceleration or deceleration can be depicted as follows:



ACCELERATION (DECELERATION) PROFILE

The equations for stopping time and stopping distance have been derived before (Ref. 17) for two cases:

(1) Stopping from maximum cruising speed V.

The stopping time is

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

The stopping distance is

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

(2) Worst-case stopping

This happens when the vehicle is accelerating toward the maximum speed and the headway sensor detects an obstacle. It takes the braking system some time to change the vehicle from accelerating to decelerating, causing additional traveling before stopping. The stopping time in this worst case is

$$T_2 = \frac{V}{A} + 2\frac{A}{R} \text{ sec}$$

The stopping distance is

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

An important design question is the following: Given a prescribed distance (related to sensor range) within which a vehicle must be able to stop, what values must be selected for deceleration (A) and jerk (R) rates?

The solutions for a 7-mph vehicle were given in Reference 17. It was shown that if the vehicle is to stop within 24 ft in the worst case, one should choose A = 5 fps^2, R = 5 fps^3. If the vehicle is to stop within 22 ft, it requires that A = 5 fps^2, and R = 6.5 fps^3.

The solutions for a 20-mph vehicle are given in Figure C-1. It can be seen that if the vehicle is required to stop within 130 ft in the worst case, A = 5 fps^2 and R = 5 fps^3 are good rates to choose.

2. Steering Control Model

A steering control simulation model was developed before (Ref. 18). The results of simulation indicated that steering angle should be proportional to the detected steering error. The proportionality constant and the steering slew rate for a 7-mph vehicle were determined according to the simulation results. The same techniques can be applied to the 20-mph vehicle and obtain steering design parameters based on simulation results.

B. SYSTEM OPERATION MODELS

1. Vehicle/Pedestrian Interface Model

This model was developed to study the effect of random pedestrian crossings upon the average operating velocity of a 7-mph AMTV (see Ref. 17). The results of simulation indicated that the average speed would be virtually unaffected by pedestrians as long as encounter frequency is less than once every 8 seconds. The average speed would reduce to half of the cruising speed if the encounter frequency increases to once every 2 or 3 seconds.

The results also indicate that significant improvement of average speed can be achieved if pedestrians can be guided to yield the right of way to an AMTV upon encounter.

This model is not needed for 20-mph operation because the vehicle would be moving on an exclusive semiguideway at any speed higher than 7 mph.

2. Scheduling model

A simulation model was developed previously (see Ref. 17) to study the impact of random traffic disturbance and stochastic demand of passengers on the average passenger waiting time at tram stops. The simulations

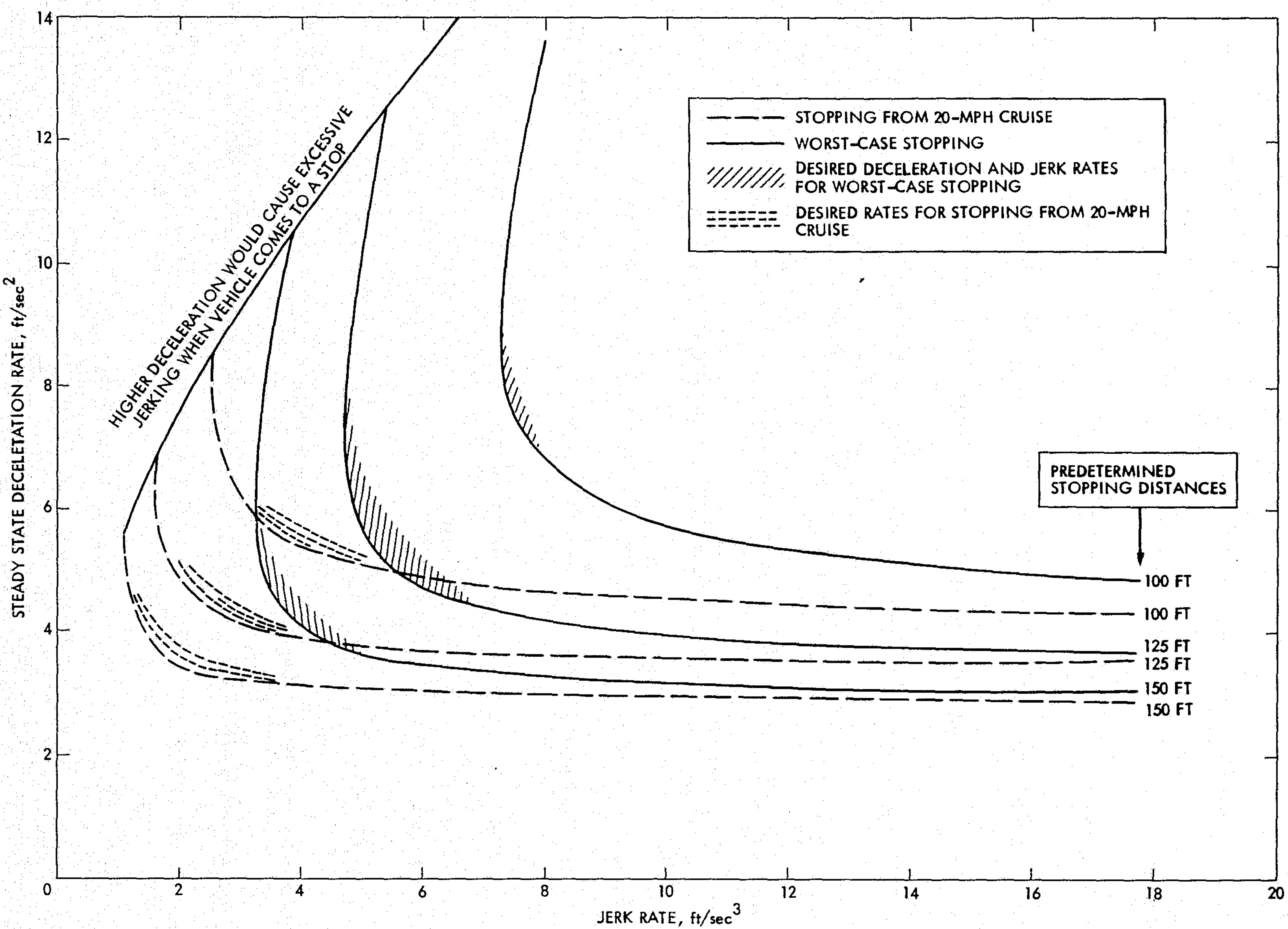


Figure C-1. Required deceleration (A) and jerk (R) rates to stop a 20 mph vehicle within prescribed distance in the worst case were conducted for 7-mph operation under various scheduling policies. The results have indicated the required frequency of tram dispatches that would keep passenger waiting time within some limits. Moreover, it was concluded that optimal scheduling policy depends on passenger demand. In low-demand hours, scheduling by clock or dispatching on demand should be adopted. In high-demand hours, vehicles should be dispatched as frequently as possible. In medium-demand hours, the frequency of vehicle dispatch should be correlated to the travel time of a vehicle needed to complete a loop.

The same method can be used to study scheduling policies for any particular application.

3. Headway Control Model

The purpose of a headway control model is to help understand the effect of headway separations on system efficiency. A simulation model was previously developed (see Ref. 17) for a 7-mph AMTV system with one loop in the route. Headway control was exercised at a designated station on the loop by withholding an AMTV from leaving the station until a predetermined headway condition was satisfied. It was concluded that vehicles should be evenly distributed along the loop to prevent bunching that, on average, prolonged passenger waiting at tram stops. In high-demand hours, however, vehicles should not be withheld but should keep moving to achieve highest volume of circulation.

The method can be used to study in detail headway policies for any application.