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SURVEY OF PRT VEHICLE MANAGEMENT ALGORITHMS

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FINAL REPORT

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16. Abstract

This document summarizes the results of a literature survey of state of the art vehicle management algorithms applicable to Personal Rapid Transit Systems(PRT).

The surveyed vehicle management algorithms are organized into a set of five major component subcategories: network routing, merge control, empty vehicle management, station management, and blocked segment management. This classification scheme enables the comparison and description of algorithms in common terms.

One intent of the survey was to form a data base for system designers and users. Another intent was to use the results of the survey to aid in designing a simulation model to evaluate and develop PRT vehicle management algorithms.

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PREFACE

The author is indebted to Mr. Joseph E. Dratch of Kentron Hawaii Ltd. who performed much of the report's detailed survey work and whose assistance was invaluable in its preparation.

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1. INTRODUCTION

This document reports on a literature survey of state of the art vehicle management algorithms applicable to Personal Rapid Transit (PRT) systems. This survey was undertaken at the Transportation Systems Center of the U.S. Department of Transportation.

A major contribution of this document is the breakdown of the surveyed vehicle management algorithms into a set of five major component subcategories. The classification scheme used enables the comparison and description of the algorithms in common terms.

This survey effort is part of a larger systems effort aimed at obtaining a comprehensive description of personal rapid transit systems. One intent of the survey was to form a data base for system designers and users. Another intent was to use the results of the survey to aid in designing a simulation model to evaluate and develop PRT vehicle management algorithms.

This document summarizes the more detailed survey of findings contained in another report and is based upon documents selected from a separate bibliography. Further information may be obtained from the detailed report or the referenced documents themselves.

2. SURVEY OF PRT VEHICLE MANAGEMENT ALGORITHMS

2.1 SURVEY SCOPE AND OBJECTIVES

This document reports on a literature survey of state of the art vehicle management algorithms applicable to personal rapid transit systems (PRT).

The objective of the survey is to establish a data base of PRT vehicle management algorithms that may be used as a focal information source. While anyone associated with PRT systems' use and design would find this survey of interest, it is anticipated that a major use of this survey will be made in the evaluation and development of vehicle management algorithms.

2.2 SURVEY APPROACH

2.2.1 Automated Transportation System Models

Algorithms applicable to PRT systems can be obtained from the whole class of automated ground transportation systems of which PRT systems are a member. Thus, literature descriptive of dual mode, demand bus service (dial-a-ride), and, in one instance, fast transit link systems was also reviewed, but did not make a major contribution to the survey. Each of these systems has the common requirement of managing large groups of vehicles in providing a mass transportation function. In most instances this management function is made explicit in a series of algorithms usually implemented in some computer configuration.

The dual mode system accepts a vehicle that has the ability to maneuver in a conventional manner through urban traffic. This vehicle is introduced into an automated guideway system via a highway entrance station. The on-guideway portion of a dual mode system is essentially the same as a PRT system. The stations, though, may be somewhat different. Thus, a dual mode system must consider the routing and scheduling of vehicles, merge conflict resolution, empty vehicle shuttling, station management, and blocked guideway management, all of which require an algorithm structure similar to that employed in PRT systems.

The demand bus system (DBS) is a distribution of buses operating over conventional streets in multistop fashion. The difference between a demand bus system and a conventional bus system is that the conventional bus system operates with scheduled station departures over fixed routes with fixed stops while a demand bus system operates upon demand over variable routes with or without fixed stops. The demand bus system considers the routing and scheduling of bus systems. It was found, however, that the differences in operation between the DBS and PRT were sufficient to render virtually all the DBS related algorithm considerations inapplicable to PRT algorithms. It is possible that some of the DBS dynamic routing algorithms will be applicable to some detailed PRT design, such as for multi-stop operations. This consideration will be of some importance in future efforts.

The line haul systems were generally not characterized by a level of automation expected of PRT systems. In a single instance, however, it was felt that the routing algorithm might be applicable and this fact was appropriately noted in this survey.

2.2.2 Survey, Bibliography, and TSC File

The first step taken was the construction of a bibliography containing documents pertinent to the survey. With a view to both completeness and further efforts, it was decided that the bibliography would include not only vehicle management articles but vehicle control documentation as well. Numerous literature sources were examined and a bibliography was constructed. The resulting bibliography was examined for documents that could be directly pertinent to the algorithm review. These latter documents were ordered and procured and placed in a TSC file that also contained documents dealing with the coordinate PRT simulation model survey. The TSC file was further expanded by contributions from various organizations and personnel contacted.

It was evident from the documents that a certain commonality and duplication of material would occur where the authors were from the same organization. Therefore, for ease of survey, the documents in the TSC file were ordered, where possible, by organization. The survey then proceeded along organizational lines.

2.2.3 Nature of Documentation and Related Statistics

From the nature of the material contained in the TSC file it was evident that a small percentage of the documents would explicitly describe the algorithms applicable to PRT vehicle management. The total file is a compendium of material covering simulation models, vehicle management algorithms, and vehicle control. In addition the documents address such topics as transportation demand determination, transportation system overviews, minimum path algorithms, surveys, evaluations, essays on the needs for particular transportation systems, etc.

Over 240 documents were reviewed. These documents were classified as to pertinency to the algorithm review or to vehicle control, systems, human factors, etc. The appendix contains a list of documents reviewed and the classification scheme. Approximately 55 organizations were identified among these documents. In nine instances an organization could not be identified and these documents were grouped in an author category. Fifty-six documents, about 23% of the total reviewed, contained information that was especially pertinent to this review. These pertinent documents were issued by 17 organizations. The organizations themselves include industrial organizations, non-profit organizations, universities, and government agencies, One of the organizations was included as a pertinent contributor because of some organized, valuable background information. However, as this information did not lend itself to this summary, only 16 organizations were included in the final survey.

In the surveyed organizations there were, in some instances, two or more distinct approaches which warranted separate surveys.

The organizations were then arranged as groups, resulting in a survey of 23 groups.

The documents reviewed as pertinent to the algorithm survey were categorized as to the nature and volume of their material. They were classified as either general studies, tradeoff studies, theses, or analyses of specific network/vehicle systems. In the general studies category, algorithms are analyzed and tested usually to show the workability of a vehicle management system. Some examples of these kinds of studies are the efforts by Applied Physics Lab/ Johns Hopkins University (APL/JHU) and TRW. In the tradeoff studies, two or more different concepts are examined and compared. Theses may often fit into both of the former categories; however, they differ oftentimes in the depth of supporting mathematical detail and general research. Analyses of specific network/vehicle systems, e.g., Morgantown Project, are constrained by the system characteristics.

A major difference among the documents is the degree of coverage and detail accorded the various aspects of the vehicle management algorithms. Some documents, for example, deal mainly with station management and tangentially discuss the handling of empty vehicles in the station and on the network. Other documents may concentrate on network management to the exclusion of any detailed station analysis. The classification of the algorithms is covered in Section 3.

2.2.4 Review Format

A survey format was established to allow the common structuring of information for each of the groups selected to be surveyed. The data gathered is given in the detailed survey document (1) and summarized as appropriate in this report (sections 3 and 4). The format is as follows:

i. Documents

1.0 Overview

2.0 Algorithm Reviews

3.0 Network/Demand Model

4.0 Vehicle/System Characteristics

5.0 Results and Tradeoffs

The 'Documents' section lists the documents reviewed. The 'Overview' section describes the contents of the documents and segregates the pertinent documents from the rest.

The 'Algorithm Review' section consists of the five subsections defined in section 2.3 below: routing, merge control, empty vehicle management, station management, and blocked segment (failure) management. This section, the core of the survey, briefly describes the algorithms employed by members of that organization being surveyed.

The vehicle management system, characterized by the algorithms, was often evaluated in an analysis or simulation program. Sections 3.0 and 4.0 describe the network and demand models and list the characteristics of the vehicle and system employed.

Pertinent results or tradeoffs resulting from the evaluation are described in the last section of the detailed survey.

2.3 ALGORITHM CLASSIFICATION

The major contribution of this survey, in addition to gathering together in one place data on various PRT vehicle management algorithms, is the development of a comprehensive classification scheme to describe the major sub-algorithms which comprise the overall vehicle management system. The classification scheme represents a logical division of the functions of vehicle management which provides the framework for reviewing, and is consistent with the exposition in, the documents surveyed. The use of such a classification scheme can also lead to the creation of new vehicle management strategies, but that activity is beyond the scope of this report, which merely reports on what is in the literature. In the classification scheme, five algorithm classes (which are not mutually exclusive) were identified:

1. Network Routing

2. Merge Control

3. Empty Vehicle Management

4. Station Management

5. Blocked Segment (or Failure) Management

Network routing considers the routing of vehicles from origin to destination. Merge control deals with the determination of and resolution of possible conflicts at intersections. Empty vehicle management considers the criteria of distribution and storage of empty vehicles. Station Management focuses on the operation of vehicles into, through, and out of the station. Blocked segment management establishes the operational modes in the event of an emergency or stopped vehicle.

Each of these classifications interrelates with and impacts the others. For example, in some documents that ostensibly discuss only station management, the empty vehicle distribution scheme is actually the determining factor in station management.

An alternative classification category could be the control philosophy: namely, the asynchronous, quasisynchronous, and synchronous operating modes. Each of these control modes, to an extent, determines the general nature of each of the five algorithm classes. Initially, it was felt that just classification by control mode or philosophy would be sufficient. However, it became apparent that it would not exhibit the capability of depth of exposition that is permitted by the selected five algorithms. The impact of the control philosophy upon the algorithm classification and subcategories is examined in Section 3.3.

2.4 ORGANIZATION OF THIS REPORT

Section 2.0 has covered general background material for the survey. Section 3.0 discusses an algorithm classification scheme. The five algorithms that are components of a vehicle management system are introduced. Each algorithm in turn is further subcategorized into considerations and conditions leading to its construction. The control philosophies, centered about the synchronous and non-synchronous modes, are discussed. These modes are then examined for impact upon the algorithms and subcategories.

Section 4.0 lists the findings of the survey. A general format is described and the 16 organizations or 23 groups are examined in survey fashion in alphabetical order. These summaries are intentionally brief to keep the report to a manageable size. This survey is done within the general format presented therein. The second part of Section 4.0 presents a series of summary charts that tabulate the information in accordance with the classifications described in Section 3.0.

Finally, Section 5.0 presents some results and statistics of the survey. In addition some observations are presented.

The appendix presents a list of the documents reviewed and classifies them according to relevance to the survey.

3. ALGORITHM CLASSIFICATION

An algorithm may be described as "a defined process or set of rules that leads to and assures development of a desired output from a given input."* Thus, an algorithm itself may be subclassified into processes or sets of rules. To compare the multiplicity of PRT vehicle management algorthms, it is beneficial to devise a subcategorization system which is relevant to the perceived "natural" divisions between the components of a vehicle management strategy. The scenarios in 3.1 gives an intuitive feeling as to how the subdivision into five categories was developed. In 3.2 a further breakdown into more detailed components is given for each of the categories.

3.1 ALGORITHM ORGANIZATION

Consider the following potential scenario describing the highlights of a passenger trip on a PRT system. A passenger arrives at a station and requests service to some destination. An available vehicle in the station is assigned to statisfy this request. If no vehicle is available, an empty vehicle may be obtained from elsewhere in the system. The passenger boards the vehicle, which is then automatically guided along a route through a series of intersections. The vehicle finally switches into the destination station and the passenger disembarks. At this point a decision is made concerning the disposition of the empty vehicle. In the unlikely instance that a vehicle is impacted during the course of its journey because of a blocked path, an effort is made to find an alternative route to its destination.

A review of the scenario points out the major decision making points in this process. For example, in the station itself there are such decisions as: where to locate the loading and unloading platforms to accommodate the expected demand; how to arrange the berths, etc. There is the decision as to which route to take in the event that the delay over a shortest time route may be large. At a merge point there is the question of how to handle the vehicles

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* Computer Dictionary and Handbook. Charles J. Sippl, Howard W. Sarns & Co., Sept. 1966

so that they may merge smoothly; i.e., conflict free, into the vehicle stream. Again, with a set of empty vehicles dispersed over the network there is the problem of how to organize their storage and movement so as to insure that passenger demands are efficiently met. The question of how the vehicles on the network and in the stations should operate in the event some maloperations occur is of critical importance.

The breakdown of these decision making operations indicates five areas for vehicle management concern: station management, network routing; merge control; empty vehicle management; and blocked segment (failure) management. Thus, one may, heuristically, describe a vehicle management system by these five algorithms.

Each algorithm can be further classified as to the components or considerations which define its functions. This detailed subcategorization is an additional significant contribution of this survey report. For each consideration, a list of the conditions is given which might satisfy it. As an example, an empty vehicle management algorithm may have as one of its considerations the basis for distributing empty vehicles around the network. The conditions which can satisfy this requirement are to use either an historical (or a priori) estimate of the demand or a real time estimate or combination of historical and real time estimates. Thus the consideration and conditions for this consideration may be subclassified under the empty vehicle management algorithm as follows:

EMPTY VEHICLE MANAGEMENT

<u>Consideration</u>	<u>Condition</u>
. . . .	. . . .
Distribution Basis	Historical (HDB)
	Real Time (RDB)
	Historical/Real Time (HRB)

In the tabulation of survey results it would be sufficient then to construct a table with organizations heading the columns and algorithms defining the rows with appropriate symbols (see, for example, Table 1). This method contrasts with the relatively inefficient method of verbally describing the algorithm details for each organization. This approach, the subclassification of algorithms into considerations and corresponding conditions, has been used in this report. The following subsection gives the subclassification and an appropriate description or comment upon the subclassification.

3.2 ALGORITHM SUBCLASSIFICATION

3.2.1 Network Routing

The network routing algorithm has been subclassified into the considerations and conditions listed in Table 1.

The vehicle status indicates whether the routing applies to a loaded or empty vehicle. In those instances where empty vehicle management is considered explicitly then the empty vehicle routing appears under the empty vehicle management algorithm. A vehicle may be assigned a priority status. As an example, a maintenance vehicle may have a higher priority than a loaded vehicle which in turn has a higher priority than an empty vehicle. The three levels could be indicated as P_3, P_2, and P_1, respectively.

Some of the network routing (Ford Motor Co.) algorithms reviewed considered a multistop operation (the vehicle makes intermediate stops to pickup and/or discharge passengers). Thus the two listed conditions are NS (non-stop) and MS (multistop).

The routing strategy considers the routing and sequencing of vehicles over the network from origin to destination. Routing refers to the selection of a geometric path to be followed from origin to destination by a vehicle. Sequencing, or ordering, refers to any time constraints which may be placed on path selection, other than travel time, such as possibly the condition that no two consecutive vehicles can go to the same destination station. The sequencing strategy can range from a no-strategy to a complete point-time path constraint. There are four routing strategies that essentially apply from origin to destination and one that applies

TABLE 1. NETWORK ROUTING

Considerations	Conditions
1. Vehicle Status	Loaded (L), Empty (E), Priority (Pi)
2. Station Stop	Non-stop (NS) Multi-stop (MS)
3. Routing Strategy	Scheduled, Real Time (RS) Prescheduled (PS) Stochastic (SS) Stochastic with Statisical Modification (SMS) Arrival Metering (AMS)
4. Route Selection	
4.1 Primary Path Considered	Yes (YP), No (NP)
4.2 Primary Path Criterion	Minimum Time Path (MTP) Minimum Distance Path (MDP)
4.3 Route Alterability	None (NRA), Prior to Departure (PRA), On Network (ORA)
4.4 Demand Basis for Route Alteration	Historical (HD), Real Time (RD), Historical/Real Time (HRD)
4.5 Criteria for Route Alteration	Link Loading (LRA), Merge Conclict (MRA), Travel Time (TRA), Wait Time (WRA)

to vehicle sequencing in some region. The five origin to destination strategies are classified as arrival metering, stochastic, stochastic with statistical modification, prescheduled, and scheduled in real time. With stochastic scheduling a vehicle is dispatched onto the network without regard to possible link congestion or merge conflicts beyond the station exit merge. With statistical modification a vehicle is again dispatched without regard to conflicts; however, the route selected does account for possible congestion recognized from past history. A prescheduled route defines a slot that moves from an origin station to a particular destination station independent of the demand. A scheduled route, real time, is created upon demand. The constructed route is a conflict-free path through the network. Sequencing in a region includes the sequencing of vehicles at an origin station such that the arrival at a given destination is spaced; this spacing is intended to reduce the possibility of station rejection or an aborted vehicle. Arrival metering is an example of this concept. This spacing at a destination station, or arrival metering, also applies to the grouping of vehicles at sidings, from which point they are spaced and sequenced into a destination station.

When a request is made for travel to a destination, the network routing algorithm performs a network path selection. The network selection may usually consider a primary route that is a minimum distance route.

For the nominal condition of a given constant velocity this minimum distance path represents a minimum time path. All the network routing surveyed assumes that a primary route between origin and destination was both a minimum distance and minimum time path. The variation in routes occurs when secondary routes are constructed. Generally, these secondary routes are required when the demand becomes relatively large, resulting in some network congestion. Thus, one may select a secondary route between a given O-D pair based upon a priori knowledge of demand increase. For example, between 7:00 A.M. and 8:00 A.M. it may be known from past experience that the primary path between a given origin and destination will be loaded to such a degree that the en route travel delays will be large. Consequently, another route between this O-D pair involving the same or less travel time will be selected prior to departure. This congestion may be determined in real time and a different optimum path may be given to a vehicle while the vehicle is en route. These considerations and conditions form the subcategories of Route Alterability, Demand Basis for Route Alteration, and Criteria for Route Alteration.

3.2.2 Merge Control

Two generic types of merge intersections have been considered. Both are assumed to have two entry links; one intersection has one exit link and the other has two exit links (see Table 2). These merge point strategies exclude the case of a station exit merge when a station management algorithm is considered separately.

Four different types of merge strategies are discussed. In the case of a scheduled merge, a merge point reservation is effectively made prior to a vehicle's departure from a station, and in this manner conflicts are avoided. There are two strategies which handle the situation when possible conflicts exist. In one, a priority may be assigned to the potentially conflicting vehicles. As an example, higher priority may always be assigned to all vehicles in the left-hand entry link of a merge. In the other case, a random merge strategy is employed in which no priorities are assigned and merge conflicts are resolved essentially on a first-come first-served basis. For completeness, a fourth merge control strategy is considered in which no rules are given.

The determination and resolution of potential conflicts at merge points is the central function of the merge control algorithms and certainly one of the key problems. The first procedure in conflict resolution is the determination of a possible conflict.

When a potential conflict occurs, a vehicle may be required to slip or advance a number of slots when the slot concept is employed. Where the slot concept is not used, then merge conflicts may be resolved by requiring some vehicles to change speeds even to the level of stopping. In some cases, where merge conflicts cannot

TABLE 2. MERGE CONTROL

Considerations	Conditions
1. Intersection Type	Two into One (OI)
	Two into Two (TI)
2. Merge Strategy	Scheduled (SMS)
	Priority (PMS)
	Random (RMS)
	None (NCR)
3. Conflict Determination	(CD)
4. Conflict Resolution Maneuver	Slot Slip (SCR)
	Slot Advance (ACR)
	Speed Alteration (SAR)
	Reroute (RCR)
5. Maneuvering Region	Link (LMR)
	Intersection (IMR)

be reasonably resolved within the management system, one of the vehicles may be rerouted.

When a vehicle maneuvers to resolve a conflict, it may be required to perform the maneuver either on the link before the intersection region or in the intersection region itself.

3.2.3 Empty Vehicle Management

Empty vehicle management encompasses the storage, distribution, and routing of empty vehicles.

Empty vehicles may be stored in a station or at some separate, static storage facility (Table 3). These storage facility may include a central or regional car barn and/or a maintenance facility and/or a siding. Alternatively, empty vehicles may be kept circulating on the network with a capability of being diverted to a station as required.

Empty vehicles are distributed to storage areas (or on paths about the network) in accordance with empty vehicle demand prediction and/or real time requirements.

Empty vehicles may be sent to a station when the station makes a specific demand. In some algorithms, where more than one station is competing for an empty vehicle, the empty vehicle is sent to the station with the greatest relative need. This relative need may be predicated upon the length of time the first passenger has been waiting in the queue and/or the size of the passenger queue.

An empty vehicle may be ejected from a station when the number of empty vehicles exceeds some threshold level. This empty vehicle is ejected usually to permit loaded vehicles to enter the station with a low probability of station rejection. An empty vehicle may also be diverted into a station in order to avoid a conflict at the station exit merge with a loaded, departing vehicle. The empty vehicle then moves through the station and back onto the main line. This latter concept has been called continuously rescheduled empties.

TABLE 3. EMPTY VEHICLE MANAGEMENT

	Considerations	Conditions
1.	Storage	Station (SES) Facility (FES) Network Circulation (NES)
2.	Distribution Basis	Historical (HDB) Real Time (RDB) Historical Real Time (HRB)
3.	Station Criteria	Relative Station Needs (RSC) Station Threshold (SSC) Continuous Rescheduling (CRE)
4.	Routing Criteria[(a)]	Minimum Empty Miles (MEM) Maximum Station Pass (MSP)

(a) Empties are considered routed, other than in network circulation, by the same strategies employed in network routing. The two listed conditions are those that differ from the ones listed under network routing.

The routing criteria for an empty vehicle can be based upon the conditions listed under the network routing conditions. In addition the empty vehicle routing may be based upon keeping the total miles traveled by empties to a minimum or, in the case of circulating empties, upon passing a maximum number of stations.

3.2.4 Station Management

A station management algorithm is particularly governed by the station model. Table 4 shows the characteristics of interest in a station model. Figure 1 illustrates some of the various station configurations.

The stations are all off-line. The initial portion of the off-line lane is a deceleration region where the vehicle decelerates to a desired speed. The exit from the station is accomplished over an acceleration region and the vehicle merges with the main line traffic at, usually, the nominal speed of the vehicles on the main line.

The station may be a single lane station or have a number of lanes. In some instances a station may have an arrival queue where entering vehicles are temporarily held before entering the platform area. There may also be a departure queue where vehicles are held prior to accelerating to merge speed velocity.

The berthing may be serial or parallel. In serial berthing the vehicles are lined up on a single lane. A vehicle cannot exit the station or lane until a preceding vehicle exits. In a parallel configuration the vehicles are parked parallel to each other (Figure 1b) and the vehicles in the platform area may exit in any sequence. This configuration usually requires two lanes.

Many studies examined the number of berths required to satisfy the demand within some performance criterion, e.g., total trip time. This number may relate to the number at the platform and, where applicable, to the number in the queue. Some studies also focused on the advisability of separate or common unload/load areas of the platform. In the common unload/load configurations an entering vehicle will usually discharge its passengers and receive incoming

TABLE 4. STATION MANAGEMENT

	Considerations	Conditions
1.	Model	
	Lane Configuration	Single (SLM), Multiple (MLM)
	Queues	Arrival (AQM), Departure (DQM) (Both QM), None (NQM)
	Berthing	Parallel (BPM), Serial (BSM)
	Unload/Load	Common (CPM), Separate (SPM)
	Turnaround Capability	(TCM)
	Vehicle Grouping	Trained (TGM), Single (SGM)
	Passengers	Grouped (PGM), Single (PSM)
	Dwell Time	Fixed (FDM), Random (RDM)
2.	Vehicle Movement	Platoon (PVM) Ripple (RVM) Conveyor (CVM)
3.	Berth Assignment	(BA)
4.	Exit Merge Resolution	Priority Mainline over Exiting (MLE) Priority Loaded over Empty (LER) Priority Exiting over Mainline (EML) Priority Exiting over Mainline Empty (EMR)
5.	Vehicle Rejection	(VR)

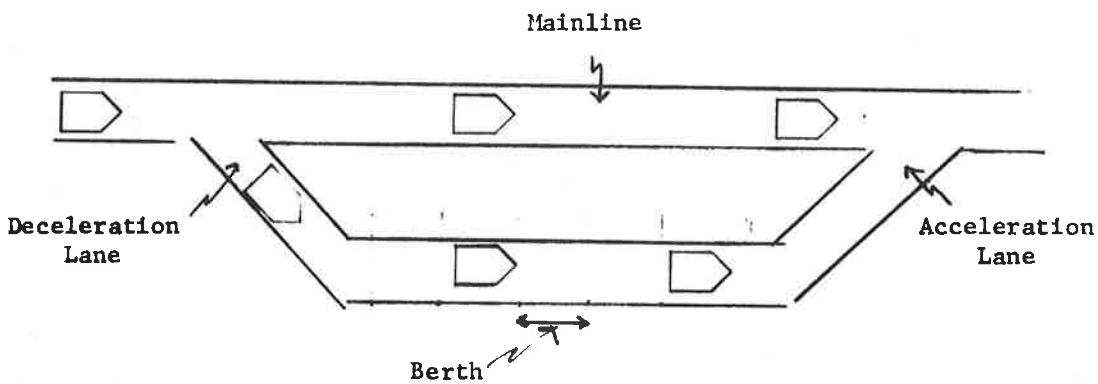

Figure 1a. Station Model. Serial Berthing

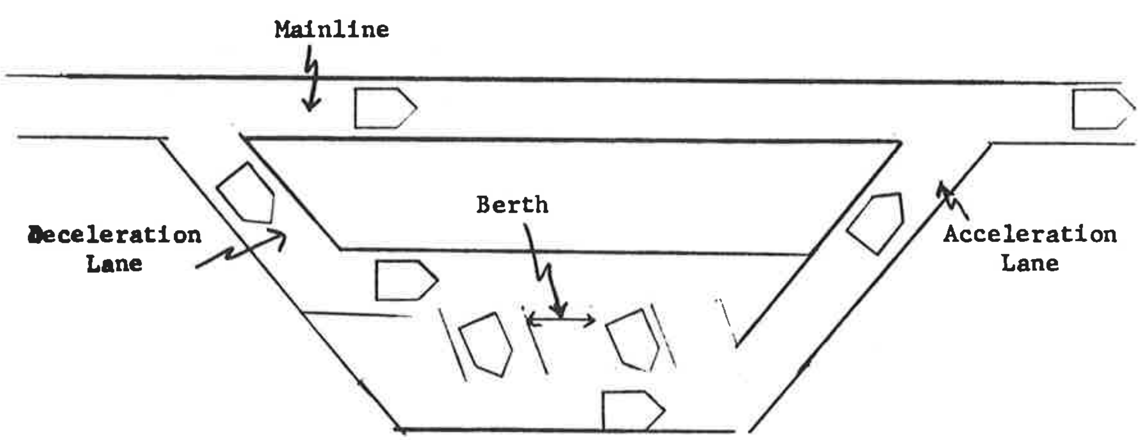

Figure 1b. Station Model. Parallel Berthing

passengers at the same position. In the separate configuration the entering vehicle will discharge its passengers in one region of the platform, then move forward to another position where the incoming passengers board.

The dwell time usually refers to that period of time in which the vehicle's doors are open for the discharge and receipt of passengers. In some studies this dwell time is assumed to be fixed. In others it is assumed to be random with some probability distribution of open or dwell time. This randomness is included to reflect the variability of a passenger's boarding.

The system described may or may not account for the grouping of passengers with a common destination. Also, in some instances, the grouping of individual vehicles into a train is considered from a PRT vehicle management standpoint. In at least one instance the vehicle at a station would have the capability of changing direction. A PRT vehicle generally enters from one direction and is constrained to exit in another direction, usually back onto the main line.

The vehicles may move through the station in a platoon fashion; i.e., grouped together. Thus, a group of vehicles stopped in an arrival queue might all move simultaneously into the platform area. The vehicles may advance singly through the station usually moving forward as a space becomes available. This results in a rippling effect of the vehicles through the station. In at least one document a conveyor concept is considered. In this concept the vehicle usually moves through the station at a constant, low speed and passengers disembark or board from a belt moving at the same speed as the vehicle.

Vehicles entering the station may be assigned specific berths or assigned berths in some order. This usually applies to multiple lane configurations. As an example a string of vehicles may be directed first into lane 1, then lane 2,. . .and then the last lane, no matter what the occupancy is in prior lanes.

When a vehicle is prepared to exit a station, there may be a potential conflict with a vehicle on the main line at the merge point. The priority may be given to the vehicle on the main line or to the exiting vehicle. In the latter case some slot slipping or speed alteration by the main line vehicle might be necessary (cf. merge control). The priority may be assigned on the basis of whether the main line vehicles and/or the exiting vehicle are in a loaded or empty state. Usually, the main line vehicle is assigned a priority over the exiting vehicle and the exiting vehicle waits for an appropriate empty slot or space at the merge prior to accelerating out of the station.

The station management algorithm may or may not permit a vehicle to be rejected. A rejected vehicle is forced to 'go around the block', i.e. find a reasonably quick path back to the station. This latter concept is implied when a vehicle is not permitted to enter its destination station; i.e., the entry is aborted.

When an empty vehicle is required by the station and there are no empties available at the station, then the station may: (1) call an empty from another station; (2) call an empty from a storage facility; or (3) divert an empty that is circulating the network. This subprocess of the station management algorithm overlaps the subprocess of storage in the empty vehicle management algorithm. From a station management standpoint it represents how empty vehicles are acquired for passengers; from an empty vehicle management standpoint it represents how empty vehicles are stored in a vehicle management system.

3.2.5 Blocked Segment Management

The blockage of any portion of the system may occur whenever a vehicle is stalled on the network.

The failure of a vehicle either may be considered as an instantaneous event in an analysis and simulation or the dynamics of stopping may be taken into account (Table 5).

Each stopped vehicle must be detected as a stopped vehicle blocking the network. One failure detection method may be a communication between a stopped vehicle and a central management source; another indication of a stoppage may be the lack of communication with a vehicle. In general, a lack of vehicle response

TABLE 5. BLOCKED SEGMENT

Considerations	Conditions
1. Mode Consideration	Dynamic (DMC) Event (EMC)
2. Detection of Blockage	Communication (CBD) Lack of Command Response (LCD)
3. Blockage Location	Link (LBL) Merge Point (MBL) Station (SBL)
4. Management Strategy	
4.1 Network Restructuring	(NE)
4.2 Vehicle Rerouting	(RE)
4.3 Vehicle on Link Recovery	(VE)
4.4 Stalled Vehicle Recovery	Push or Pull (PSR) Maintenance Vehicle (MSR)

to commands is also indicative of a stopped vehicle. Numerous other modes may be available, usually in the form of some specific equipment configuration, but the detection method is not significant in terms of the management algorithm. A detected, stopped vehicle may be located at key points of the network: on a link, at a merge switch, or in a station.

The strategy that accounts for system functioning in a stalled vehicle situation may be classified in twofold fasion as: (1) network management restructuring and (2) vehicle recovery.

In network management restructuring those vehicles that are supposed to traverse the point occupied by the stopped vehicle are intercepted and rerouted around the blocked point. Also, all origin-destination paths for vehicles at stations are structured without the use of the blocked point.

Vehicle recovery is performed for any vehicle forced to stop behind the stalled vehicle (because it cannot be dynamically re-routed) and for the stalled vehicle itself. In the former case, the vehicles may be backed up upstream of the first demerge point and rerouted. If there is no backup capability, then the vehicles will have to wait for recovery of the stalled vehicle. The stopped vehicle may be recovered by a maintenance vehicle that has a repair capability or a backup capability. The stalled vehicle might also be removed by a following vehicle. In this case the following vehicle may push, or pull if a backup capability exists, the failed vehicle to the nearest siding, station, or maintenance facility.

3.3 CONTROL PHILOSOPHY

3.3.1 Types of Control Philosophy

The algorithms classified in the previous subsection have been presented as descriptive of vehicle management operation. Another method commonly used in describing vehicle management systems is the control philosophy employed in the management structure. There are three basic traffic management control modes: synchronous, quasi-synchronous, and asychronous. The synchronous mode employs the slot concept wherein a discrete physical length travels over the network at a given speed or speeds like an escalator step. The slot length (one headway unit) is large enough to accomodate a PRT vehicle. Thus, a group of vehicles in adjacent slots might move around the network with an appropriate headway between each vehicle. The vehicle control approach generally used for synchronous systems is the point follower scheme.

In the synchronous mode a vehicle is assigned a slot from origin to destination. Over this route the slot has a reservation on all links and merge and demerge points. Thus, under normal operation, there are no conflicts at merge points or at station entrances and exits.

A modification to the synchronous mode is the concept of synchronous cycle. A cycle is composed of a group of adjacent slots. Within the cycle the slots are not specifically reserved. That is, the vehicle in a slot in a given cycle is capable of moving to another slot within that cycle. This phenomenom of moving from one slot to another slot is described as slot slip - for moving to a trailing slot - or slot advance - for moving to a leading slot. Thus, a vehicle may arrive at its destination in a different slot than the one occupied at the start of the trip. However, the cycle, i.e., the given group of slots, is scheduled or holds reservations throughout the trip. There are no conflicts between cycles at any merge points. However, there may be conflicts within a given cycle at merge points. These conflicts are resolved by slot slipping or advancing within the cycle. Figure 2 illustrates the concept. The uncertainty in arrival time at a given point is, therefore, no more than the number of slot times in a cycle. Thus, if a cycle has five slots and a slot length of 20 feet that is traveling at 40 ft/sec, then the uncertainty in arrival time should be no more than two seconds. The synchronous mode described in the previous paragraph may be assumed to be a synchronous cycle that has only one slot.

The quasi-synchronous mode employs the slot following concept. However, this slot is not reserved through the network. Thus, a vehicle in one slot might be competing with a vehicle in another

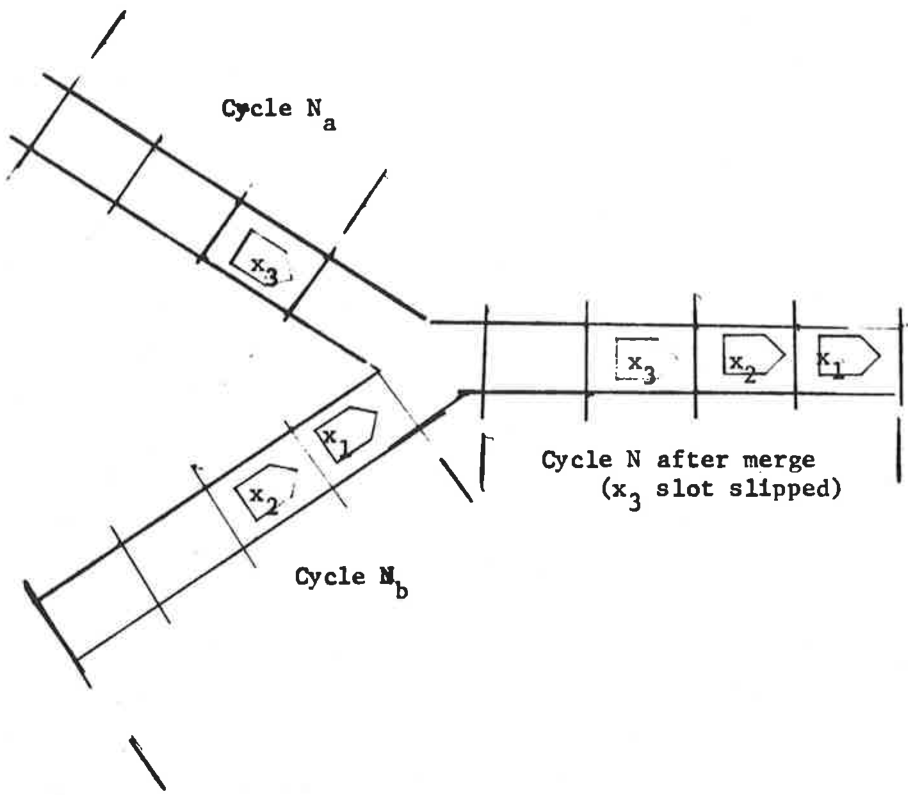

Figure 2. Slot Slip within Cycle at Merge Point

slot at a merge point. Such a potential conflict is usually resolved by having one vehicle slot slip or slot advance. Since there are no reservations at the merge intersections, a vehicle may be required to slip numerous slots. However, the number of slots required to be slipped may be infeasible from a performance standpoint. In that event the vehicle may not be permitted to go on its intended path but directed along another route; i.e., aborted. This latter concept, the possibility of an abort, is one of the features that distinguishes the quasi-synchronous from the synchronous cycle concept.

The asynchronous traffic management system, as commonly considered, does not employ the direct slot concept in which vehicles are a priori restricted to discrete portions of the guideway, but rather, if there are no conflicts, allows a vehicle to enter the guideway whenever it is ready, much like the way automobiles operate on highways. The vehicle control scheme generally employed to implement this approach is a vehicle following system. In this concept a vehicle will, through some communication with the vehicle ahead and the vehicle behind, maintain some fixed spacing in time and/or position with the vehicle in front of it. Thus, if a preceding vehicle alters speed, the vehicle behind will alter speed to maintain the spacing rule.

As with the quasi-synchronous system a vehicle is dispatched in the asynchronous mode with no reservation through the network. Merge conflicts are resolved usually through speed alteration. Thus, one vehicle on one link may slow down in order to resolve a conflict. Vehicles behind this vehicle in turn slow down.

3.3.2 Impact of Control Philosophy on Algorithms

The control philosophy adopted in a particular vehicle management system determines to an extent the structure of the vehicle management algorithm. The discussion that follows heuristically presents some of the implications of control philosophy upon algorithm structure. The primary reason for this presentation is that the surveyed literature to a large extent does describe vehicle management systems within the context of a control philosophy.

Thus, in the interest of survey completeness, some possible relations between control philosophy and the algorithm classification of Section 3.2 are presented. The impact of the control modes is primarily felt in the network routing and the merge control algorithms. No evidence was given that the strategies used were the only ones possible or the most effective.

Network Routing. The routing strategy consideration is affected by the control philosophy. The synchronous modes generally imply in the surveyed work a prescheduled or real time scheduling routing strategy while the quasi-synchronous and asynchronous modes imply a stochastic scheduling with or without statistical modification. The concept of metering the flow of vehicles into a destination station was used with a synchronous mode of operation but it is also possible to employ this concept with the other modes.

The synchronous mode efforts surveyed were more prone to use the wait time as a criterion for altering a route prior to departure while the non-synchronous modes were more likely use travel time or link loading or merge conflict potential as the criteria for route alteration.

Merge. For the synchronous mode work reviewed the merge strategy after employing a scheduled merge scheme. The quasi-synchronous and asynchronous control efforts, on the other hand, more often employed a random or priority merge strategy.

4. SURVEY FINDINGS

4.1 SURVEY BY ORGANIZATION

This subsection presents in summary form the survey of PRT vehicle management systems by organization. This report summarizes material appearing in a detailed internal DOT/TSC survey.

The format used in this survey summary section is shown in Table 6a. The comments section contains some notes that briefly elaborate upon the particular survey approach. In general the material presented in the summary section is self-explanatory; thus, no comment is made in a number of survey instances.

The system type identifies the type of transportation system considered. In general three types are considered: PRT, dual mode, and line haul. Two specific examples were further broken out: The Morgantown system and the Dallas-Ft. Worth regional airport. These classifications and corresponding symbols for focus, study type, and control mode are listed in Table 6b.

The focus identifies the primary emphasis of the study or documents. In some instances a study would focus on a given algorithm. As an example, the thesis effort by M. Godfrey focused solely on merge controls. The focus identifies which of the five algorithms were focused upon. Even though one algorithm may be focused upon, other algorithms are touched upon. Thus, in the survey itself, these other algorithms are expressed according to the appropriate classification.

The study type identifies the nature of the document as a systems study, a tradeoff study, or a thesis effort. The systems study generally concentrates upon a specific vehicle management approach and examines the performance of a system with some demand and network configuration. A tradeoff study may pose two or more different approaches to an algorithm and make comparative statements, e.g., a tradeoff study between common and separate unload/

TABLE 6a FORMAT FOR SURVEY BY ORGANIZATION

Organization Name

- Comment
  - System Type
  - Focus
  - Study Type
  - Control Mode
- Algorithms
  - Network Routing...
  - Merge Control...
  - Empty Vehicle Management...
  - Station Management...
  - Blocked Segment Management...

TABLE 6b CLASSIFICATIONS AND SYMBOLS USED IN SURVEY

	Classification	Symbol
1) System Type	PRT --	P
	Morgantown	PM
	Dallas - Ft. Worth	PDW
	Dual Mode	DM
	Line Haul	LH
2) Focus	Network Routing	R
	Merge Control	M
	Empty Vehicle Management	E
	Station Management	SM
	Blocked Segment Management	B
3) Study Type	System	SY
	Tradeoff	TR
	Thesis	TH
4) Control Mode	Synchronous	S
	Synchronous, Cycle	SC
	Synchronous, Modified	SM
	Quasi-Synthronous	QS
	Asynchronous	AS

load platforms in station management. A thesis type identifies that the document was a thesis effort.

The control mode identifies the control philosophy (see Table 6b). Except for "synchronous, modified" these terms have all been discussed elsewhere. The synchronous, modified control refers to a single instance [MIT(S)] where the synchronous approach is slightly modified to account for a station entrance rejection.

The algorithm survey is briefly summarized under the appropriate algorithm (Table 6a). In those cases where there is no algorithm material available no written summary is included.

Sixteen organizations are included in this survey. With some organizations the approach to a given algorithm varies sufficiently such that more than one algorithm survey is required. This occurs in three instances. Thus, the number of distinct surveys is twenty-three, which is reflected in the summary charts of section 4.2.

4.1.1 Aerospace Corporation (AERO)

Comments - The documents from Aerospace Corporation represent three separate efforts. One effort focuses on merge conflict resolution with quasi-synchronous control and a comparison of a taxi type station with a conveyor type station. A second effort is a tradeoff study of a separate vs common unload/load platform station; and the third effort focuses on failure management. Thus, there are three groupings of algorithms reflected in the following summary.

System Type	P
Focus	R, M, SM, B
Study Types	SY, TR
Control Mode	QS

Algorithms

Network Routing - The routing strategy is essentially stochastic with statistical modification. The route selection is based on a 'minimum' time path that adjusts a minimum distance path with stochastic behavior at intersections. Thus, a prior departure route alteration is possible. An on-network route alteration is implied in the reroute capability resulting from a forced miss of a turn.

Merge Control - The merge strategy is a random one with the capability of a priority merge. A potential conflict is determined at some decision point on the link prior to the switch. The conflict resolution maneuver is a slot slipping one with a reroute where slot slipping is unreasonable. The maneuver is performed on the link prior to the switch. Maneuvering on the intersection portion between switches was rejected.

Empty Vehicle Management - Empty vehicle management is likened to an inventory control problem and is not discussed.

Station Management: Moving Belt - The moving belt station is a single lane station with no queues, separate unload/load platforms, and serial berths ranging from 1-80. The movement of the vehicles through the station is conveyor fashion. A vehicle is rejected when no space is available. An exit merge conflict with a mainline vehicle may be resolved by forcing the mainline vehicle to enter the station. This diversion is preferred to the alternative of stopping the belt.

Station Management: Taxi - Two platform configurations are examined: common unload/load and separate unload/load. A single lane station with arrival and departure queues, serial berthing, and random dwell times is assumed. Both platoon and ripple movements are considered. It is concluded that a common unload/load is preferred to separate unload/load and that ripple movement is preferred to platoon movement.

Blocked Segment Management - The dynamics of vehicle stalling are considered and detection assumed. The stopped vehicles may be on links, on intersection turns, or at merge points. The management strategy consists of rerouting vehicles when possible and restructuring origin to destination paths. Vehicle recovery of the stopped vehicle may be performed by the pushing of a vehicle by a following vehicle or by the use of a stop and clear strategy.

4.1.2 Applied Physics Lab/Johns Hopkins University (APL)

Comments - Three classes of strategies are considered which represent three vehicle management systems or algorithms. The strategies proceed from a low level of computation and communication capability to a high level. Preliminary separate studies comparing quasi-synchronous and synchronous operation imply thruput by use of a synchronous capability. The main studies, however, center around an asynchronous system. Separate documents discuss empty vehicle management and failure management.

System Type	P
Focus	R, E, B
Study Type	SY
Control Mode	AS

Algorithm, Class I

Network Routing - Vehicle routing is stochastic with statistical modification. The basic criterion is that the flow over any given link is kept far below expected flow so as to accommodate random fluctuations and still minimize dead head time. A non-alterable path for loaded vehicles is set prior to departure and is fixed in accordance with historical demand.

Merge Control - Merge control is not explicitly discussed. Queues are allowed to build up at merge points as they occur. Conflict resolution is apparently handled by a speed alteration maneuver.

Empty Vehicle Management - Station storage of empties is assumed and the possibility of network circulation is considered. If no network circulation is employed, then empties are distributed according to historical demand. If there is network circuculation, then an empty is diverted by a station based on the station's threshold setting. The empties, in network circulation, may use a maximum station pass criterion.

Algorithm, Class II

Network Routing - Due to the use of an asynchronous scheme, the routing is essentially stochastic. The shortest route is tested for anticipated link flow based on actual demand. If the link flow is high, then alternate routes prior to departure are examined. If these alternate routes are unreasonably high-time routes, then the departure may be delayed.

Merge Control - Merge control is not explicitly discussed. Conflict resolution is apparently handled by a speed alteration maneuver.

Empty Vehicle Management - Empty vehicles are stored in stations; network circulation is not mentioned. Empty distribution is based upon real time (one-minute interval) computation of relative station needs. Relative station needs are based upon the sum of times each party has been waiting, or, with no passenger demands, upon the number of unoccupied berths. An empty vehicle may be diverted by a station with a greater relative need than the destination station. Routing is apparently similar to that of loaded vehicles.

Algorithms, Class III

Network Routing - The network routing is essentially stochastic and the shortest and alternate routes are examined, as in Class II. However, on networks, vehicles may be rerouted, or routed at different speeds over the original path to avoid congestion over future links.

Merge Control - The merge strategy, as with the other classes, appears to be a random merge. Conflict resolution is handled by a speed alteration maneuver.

Empty Vehicle Management - The empty vehicle management strategy is similar to the Class II strategy. In the Class III strategy the relative station needs are based on the predicted number of passengers at about the time of arrival of an empty vehicle the number of arriving, loaded vehicles at that time, and the number of empties at the station at that time.

Algorithms

Blocked Segment Management - A failure is considered as an event that has occured and renders impassable a section of guideway. The management strategy reroutes vehicles on the network and those in stations destined to use the blocked section. Vehicles which have entered the blocked section are removed and the stalled vehicle is recovered.

4.1.3 Boeing (BOE)

Comments - The Boeing simulation was used to evaluate the vehicle management algorithms used in the three-station Morgantown Project. The actual system will operate in scheduled mode from 6:45 A.M. to 6 P.M. and in demand mode the rest of the time. The two end stations are on-line and the middle station and storage facility are off-line. With a 15 sec. headway, two channels in each of the on-line stations, separate unload and load berths, and the time constraints to handle up to 21 passengers per vehicle, only two out of three guideway slots going to the end stations can be occupied.

System Type	PM
Focus	R, E, SM
Study Type	SY
Control Mode	S

Algorithms

Network Routing - A vehicle is dispatched into an empty slot passing the origin station. No reservations are made at future merges because of the small number of stations. No more than two consecutive slots on the main guideway may be occupied, so some sequencing constraints are employed.

Demand mode operations are simple with, if possible, only one channel per platform in service. Scheduled mode, in simple terms, is controlled by the dispatch rates from the middle station. There are also occasional trips between the two end stations. Dispatch rates are established to meet the expected demand during each half hour interval, with a maximum allowable dispatch rate of 2/3 full guideway flow. The two end stations dispatch vehicles as fast as possible, subject to the constraint that there be some specified minimum number of vehicles (zero during full demand periods) in the station before allowing a dispatch.

Empty Vehicle Management - In demand mode, if the destination station is full, an empty vehicle is dispatched to the origin station. Additionally, each channel is given an inventory goal and empty vehicles are moved around to achieve these goals. In scheduled mode, empty vehicles are moved in response to changes in the inventory goal of the storage facility.

Station Management - The forward-most berth in each channel is reserved for passenger loading. The other berths are for passenger unloading, so normally a vehicle makes two stops in a channel. Some channels at the middle station are turnaround channels sending vehicles back to the end station from which they came. There are also channels which allow the vehicle to continue in its original direction. If the middle station is full, a vehicle destined for it bypasses the station and continues on to the next station. A vehicle on the main guideway has priority over a vehicle in a station awaiting dispatch.

4.1.4 Calspan (CLSPN)

Comments - The surveyed document reports on a dual mode system designed to serve the Buffalo area. The major PRT pertinent algorithm deals with the station exit merge. In this approach, when a vehicle departs a station a gap may be created in the main line by slowing down vehicles on the main guideway.

System Type	DM
Focus	--
Study Type	SY
Control Mode	--

4.1.5 Ford Motor Company (FMC)

Comments - The documents surveyed generally refer to dual mode applications with, from a PRT standpoint, emphasis upon merge control. A synchronous cycle control philosophy is employed. The network routing model is derived from a line haul, multistop system. The station management concepts are obtained from a study of the number of spaces required in an off-line station to handle various flow rates for given probabilities of station rejection.

System Type	DM, LH
Focus	M
Study Types	SY, TR
Control Mode	SC

Algorithms

Network Routing - A multistop, line haul is considered.

Merge - Generally a two into one intersection is considered with apparently random merge. Conflict resolution is by slot slipping or slot advancing within the synchronous cycle.

Station Management - A single lane configuration with a common unload/load platform and serial berthing is considered. All models have arrival queues and two have departure queues. The vehicles move through the station in ripple fashion and vehicle rejection occurs when the most rearward position is occupied.

4.1.6 General Motors Corporation (GMR)

Comments - Some network routing and merge algorithms are considered for possible use in a simulation. A separate study of possible station management is made.

System Type	DM
Focus	SM
Study Types	TR
Control Mode	SC

Algorithms

Network Routing - The routing strategy might be a real time scheduled one. In another study an arrival metering concept is considered.

Merge - The merge strategy utilizes a scheduled merge with slot slipping within a cycle to resolve conflicts.

Station Management - The model analyzed is a multilane model with serial berthing, common unload/load platforms, and a random dwell time. The vehicles are assigned berths in cyclic fashion within a given lane.

4.1.7 Honeywell (HNY)

System Type	P
Focus	R, M, E, SM
Study Type	SY
Control Mode	QS

Algorithms

Network Routing - A minimum path routing between origin and destination is employed.

Merge Control - A line priority is used in the merge strategy. Potential conflicts are resolved by slot slipping.

Empty Vehicle Management - Empty vehicles are stored in a station or central facility. Empties are distributed according to an a priori or historical surplus-deficient matrix. An empty may be called from storage to serve a station and an empty dispatched to a central facility may be diverted by a station. If the vehicle buildup at a station exceeds some threshold value, the empties are sent to a central facility. The empties are routed on minimum path routes such that the total miles traveled by empties is a minimum.

Station Management - A single lane station model is used with a common unload/load platform. The berthing is serial and there are provisions for both an arrival and departure queue. Passengers with common destinations may be grouped in a queue for loading into a single vehicle. The vehicles move through the station in a ripple fashion.

4.1.8 International Business Machines (IBM)

System Type	P
Focus	R, M, E
Study Type	SY
Control Mode	S

Algorithms

Network Routing - The routing strategy is a real time scheduled one. Routes may be selected from a schedule table and the routes apparently are alterable while the vehicle is on the network. The selected route may be established on a real time basis using a wait-time criterion.

Merge Control - The merge strategy is a scheduled one and no conflict resolution maneuver is required.

Empty Vehicle Management - Empties may be stored in stations, at a facility, or in network circulation. The empties are distributed essentially on a historical basis and may be diverted to a station.

Blocked Segment Management - All unusual or unexpected events are routed to a central computer and classified according to immediacy of required action. All vehicles converging on the blocked link are diverted. Vehicles on the same link may be moved close to the stopped vehicle to permit an escape chute for vehicles which cannot be rerouted at the switch to the link.

4.1.9 Jet Propulsion Laboratory (JPL)

System	PM
Focus	R, M, E, SM
Study Type	SY
Control Mode	S

Algorithms

Network Routing - The routing strategy is a real time scheduled one and no route alternation is considered.

Merge Control - The merge strategy is a scheduled one with no conflict maneuvers necessary.

Empty Vehicle Management - An empty vehicle is stored in a station or at a facility. An empty vehicle not needed at one station is assigned to another station with the greatest need. The need of a station is defined by the number of groups waiting less vehicles available and/or due in that station.

4.1.10 Massachusetts Institute of Technology (MIT)

Comments - The PRT pertinent work at MIT was done largely as theses efforts. In general, there are two main focuses: merge and station management. In the station management effort a series of theses were developed where each thesis assumed the preceding one as a reference point. The theses or documents are surveyed individually under the name of the document author rather than as an organizational effort.

4.1.10a MIT [W. Carlson] [MIT (C)]

Comment - The document defines and examines a number of routing strategies and assesses the delay associated with these strategies. The evaluation is performed as a combination of heuristic, analytic, and simulation efforts. The document concludes that a routing strategy using real time scheduling results in low delay values. For classification purposes the following is noted:

System	P
Focus	R
Study Type	TH
Control Mode	S

Algorithms

Network Routing - The preferred routing strategy may be classified as real time scheduling. A number of routes alternate to a minimum path route may be considered prior to departure.

Merge Control - In the preferred control mode; i.e., synchronous, the merging strategy would be classified as scheduled.

4.1.10b MIT [D. Miller] [MIT (M)]

Comment - This thesis document examines three kinds of vehicles dispatched from a PRT station: (1) first-come first-serve with no provision for empty distribution; (2) a prescheduled network routing strategy; and (3) first-come first-serve and empty vehicle dispatch to a station whose inventory is below a certain value. The wide range of dispatch policy requires different classification according to subcategory, as reflected in the classification below.

System	P
Focus	R, E
Study Type	TH
Control Mode	---

Algorithms

Network Routing - Two routing strategies are considered: stochastic and prescheduling.

Empty Vehicle Management - Empties may be stored in stations. Empties may be distributed to stations whose inventory of vehicles fall below a threshold even though origin stations have a passenger queue.

4.1.10c MIT [R. Walker] [MIT (W)]

Comments - This thesis examines a network circulating empty vehicle management scheme and compares it with the concepts investigated in the thesis work of MIT (Miller) presented above. The classification presented below does not include the subcategories expressed in the previous thesis effort.

System	P
Focus	E
Study Type	TH
Control Mode	S

Algorithms

Network Routing - The routing strategy is essentially synchronous.

Empty Vehicle Management - Empties are circulating the network and called in as required. A loaded vehicle exiting the station has priority over an empty on the main line. In the event of conflict the empty is forced to enter the station.

4.1.10d MIT [M. Godfrey][MIT (G)]

Comment - This Ph.D thesis focuses solely on the problem of merge control. Six merging strategies are described and evaluated. Each merging strategy permits slot slipping or slot advancing with its implication of quasi-synchronous control.

System	P, DM
Focus	M
Study Type	TH
Control Mode	QS

Algorithms

Merge - The intersection type considered is a two-into one merge. Six merging strategies are discussed, five of which assign a certain priority and one of which is random. Potential conflicts are resolved by slot slipping or slot advancing.

4.1.10e MIT [M. Sirbu] [MIT(S)]

Comments - This Ph.D thesis examines a number of concepts from a station management standpoint. Underlying the presentation is a comparison of parallel and serial berthing. The concepts of continuously rescheduled empties and arrival metering are introduced. The control mode is termed a modified synchronous one in which reservations are made from origin to destination; however, some slot space is reserved for slot slipping. In this survey terminology the control mode falls somewhere between synchronous and quasi-synchronous.

System	P
Focus	SM
Study Type	TH, TR
Control Mode	SM

Algorithms

Network Routing - The routing strategy is a real time scheduled one and an arrival metering constraint may be employed.

Empty Vehicle Management - Empty vehicles are stored in stations. Empties are distributed according to historical data. An empty scheduled for one station finding that it is not needed upon approach to the station is, if possible, rescheduled to another station. If not, it enters that station. This strategy is known as continuously rescheduled empties.

Station Management - Two station models are examined: parallel and serial berthing. The serial berthing is a single lane configuration, has arrival and departure queues, and a common unload/load platform. The parallel berthing has a common unload/load platform but no arrival or departure queues. Both configurations employ a random dwell time. The movement through the serial berthing model is done in platoon fashion.

A vehicle is rejected when the arrival queue is full. The rejected vehicle goes 'around the block.' The modified synchronous routing strategy permits slot slipping to accommodate the rejected vehicle as it goes around the block. At the appropriate diverge point the other vehicles involved in the slot slipping perturbation are repositioned in their original slots.

4.1.11 Norden (NRDN)

System	P
Focus	SM
Study Type	SY
Control Mode	AS (assumed)

Algorithms

Merge - The merge strategy is random. Speed alteration is used to resolve a conflict.

Empty Vehicle Management - Empty vehicles are stored in the stations. Empties are initially distributed to satisfy a peak 10 minute demand. The empties are distributed by projection of vehicle excesses and deficiencies.

Station Management - The station has separate unload and load platforms. The berths at each platform are parallel. A slack track between the unload and load platforms stores empty vehicles. There are no arrival or departure queues.

The station is given sufficient capacity such that a station overload does not occur. Thus, there is no criterion for vehicle rejection.

Vehicles are berthed in cyclic fashion at both the unload and load platforms. Empty vehicles move from the slack tracks to the load platforms. Empty vehicles destined to another station may bypass the load platform. Empty vehicles entering the station may bypass the unload platform and proceed to the load platform or to the slack track. Empty vehicles move in ripple fashion from the slack track to the load platform control point.

4.1.12 TRW Systems (TRW)

System	DM
Focus	R, M, B
Study Type	SY
Control Mode	SC

Algorithms

Network Routing - The routing strategy is a real time scheduled one with a reservation mode for a cycle from origin to destination. A minimum time route is chosen for an O-D pair. If no cycle reservation is possible for a trip on a minimum time route, then an alternate route is used whose transit time is equal to the minimum time path transit plus the predicted waiting time. The alternate is selected in a route sequence search which reviews a number of paths and examines the reservation possibilities. If a number of searched routes yield no path, the passenger is put in a queue.

Merge Control - The merge strategy is a scheduled one. Merge conflicts are resolved by slot slipping or advancing in a cycle.

Blocked Segment Management - The blockage of a link is considered as an event. Vehicles are rerouted before a diverge point upstream of the blocked link. If new routes cannot be found, the vehicles will be forced off the network and given new routes later. Vehicles caught on the clocked link can be diverted to a temporary entrance which is an installation at the downstream end of each link.

4.1.13 Transportation Systems Center (TSC)

Comments - A number of TSC studies are pertinent to PRT algorithm structure. Many of these are tutorial and in the form of a review at the time they were conducted. These are redundant to this survey effort and therefore are not discussed. One explicit station management study is appropriate for review in this survey.

System	PM
Focus	SM
Study Type	SY
Control Mode	S

Station Management - The station model is a multiple lane one with serial berthing, no queues, and a turnaround capability. Both a common and separate unload/load platform are considered. The study concentrates upon berth assignment rules and considers vehicle cycling for both the common and separate platforms.

4.1.14 University of Minnesota (UM)

System	P
Focus	M, E, SM
Study Type	SY
Control Mode	QS

Algorithms

Network Routing - Route selection is presented primarily in the event of a rerouting requirement at a merge point. At each intersection the vehicle's destination is interrogated where a minimum path table is examined. Thus, the system would have an on-network route alterability where the route alteration may be performed in real time.

Merge Control - The intersection types are both two into one and two into two. The merge strategy is essentially random. Merge conflicts are resolved by slot slipping in the intersection region.

Empty Vehicle Management - Vehicles are distributed on an historical time basis. Empty vehicles are assigned to a station when called and are dispatched empty to make room for entering vehicles. When vehicles are distributed on an historical time basis they are routed to minimize average total empty trip mileage per hour.

Station Management - The station model is a single lane model with arrival and departure queues, serial berthing, and common unload/load platforms. The station dwell time is fixed. Vehicles move through the station in platoon fashion and vehicles are re-jected when the arrival queue is filled.

4.1.15 Varo, Monocab (VARO)

System	PDW
Focus	M, E, SM, B
Study Type	SY
Control Mode	AS (assumed)

Algorithms

Network Routing - The system has a multistop capability. The routing strategy assumed from the control mode is stochastic.

Merge Control - At a merge a line may have higher priority than another one.

Empty Vehicle Management - Empties may be stored in stations or in a facility. Empties are dispatched to a station with a need or by a central control operator. When an empty is required, the proceding stations are searched in sequence until an empty is found. Empty vehicles are moved out of a station to make room for entering loaded vehicles.

Station Management - The station model is a single lane one with an arrival queue, serial berthing, and a common unload/load platform. Vehicles move through the station in ripple fashion. A vehicle is rejected when the station is full. A rejected vehicle takes the shortest return loop to the station.

Blocked Segment Management - The blocked link is considered as an event. The vehicle is stopped when it does not receive or recognize correct instructions from the guideway or from any leading vehicle. A central control operation can restructure the network and reduce speeds on the guideway. A manned maintenance vehicle may be used to correct the blockage.

4.1.16 West Virginia University (WVU)

System	PM
Focus	E
Study Type	SY
Control Mode	S

Algorithms

Network Routing - The system has a multistop character. The routing strategy is a real time scheduled one.

Merge Control - The merge strategy is a scheduled one with no conflicts permitted.

Empty Vehicle Management - The empty vehicle management scheme looks ahead for the next five minutes to estimate empty needs. If the vehicle outflow exceeds inflow, empty vehicles are shuttled around in anticipation of the needs. The closest empty vehicle may be called to the station to service a passenger request.

4.2 SUMMARY TABULATION AND DISCUSSION

This section summarizes, on a set of charts, the types of systems studied and the emphasis of the various efforts. Presenting the material in this manner allows for a concise reference to the alternate algorithms which have been considered. The abbreviations used are those defined in Section 3.

4.2.1 Summary of Control Modes and Document Types

The first level of breakdown for the efforts pursued by the various organizations is simply the type of system studied, the control mode, the major focus areas, and the type of study. At this level there is just one entry for each of the sixteen organizations listed in Figure 3, except that the five MIT thesis efforts are listed separately, giving a total of 20 entries. The later detailed algorithm classification charts refer to all 23 possible groups. Table C-1 gives a summary of the classifications used in Figure 3 and the number of efforts in each area.

Most of the documents are definitely PRT related. The count of 16 includes those dealing with Morgantown and the Dallas-Ft. Worth regional airport. In one instance -- MIT(G) -- the effort may be assumed related to both a PRT merge and a Dual Mode merge. A line haul system was included with the dual mode considerations by FMC.

With regard to the focus of the documents, relatively few concentrate on management of a PRT system when a portion of the system is blocked or inoperative. The focus upon the other four algorithms was essentially evenly divided among the four. In one instance, CLSPN, it was difficult to determine the focus of the effort.

Most of the documents were of the systems study type with only a few concentrating upon tradeoffs. The thesis efforts usually contained some tradeoff elements. However, only MIT(S) was considered to fall distinctly within the tradeoff type.

The synchronous approaches happened to outnumber the others by a margin of eleven to seven. In two instances it was difficult to determine the approach [CLSPN, MIT(M)]. In some instances the approach was not explicitly stated but assumed from the description of the algorithms. This was the case for NRDN and VARO, and, to an extent, MIT(G).

4.2.2 Summary of Algorithms Treated

Figure 4 lists for each organization or group the algorithms that were discussed. Table C-2 provides the corresponding numerical breakdown of this algorithm treatment.

	AERO(1)	AERO(2)	APL(1)	APL(2)	APL(3)	BOE	CLSPN	FMC	GMR	HNY	IBM	JPL	MIT(C)	MIT(M)	MIT(W)	MIT(G)	MIT(S)	NRDN	TRW	TSC	UM	VARO	WVU
System Type	P		P			PM	DM	DM LH	DM	P	P	PM	P	P	P	P DM	P	P	DM	PM	P	PDW	PM
Focus	R,M, SM,B		R, E,B			R,E, SM	--	M	SM	R,M, E,SM	R, R,E	R,M, E,SM	R	R,E	E	M	SM	SM	R, M,B	SM	M,E, SM	M,E SM,B	E
Study Type	SY TR		SY			SY	SY	SY TR	TR	SY	SY	SY	TH	TH	TH	TH	TH TR	SY	SY	SY	SY	SY	SY
Control Mode	QS		AS			S	--	SC	SC	QS	S	S	S	--	S	QS	SM	AS	SC	S	QS	AS	S

Figure 3. Document Type Summary*

*For definition of symbols see Table 6b.

TABLE C-1 NUMERICAL CLASSIFICATION OF DOCUMENT TYPE

	# of Groups
System Type	
PRT Related	16
Morgantown	4
Dallas-Ft. Worth	1
Dual Mode Related	5
Line Haul Related	1
Focus	
Routing	9
Merge	9
Empty Vehicle	9
Station	10
Blocked Segment	4
Study Type	
System	14
Trade	4
Thesis	4
Control Mode	
Synchronous	7
Synchronous, Cycle	3
Synchronous, Modified	1
Quasi-Synchronous	4
Asynchronous	3

Total Number of Groups -- 20

	AERO(1)	AERO(2)	APL(1)	APL(2)	APL(3)	BOE	CLSPN	FMC	GMR	HNY	IBM	JPL	MIT(C)	MIT(M)	MIT(W)	MIT(G)	MIT(S)	NRDN	TRW	TSC	UM	VARO	WVU
Network Routing	✓		✓			✓		✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓
Merge Control	✓		✓					✓	✓	✓	✓	✓				✓		✓	✓		✓	✓	✓
Empty Vehicle Management			✓			✓				✓	✓	✓		✓	✓		✓	✓			✓	✓	✓
Station Management	✓					✓		✓	✓	✓							✓	✓		✓	✓		✓
Blocked Segment Management	✓		✓								✓								✓				✓

Figure 4. Algorithm Treatment Summary

TABLE C-2 NUMERICAL CLASSIFICATION OF ALGORITHM TREATMENT

	# of Groups
Network Routing	16
Merge Control	13
Empty Vehicle Management	12
Station Management	10
Blocked Segment Management	5
Number of Groups Treating Two or More	16
Number of Groups Treating Three or More	13
Number of Groups Treating Four or More	6
Number of Groups Treating All Five	1

Total Number of Groups -- 19

Of all the groups only one treats all five algorithms with sufficient consideration while a third of the groups treat four or more algorithms.

The number treating blocked segment management is larger than the number focusing on blocked segment management (Figure 3). This is due to the addition of IBM as treating blocked segment management without focusing on it.

The number treating station management is less than those treating the other algorithms -- excluding blocked segment management. However, the treatment of station management in a number of instances was more intensive and complete than the treatment of the other algorithms.

4.2.3 Summary of Network Routing Algorithms

Figure 5 summarizes the network routing algorithms by organization. Eighteen organizations or groups are represented. Table C-3 is a numerical classification summary of Figure 5.

The station stop consideration is generally non-stop. The FMC multistop case relates to a line haul system and generally adds little to routing algorithm considerations. The WVU and VARO systems entertain a multistop consideration. In general, most systems, especially those dealing specifically with PRT, employ a nonstop criterion. In a number of instances non or multistop consideration was not stated. It was assumed in the survey that PRT and automated dual mode systems were nonstop operations unless specifically stated otherwise.

In determining the routing strategy it was assumed, where not explicitly stated, that a synchronous system was a real time scheduled system (cf. Section 3.3). A prescheduling routing strategy was ascribed only to those groups that specifically designated a prescheduling strategy. In some instances the stochastic classification was assigned to a group because the control mode implied stochastic, e.g. quasi-synchronous, and not because it was specifically stated. Two of the groups used some

	AERO(1)	AERO(2)	APL(1)	APL(2)	APL(3)	BOE	CLSPN	FMC	GMR	HNY	IBM	JPL	MIT(C)	MIT(N)	MIT(W)	MIT(G)	MIT(S)	NRDN	TRW	TSC	UM	VARO	WVU
Station Stop	NS		NS	NS	NS	NS		MS	NS	NS	NS	NS	NS	NS	NS		NS		NS		NS	MS	MS
Routing Strategy	SMS		SMS	SS	SS	RS			RM-AMS	SS	RS	RS	RS	PS-SS	RS		RS-AMS		RS			SS	RS
Primary Path Considered				YP	YP					YP									YP				
Primary Path Criterion				MDP	MDP					MTP									MTP				
Route Alterability	PRA-ORA		NRA	PRA	PRA-ORA					NRA	PRA-ORA	NRA	PRA						PRA		ORA		
Demand Basis for Route Alteration	HD		HD	RD	RD						RD								RD				
Criteria for Route Alteration	MRA		LRA	LRA	LRA						WRA								WRA		MRA		

Figure 5. Network Routing Summary*
*For definition of symbols see Table 1.

TABLE C-3 NUMERICAL CLASSIFICATION OF NETWORK ROUTING

	# of Groups
Station Stop	18
Routing Strategy	16
Primary Path Considerations	4
Primary Path Criterion	4
Route Alterability	10
Demand Basis for Route Alteration	6
Criterion for Route Alteration	7

Total Number of Groups -- 18

form of arrival metering. MIT(S) specifically suggested it while GMR suggested some form of ordering prior to station arrival in order to accommodate a cyclic berth assignment at a station.

In the route selection it may be imagined that some primary path might be considered prior to selecting an alternate. Since pre-stored minimum distance paths, and, therefore, minimum time paths, are relatively easy to store and use, it might be logical to assume that such primary path considerations would be employed. However, the route selection process could be such that primary paths are melded into the total selection process to the extent that no primary path is considered but that all paths are essentially simultaneously considered. It was, therefore, considered prudent to ascribe a primary path consideration only when explicitly stated. This occured in four instances.

Route alterability in most cases assumed that a number of paths were selectable. Here again, route alterability was ascribed to a group only when explicitly stated. In one case (UM) the route alterability was posed explicitly within the context of path selection upon aborting or missing a turn at an intersection. The same applies to the AERO consideration; however, here a route could also be selected prior to departure based, in part, upon a statistical estimate of merge delays. In the case of IBM the path alterability while on the network is suggested in a statement that dynamic path changes may occur to accommodate emergency occurrences. In this instance, because the simulation was not in full operation at the time of documentation, it may be questioned whether this on-network route alterability was ever implemented or is simply speculative and indicative of a desired operational mode. In a converse sense, the HNY system suggests a non-alterable route selection process but the apparent extent of the simulation would suggest that such alteration could be implemented. In this case it appears that the group (HNY) is presenting a current simulation model and is not suggesting that route non-alterability is a desired characteristic nor that it could not be implemented. Indeed, this latter consideration applies to many of the algorithm descriptions. Usually only tradeoff studies, which recommend one course of two or more, define a desired system operation to the exclusion of others. An example of this occurrence is the comparison of the synchronous vs asynchronous control concepts by APL. In this case an organization characterized by studies of asynchronous systems (Figure 3) adapts the simulation model to the synchronous mode and concludes in a tradeoff study that the synchronous mode is superior under some conditions to the asynchronous one.

Four groups considered route alteration on a real time basis while two considered it on an historical basis. The criterion for real time operation is somewhat subjective. In some cases real time could mean a five minute reporting and processing delay. In general, historical implies time delay measured in terms of hours while real time is in minutes to instantaneous.

4.2.4 Summary of Merge Control Algorithms

Figure 6 summarizes the merge control algorithms by organization or group. Sixteen groups are represented. Table C-4 is a numerical classification of Figure 6.

Four groups are listed as expressing the intersection type. In most of the 16 cases one might assume that those dealing with PRT are implying a two into one (OI) intersection and it probably would be correct to assume that such a classification holds for these groups. However, it was felt that unless the intersection was definitely described, this assumption would not be made. The MIT(G) intersection type is classified as a two into one; however, it could be argued that the analysis also applies to a two into two category. The UM classification of two into one includes a 'tee' intersection on the PRT network model.

The merge strategy may essentially be assumed as a consequence of the control mode. For convenience, the control mode employed by these groups (as listed on Figure 3) are also listed here. Those employing a scheduled merge strategy are associated

	AERO(1)	AERO(2)	APL(1)	APL(2)	APL(3)	BOE	CLSPN	FMC	GMR	HNY	IBM	JPL	MIT(C)	MIT(M)	MIT(W)	MIT(G)	MIT(S)	NRDN	TRW	TSC	UM	VARO	WVU
Intersection Type	TI					OI		OI								OI					OI-TI		
Merge Strategy	PMS		RMS			SMS		SMS-RMS	SMS-RMS	PMS	SMS	SMS				PMS RMS		RMS	SMS-RMS		RMS	PMS	SMS
Conflict Resolution Maneuver	SCR-ACR		SAR					SCR	SCR	SCR	NCR	NCR				SCR-ACR		SAR	SCR-ACR		SCR	SAR	NCR
Maneuvering Region	LMR							LMR													IMR		
Conflict Determination	CD																						
Control Mode	QS		AS					SC	SC	QS	S	S				QS		AS	SC		QS	AS	S

Figure 6. Merge Control Summary*

*For definition of symbols see Table 2.

TABLE C-4 NUMERICAL CLASSIFICATION OF MERGE CONTROL

	# of Groups
Intersection Type	5
Merge Strategy	14
Conflict Determination	1
Conflict Resolution Maneuvers	13
Maneuvering Region	3

Total Number of Groups -- 14

with the synchronous modes. These not associated with a scheduled merge strategy employ either a quasi-synchronous or asynchronous control mode.

The conflict resolution maneuver is also associated with the control mode. In the purely synchronous mode (S) there is no conflict at the merge so no conflict resolution is required. In the synchronous cycle mode (SC) a conflict may exist which could be resolved by slot slipping or advancing within the cycle. In the quasi-synchronous mode a potential conflict may be resolved by slot slipping or advancing. In the asynchronous mode conflicts at the merge may be resolved by altering the speed of the vehicle.

Thus, there is a correlation among the control mode, merge strategy, and conflict resolution. Indeed, from the definition of the control modes it may be assumed that given a control mode the merge strategy and conflict resolution mode may be determined. This correlation was used, in some instances in the survey, to assume what the merge strategy and conflict resolution maneuver would be where it was not explicitly stated and a control mode was given. The priority assignment condition to the merge strategy was used only when stated in the referenced documents.

In only one case was a conflict determination point clearly stated. It is recognized that a potential conflict must first be detected at a point on the network early enough to permit a successful resolution maneuver. Thus, it might be feasible to assign a CD status to all the groups. However, in this reporting function, it was decided to assign a CD status only where explicitly reported.

Three organizations reported on the maneuvering region. The AERO group also reported on maneuvering within the intersection region but discarded it in favor of a link maneuvering region.

4.2.5 Summary of Empty Vehicle Management Algorithms

Figure 7 summarizes the empty vehicle management algorithms by organization or group. Fourteen groups are represented. Table C-5 is a numerical summary of the classification.

	AERO(1)	AERO(2)	APL(1)	APL(2)	APL(3)	BOE	CLSPN	FMC	GMR	HNY	IBM	JPL	MIT(C)	MIT(M)	MIT(P)	MIT(G)	MIT(S)	NRDN	TRW	TSC	UM	VARO	WVU
Storage			SES-NES	SES	SES	SES FES				SES-FES	SES FES NES	SES FES		SES	NES		SES	SES				SES FES	
Distribution Basis			HDB	RDB	RDB	RDB				HDB	HDB						HDB	HDB			HDB	RDB	RDB
Station Criteria for Distribution			SSC	RSC	RSC	SSC				RSC-SSC	RSC	RSC		SSC	RSC		CRE				SSC	RSC-SSC	RSC
Routing Criteria			MSP							MEM											MEM		

Figure 7. Empty Vehicle Management Summary*

*For definition of symbols see Table 3.

TABLE C-5 NUMERICAL CLASSIFICATION OF EMPTY VEHICLE MANAGEMENT

	# of Groups
Storage	12
Distribution Basis	11
Station Criteria for Distribution	13
Routing Criteria	3

Total Number of Groups -- 14

In general most of the groups assume an ability to store in a station. Facility storage is expressed only in a few cases. In a real PRT system operation it may be assumed that some kind of maintenance facility capable of handling vehicles on a scheduled or emergency basis would be available. However, the nature of the studies is such that maintenance or facility storage need not be explicitly considered.

In virtually all instances it may be assumed that an empty may be called by a station with a need. The use of relative station needs represents a level of sophistication upon the simple station call.

The routing criterion for most of the cases would essentially be the same as the routing criterion for a loaded vehicle. The variation occurs for empty vehicles circulating the network and as listed in Figure 7.

4.2.6 Summary of Station Management Algorithms

Figure 8 summarizes the station management algorithms by organization or group. Thirteen groups are represented. Table C-6 is a numerical classification of Figure 8.

In the queues classification it might be safe to assume that where no queues are mentioned there are no provisions for distinct vehicle queuing regions. Hence, this consideration was assigned only when stated or clearly evident.

In some of the considerations there is a slash separating two different conditions, e.g., QM/NQM under MIT(S). This signifies that two different configurations were analyzed and traded off. Thus, in the MIT(S) group a single lane model with arrival and departure queues and serial berthing was evaluated against a single lane model with no queuing regions and parallel berthing.

Two groups (BOE & TSC) considered a turnaround capability characteristic of the Morgantown project. The other Morgantown related studies did not examine station operation details sufficient for reporting in this survey.

	AERO(1)	AERO(2)	APL(1)	APL(2)	APL(3)	BOE	CLSPN	FMC	GMR	HNY	IBM	JPL	MIT(C)	MIT(M)	MIT(W)	MIT(G)	MIT(S)	NRDN	TRW	TSC	UM	VARO
Lane Configuration	SLM	SLM				MLM		SLM	MLM	SLM							SLM	MLM		MLM	SLM	SLM
Queues		QM				NQM		QM		QM							QM/ NQM			NQM	QM	AQM
Berthing	BSM	BSM				BMS		BSM	BSM	BSM							BSM/ BPM	BSM		BSM	BSM	BSM
Unload/Load	SPM	SPM/ CPM				SPM			CPM	CPM							CPM	SPM		CPM/ SPM	CPM	CPM
Turnaround Capability						TCM														TCM		
Passenger Grouping						PGM				PGM												
Dwell Time		RDM				FDM			RDM								RDM				FDM	
Vehicle Movement	CVM	PVM/ RVM				RDM		RVM		RVM							PVM/			/RVM	PVM	RVM
Berth Assignment						BA			BA									BA		BA		
Exit Merge Resolution							EML								EMR							
Vehicle Rejection	VR					VR		VR									VR				VR	VR

Figure 8. Station Management Summary*

*For definition of symbols see Table 4.

TABLE C-6 NUMERICAL CLASSIFICATION OF STATION MANAGEMENT

	# of Groups
Lane Configuration	11
Queues	8
Berthing	11
Unload/load	10
Turnaround Capability	2
Passenger Grouping	3
Dwell Time	4
Vehicle Movement	8
Berth Assignment	4
Exit Merge Resolution	2
Vehicle Rejection	6

Total Number of Groups -- 13

Most of the studies dealing with PRT vehicle management did not consider passenger grouping even though some passenger grouping to common destinations should occur. Indeed, the single case mentioned did not evaluate the effect of passenger grouping upon station management performance measures.

The dwell time was considered to be fixed unless called out explicitly as a random dwell time. In this classification the dwell time was designated only when explicitly described.

The vehicle movement in MIT(S) refers only to the serial berth configuration. In the parallel berth configuration none of the vehicle movement terms would apply.

The CLSPN exit merge resolution consideration is the only contribution that CLSPN makes to this survey. The MIT(W) exit merge resolution complements the MIT(W) contribution to the empty vehicle management and network routing algorithms.

4.2.7 Summary of Blocked Segment Management Algorithms

Figure 9 summarizes the blocked segment management algorithms by organization or group. Five groups are represented. A numerical classification table does not accompany this chart.

Of the five groups one (AERO) includes the dynamics of blockage occurrence as an intergral part of the algorithm. The others assume that a blockage has occurred.

Two groups discuss the detection mode. However, it would be safe to assume that some relatively sophisticated and rapid detection system would be operative in any blocked segment management system.

All the groups undertake some form of network restructuring. Virtually all discuss the rerouting of vehicles on the network and vehicle recovery modes.

	AERO(1)	AERO(2)	APL(1)	APL(2)	APL(3)	BOE	CLSPN	FMC	GMR	HNY	IBM	JPL	MIT(C)	MIT(M)	MIT(W)	MIT(G)	MIT(S)	NRDN	TRW	TSC	UM	VARO
Mode Consideration		DMC	EMC								EMC								EMC			EMC
Detection of Blockage			CBD LCD																			LCD
Network Restructuring		NE	NE								NE								NE			NE
Blockage Location		LBL-MBL																	LBL			
Vehicle Rerouting		RE	RE								RE								RE			
Vehicle Link Recovery		VE	VE								VE								VE			
Stalled Vehicle Recovery		PSR-MSR	MSR								MSR								MSR			MSR

Figure 9. Blocked Segment Management Summary*

*For definition of symbols see Table 5.

5. CONCLUSIONS

5.1 SURVEY APPROACH AND STATISTICS

The objectives of the survey were to establish a data base of PRT vehicle management system algorithms, and to aid in the design of a simulation model to evaluate and develop PRT vehicle management algorithms.

A bibliography that lists relevant documents was assembled and a TSC file of documents selected from the bibliography was established.

In the course of the survey over 240 documents were examined. These documents embraced PRT, dual mode, dial-a-bus, line haul, and conventional transportation systems.

Approximately 55 organizations were identified among the documents reviewed. Fifty-six of these documents were considered pertinent to the PRT vehicle management algorithm survey. Sixteen organizations were surveyed and classified according to algorithm contribution. Because of multiple contributions these 16 organizations were further broken down into 23 contributing groups.

Five general algorithms were identified and subcategorized for survey purposes and each group was classified according to algorithm subcategory contribution. The results of the survey appear in Section 4.0.

5.2 OBSERVATIONS

In a survey of this type it is difficult to draw conclusions primarily because it is a 'first' of its kind. Thus the usual comparisons between a latest survey and previous ones are difficult to make. However, some observations of a subjective, qualitative nature may be made.

1. Very few of the organizations examine all the algorithms extensively against a given system. The single exception is for the relatively simple system.

2. The controversy about the relative control modes is usually couched in heuristic terms. There is a single instance of a direct, simulation comparison of synchronous vs asynchronous from the standpoint of central computer processing. However, even here the results are hedged against what might occur in the event of a blocked segment.

3. The amount of effort devoted to blocked segment management is surprisingly little and skimpy. There does not appear to be any simulation of this algorithm while simulation of the other algorithms is comparatively extensive. This fact is all the more surprising when the management of the system under a blockage is perhaps more difficult and certainly dramatic to the system's users.

This survey report did not compare the different algorithms that were reviewed but simply reported on the alternative approaches that were considered. The context in which each organization presented its algorithms was usually unique to the organization, and detailed results were generally not presented. Thus, performing a comparison and evaluation of differing algorithms would be a formidable effort which is left for a future study.

APPENDIX: REFERENCES

This appendix contains a list of the documents reviewed in the course of the survey.

The documents, in general, are ordered by the organizations whose literature formed the base of the survey. A letter, denoting the class to which each document is assigned, precedes the document description. The symbol and its meaning are listed below.

- M This symbol means that the document is pertinent to the algorithm survey as discussed in the main text.
- S The documents classified by this symbol describe a system aspect of PRT systems. These aspects include general systems studies, economics of transportation systems, demand analysis, and general mathematical documents.
- C The documents classified by this symbol describe general vehicle control aspects. These aspects include vehicle control laws, vehicle dynamics, communication, and equipment configurations.
- P The documents classified by this symbol describe some aspects of computer use. These aspects include computer configuration and computer programming.
- I The documents classified by this symbol describe a specific vehicle system.
- H The documents classified by this symbol deal with human factor aspects.
- D The documents described by this symbol include: presentation material, memos, notes, bibliographies, and general miscellaneous.
- A The documents classified by this symbol deal with minimum path algorithm.

The reviewed documents are preceded by three documents that have been referenced in the text and that are not part of the reviewed material.

Aerospace

M 1. "Quasi Synchronous Control of High-Capacity PRT Networks," National Conference; PRT, April 1972, A. Munson et al.

M 2. "Development Simulation of an Urban Transit System," Summer Computer Simulation Conference, July 1971, A. Munson, T. Travis

M 3. "PRT Station Design and Simulation," International Conference, PRT, May 1973

M 4. "Emergency Strategies for Safe Close-Headway Operation of PRT Vehicles, " National Conference, PRT, April 1972, H. Bernstein, A. Snitt

S 5. "The Economics of High Capacity PRT," National Conference PRT, April 1972, L. Bush

C 6. "An Integrated Concept for Propulsion Braking Control and Switching of Vehicles Operating at Close Headways," National Conference PRT, April 1972, R. Fling, C. Olson

Applied Physics Laboratory, Johns Hopkins University

M 1. "Operating Strategies for Demand-Activated AC GV Systems," Vols. I and II, Roesler et al, August 1971, March 1972

M 2. "Vehicle Management for PRT Systems," Ford et al, 2nd PRT Conference, April 1972

M 3. "Merge Control in PRT Networks," Abstract of paper for 1973 Intersociety Transportation Conference, Denver, September 24-27, 1973

M 4. "Comparisons of Synchronous and Synchronous PRT Vehicle Management and Some Alternative Routine Algorithms," Roesler et al, 2nd PRT Conference, 1973

M 5. "Use and Control of Trains in Personal Rapid Transit Systems," M. Waddell

M 6. "Local Failure and Vehicle Management in a PRT System," M. Waddell, APL/JHU, October 1973

M 7. "Disposition of Empty Vehicles in a Personal Rapid Transit System," M. Waddell, W. Williams, B. Ford

S 8. "Methods for Trip-Time and Cost Computations," B. Ford, W, Roesler, M. Waddell, April 1970

S 9. "Parametric Analysis of Generic Urban Transit Systems," PB 188984, B. Ford, W. Roesler, M. Waddell, December 1969

C 10. "Stability in a String of Vehicles Employing Vehicle Follower Control Systems," MCS-6-153, P. Voss, July 1972

C 11. "Design Considerations for Point Follower Type Vehicle State Control," Abstract of paper for presentation at 1973 PRT Conference, S. Brown

C 12. "Vehicle Models for the Transportation Control Allocation Studies," MCS-3-282, G. Pitts, October 1972

C 13. "Control Considerations for Short Headway AC GV Systems," PB 205013, E. Hinman, October 1971

C 14. "Characteristics of a Linear Regulation Control Law for Vehicles in an Automatic Transit System," CP 009/TPR 020, S. Brown, January 1972

C 15. "Augmented Block Guidance for Short Headway Transportation Systems," CP 019 TPR 023, G. Pitts, September 1972

C 16. "Practical Safety Considerations for Short Headway Automated Transit Systems," Extended abstract of a paper for presentation in 2nd PRT, E. Hinman, G. Pitts.

P 17. "A General Purpose Computer Program for the Dynamic Simulation of Vehicle Guideway Interactions," PB 214339, W. Caywood et al, January 1972

I 18. "Scherer Monobeam Suspension Concept for Mass Transportation. Technical Review of the Baseline Definition," TPR 008, W. Caywood, June 1970

C 19. "Speed and Headway Considerations for the New Urban Demonstration," E. Hinman, G. Pitts, January 1973

H 20. "Human Sensitivity of Whole Body Vibration in Urban Transportation Systems: A Literature Review." R. Haue, May 1970

I 21 "Gravity Vacuum Transit System: Baseline Definition of Airport Access and Corridor Systems," May 1970

I 22. "The Aerial Transit System: Baseline System Definition," APL/JHU, January 1970

I 23. "General Electric Aerial Transport System: A Baseline Definition," APL/JHU, May 1970

I 24. "Scherer Monobeam Suspension Concept of Mass Transportation," Scherer Monobeam Company, May 1970

I 25. "Evaluation of the Varo Monocab Fixed Block Headway Control System," J. Wildes, March 1970

Boeing

M 1. Frank Burns & Leroy Moen, "Vehicle Management Rules," internal Boeing memorandum, Feb. 1973.

S 2. Performance/Design and Qualification for the Morgantown Operational Personal Rapid Transit System, Boeing, Nov. 1973

Calspan

M 1. "Bimodal Urban Transportation System Study, Vol. 1 -- March 1968; Vol. II - March 1968; Vol. III - May 1968"

A 2. "A Sequential Deletion Algorithm for the Design of Optimal Transportation Networks," A. O'Connor et al., April 1970

C 3. "Dynamics of Automobiles During Brake Application -- Validation of a Computer Simulation," R.A. Piziali, July 1971

S 4. "A Functional Analysis of Command and Control for Urban Guideway Transportation Systems, C.A. Miller, March 1973

S 5. "Guideway Transportation System Requirements for Dual Mode and Personal Rapid Transit Systems," C.A. Miller, May 1973

D 6. "Some Sources of Information on Guideway Transportation Systems", C.A. Miller, Spring 1973

D 7. "Bibliography of Sources of Information on the Urban Transportation Problem," C.A. Miller, April 1973

S 8. "Urban Travel Patterns," C.A. Miller, April 1973

S 9. "Synthesis of New Ground Transportation Systems," C.A. Miller, March 1973 (DOT Restricted)

C 10. Kinematics of the Emergency Braking of Cascaded Guideway Vehicles," C.A. Miller (undated)

D 11. "Air and Noise Pollution Aspects of Urban Transportation," C.A. Miller, April 1973

D 12. "The Petroleum Crunch as a Factor in the Development of Urban Guideway Transportation Systems," C.A. Miller, April 1973

Ford Motor Company

M 1. "Network Implications on Control System Design," (71-4), R. Stefanek

M 2. "Network Effects on the Interface Problem for a Dual Mode Transportation System," (71-8), June 1971, R. Stefanek

M 3. "Evaluation of the Operating Conditions on a Detroit Dual Mode Vehicle Network," (71-15), October 1971, R. Stefanek, and S. Kiselewich

M 4. "An Analysis of Interchange Operation in an Urban Automated Transportation Network," (71-12 Rev), August 1971, S. Kiselewich and R. Stefanek

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C 5. "PRT Performance Requirements and Allocation," D. Smith, V. Yormack, April 1972

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P 5. User's Guide to NGPSS

P 6. Typical Graphics Output

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D 5. "Chapter II Documentation Standards"

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