A Model for the Test & Evaluation of Advanced Group Rapid Transit (AGRT) Systems

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Abstract

The design and evaluation of the Central Management System (CMS) for an Advanced Group Rapid Transit (AGRT) system is a very complex undertaking. The CMS is responsible for the routing and scheduling of hundreds of vehicles and for the making of thousands of passenger-vehicle assignments per hour in order to transport passengers between the various guideway stations in the network. This volume of decision making, coupled with the level of detail and complexity commonly found in CMS algorithms, forces the system designer/evaluator to employ computational tools to assist him in his work.

This paper describes such an analysis tool. The results of applying this discrete-event simulator to an illustrative AGRT network have been previously described (5).

The simulator actually encompasses two different systems. One system models the actual decision logic of the CMS algorithms. Thus, vehicle locations and waiting passengers are tracked at all times, and the appropriate vehicle routings and passenger-vehicle assignments are made.

The other system must model the effects of the vehicle control system. Otherwise, vehicle locations would not be properly identified for the CMS decision algorithms. Normally, the accurate tracking of vehicle locations involves the maintenance and frequent recalculation of vehicle velocities and accelerations. This volume of calculation causes the simulation to execute slowly, to be expensive, and hence to be considered ineffective in studying CMS-level problems.

Our approach permits vehicle positions to be updated accurately at only those points where the information is needed for decision making, significantly reducing computational requirements. The foundations of our approach are set forth in the paper, so that other investigators may apply this technique.

The simulator is designed to accommodate a very broad range of network configurations, traffic loads, vehicle populations, and operating policies via parametric adjustments, so that this tool can be used by a broad community of investigators.

I. Introduction

The Advanced Group Rapid Transit (AGRT) system is intended to provide individualized, origin-destination transportation service across a fixed-guideway network through the use of advanced computer technology. From the time a passenger enters the system until he departs at his destination, his travel desires are scheduled and controlled by the computer. The computer arranges for a vehicle to pick up the passenger with a minimum of waiting at the origin station, organizes a route through the network that seeks to minimize both travel time and number of intermediate stops, controls the movements of his vehicle as it transverses the network, and monitors the entire system to assure efficient equipment utilization and proper levels of passenger service.

The Central Management System (CMS) is responsible for the minute-by-minute routing and scheduling decisions for hundreds of small, computer controlled vehicles and for the making of thousands of passenger-vehicle trip assignments per hour. On the network studied, vehicles were moving along the guideways at 4 to 6 second headways and up to 10,000 passengers per hour were seeking service. In addition, the CMS must continuously provide profiles for desired vehicle movements to the vehicle control computer system and receive updated vehicle location information from the control system. The volume of decision making required of the CMS, coupled with the level of detail and complexity commonly found in CMS allocation algorithms, makes the design and evaluation of central management systems a very complex undertaking. The use of computational assistance by the designer/evaluator is a necessity. Although no single criterion of efficiency can be realistically defined, computer-generated performance measures such as the following can be used by the designer to compare various alternative vehicle

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and passenger management strategies:

- Waiting and trip times of passengers.
- Number of intermediate stops between various O/D pairs.
- Deviations from shortest distance routes between O/D pairs.
- Vehicle fleet size required.
- Vehicle flows on links and in stations.
- Delays under failure conditions.
- Capital and operating costs.

As part of an AGRT design study sponsored by the Urban Mass Transit Administration (UMTA), SRI International subcontracted to Rohr Industries to develop a CMS simulator that could be used to test and evaluate various CMS strategies (1). This paper describes the simulator that was developed, some of the design approaches underlying its construction, and some of the benefits that were obtained through its use. Further details of the simulator are contained in references 2, 3, and 4; further descriptions of the AGRT network and CMS strategy evaluations are contained in references 1 and 5.

II. The Role of simulation in central management system evaluation

Fundamentally, the objective of central management in an AGRT system can be stated as follows: Given a guideway network in terms of the origin-destination (O/D) nodes (passenger stations) and the connecting links (guideway), and given the O/D demand data of passengers and the capacity of AGRT vehicles, operate the network equipment efficiently while serving the passengers' service needs promptly.

The design alternatives available to the designer of a central management system essentially consist of two types of design variables:

(1) Planning variables: variables which must be defined early in the design process (e.g., station sizes, turnarounds, bypasses, live and dead storages, total fleet size)

(2) Operating variables: variables that can be adjusted dynamically once the AGRT system has been constructed (e.g., stopping policies, vehicle assignment policies, vehicle routing policies, operating fleet size)

The number of possible ways of combining these design variables is obviously very large and requires considerable human judgment. On the other hand, calculation of various performance measures mentioned above for different combinations of design variables is an exceedingly difficult and laborious process, if performed manually.

Additionally, some of the major central management problems of AGRT systems relate to interactions between many vehicles moving through a large network of guideways and stations. While the individual effects of one system element on another at the microscopic level are readily understood (e.g., single vehicle-to-vehicle interactions), the number of system interactions in a large network with many vehicles introduces too much complexity. System behavior cannot be comprehended easily, and it cannot simply be extrapolated from understandings at the microscopic level.

In view of these considerations, a methodology was needed in which complex judgmental decisions (such as defining alternative stopping policies, choosing between demand responsive and special service requests) could be made by experienced transit system operators, and the extensive and repetitive calculations needed to calculate various performance measures (such as passenger waiting times, travel times, link and station flows) could be performed by a computer.

A computer simulation is a very appropriate method to study CMS problems, since a computer simulation can efficiently and accurately keep track of the consequences of a large number of simple interactions such as those occurring in an AGRT system. Furthermore, a computer simulation of the CMS algorithms allows the analyst to investigate problems and test alternatives which would be too costly to investigate using engineering prototypes or mockups. Since software can be more easily modified than hardware, and since an efficiently designed CMS simulation will run much faster than real time, parametric sensitivity studies and design modifications can be inexpensively and quickly made and analyzed.

The Central Management System simulation program described herein, was developed to serve these goals and did enable the Rohr/SRI design team to test and evaluate a variety of CMS strategies and AGRT network design variables. As a result of the feedback provided by the simulator, a very efficient set of central management strategies was constructed.

III. Overview of the CMS Simulation Model

The CMS Simulation model was specifically designed to facilitate the analysis and evaluation of central management strategies employed in a large, deployed AGRT network. As a result, the basic capabilities required of the simulator focus on those decision-making functions that are to be performed by the central management system. These major functions are:

- The efficient routing of vehicles through the network
- The assignment of an appropriate vehicle to a party requesting service
- The appropriate dispatching of vehicles into and out of stations
- The distribution of empty vehicles to locations where needed
- The effective management of network congestion and system failures.

A. Implementation Requirements

The implementation of these functional capabilities required that sufficient detail be incorporated into the representation of the guideway network and of vehicle and passenger movements to reflect system-level behaviors accurately. On the other hand, in order for the resultant simulation model to be an effective analysis tool, it had to be relatively inexpensive to execute. This required that attention be paid to making appropriate simplifications and approximations wherever possible and that execution efficiency be included as one of the technical design goals.

Combining the requirements for the CMS simulation at both the functional and technical levels produced the following set of characteristics which the implementation has met:

- The geometry and limitations of the AGRT network to be simulated are completely specifiable as input data to the model (rather than imbedded within the program itself), so that all guideway connections, speed limits, zone memberships, and the like can be provided as input parameters.
- Vehicle guideway position information is furnished only to the link level, which is sufficient so long as proper vehicle headways and link exit times are enforced at the point of each link to link transition on the guideway.
- Passenger vehicle assignments and passenger movements through the network are tracked down to the individual vehicle level.
- The operation of intermixed trained and non-trained vehicles over the guideway is properly reflected, with such details as longer switch clearance times for trained vehicles being taken care of automatically and with the length of each vehicle train being adjustable parametrically.
- Demand-responsive vehicle operations, routed service operations, as well as any combination of these two forms of operation, are permitted.
- Detailed routing decisions for vehicles (including responses to congestion, failures, and diversions for additional passengers) are adjustable and controllable via parameter changes rather than via program changes.
- Vehicle merge behaviors at guideway merge points may be controlled parametrically.
- Simulation model status may be checkpointed at any time, so that simulation status after an initialization run can be subsequently reused as the starting point for several different runs without having to re-execute the initialization sequence.

Throughout the specifications for the implementation of these capabilities, attention was directed toward the representation or modeling of the effective behavior of vehicles and passengers in an AGRT network rather than toward the explicit modeling of the detailed, underlying behaviors. This focus permitted the construction of a simulation that faithfully reflects the observable behavior of AGRT systems at the level at which measurement and performance data are required. At the same time, by avoiding the need to model every aspect of the underlying vehicle behaviors, it was possible to achieve significant computational efficiencies. These computational efficiencies, coupled with the model's flexibility, have resulted in a tool which can efficiently and effectively assist designers in the testing and analysis of system algorithm performance in an AGRT environment.

B. Simulator Structure

The Central Management System simulation is structured modularly with a main program that controls initialization and execution of the simulation. Fifty-seven additional functions and subroutines, each performing one specific task, form the body of the simulation. All told, approximately 6000 lines of commented Fortran code comprise the simulator. Data about the status of the simulated AGRT system and its passengers are contained in tables (located in Fortran Common) that are accessed and altered by the various program modules as necessary.

The simulator was designed so that it is possible to model a large number of different network configurations without revision of the program. However, some restrictions are imposed by the Fortran programming language which requires that the sizes of the common data tables be declared at compile time. In most cases, these limitations can be relaxed merely by redimensioning the appropriate variables in the affected Fortran common block and changing an input data parameter to indicate the new table size.

The basic structure of the simulation model is shown in the flowchart in Figure 1. Execution of the simulation begins with the initialization of variables and the input data specifying the AGRT system to be modeled. An extensive set of checks on the validity of the input data is then performed. The simulation will terminate after all checks have been performed if any input data errors are detected.

The simulation is a discrete-event simulation, which stores events scheduled to occur in the future in a time-ordered event list. The event which will occur next in time is removed from the event list, and time in the simulated system is then advanced to the time at which that event was to occur. The appropriate event-processing routine to simulate the actual occurrence of the event is then called. Five types of events may be scheduled in the simulator: (1) the arrival of a vehicle at the end of a link, (2) the departure of a vehicle from a station, (3) the entry of a passenger party into the system, (4) the occurrence of a central management scan which performs periodic central management functions, and (5) the occurrence of an exogenous event (which is a user-specified event occurring outside of normal system processing). The processing of each event concludes with the scheduling of the next event of that same type that will occur. Simulation processing continues until an end-of-simulation exogenous event occurs.

IV. Principal Models

The CMS simulator is intended to model the CMS system, but in actuality it must model the AGRT system from two perspectives. First, as described above, it must reflect the CMS decision logic (e.g., the allocation and scheduling algorithms). Thus, many of the principal models within the simulator are designed to duplicate the CMS decision-making with respect to vehicle routing, passenger-vehicle assignments, congestion management, and so forth.

Second, the simulator must reflect the underlying vehicle control systems actions. Although the actions of the vehicle control system are not an objective per sé of the simulator, these actions must be reflected in the simulator if the information on vehicle locations (upon which many of the CMS algorithms depend) is to be accurately maintained. Thus, of necessity, some of the principal models of the simulator are concerned with aspects of the vehicle control system.

The purpose of each of the principal models of the simulator are identified in the following two sections. For illustrative purposes, one model of each type (CMS and vehicle control) is described in further detail.

A. Central Management System Functional Models

Each of the functional models listed in Table 1 performs one (or a portion of one) of the basic CMS functions listed at the beginning of Section III.

The Trip Assignment model has been selected to illustrate the CMS functional models because it shows some of the interactions that take place between the passenger and vehicle systems. Basically, Trip Assignment is called upon each time a passenger enters the system (arrives at a station) and makes a trip request. The function of trip assignment is to locate the "best" vehicle to assign to serve that passenger trip.

The major parameters involved in the trip assignment function are:

- The search region of links and stations associated with the requesting station
- The search priority of each vehicle type
- The compatibility of the vehicle (in terms of the planned stops for assigned passengers) with this trip request

The designer, as a part of the input data, specifies a vehicle search region for each requesting station in terms of the upstream links and stations which should be searched for vehicles that might satisfy the trip request. The program is designed to search for vehicles sequentially in the specified links and stations.

All vehicles in the system may be classified into five types for the trip assignment process:

- Special service route vehicles
- Empty vehicles
- Vehicles that will become empty at the requesting station
- Vehicles that will stop at the requesting origin station or at the requested destination station
- Loaded vehicles that would not otherwise stop at origin or destination

The designer also specifies, in the input data, the relative priority of each type of vehicle in the search process (e.g., first look for a vehicle that will stop at the requesting station or stop at the requested destination; if no such vehicle is found, look for a vehicle to become empty, and so on). The program is designed to search for the best vehicles in the specified capture region. Each capture region can be decomposed into subsets, and different vehicle search priorities can be specified for each subset. The point of division between the two capture regions can also be made to vary with the level of demand from the passenger's origin to his requested destination.

When a vehicle of a higher priority than any previously acceptable vehicle is found, a test is made to ensure that assignment of this vehicle to

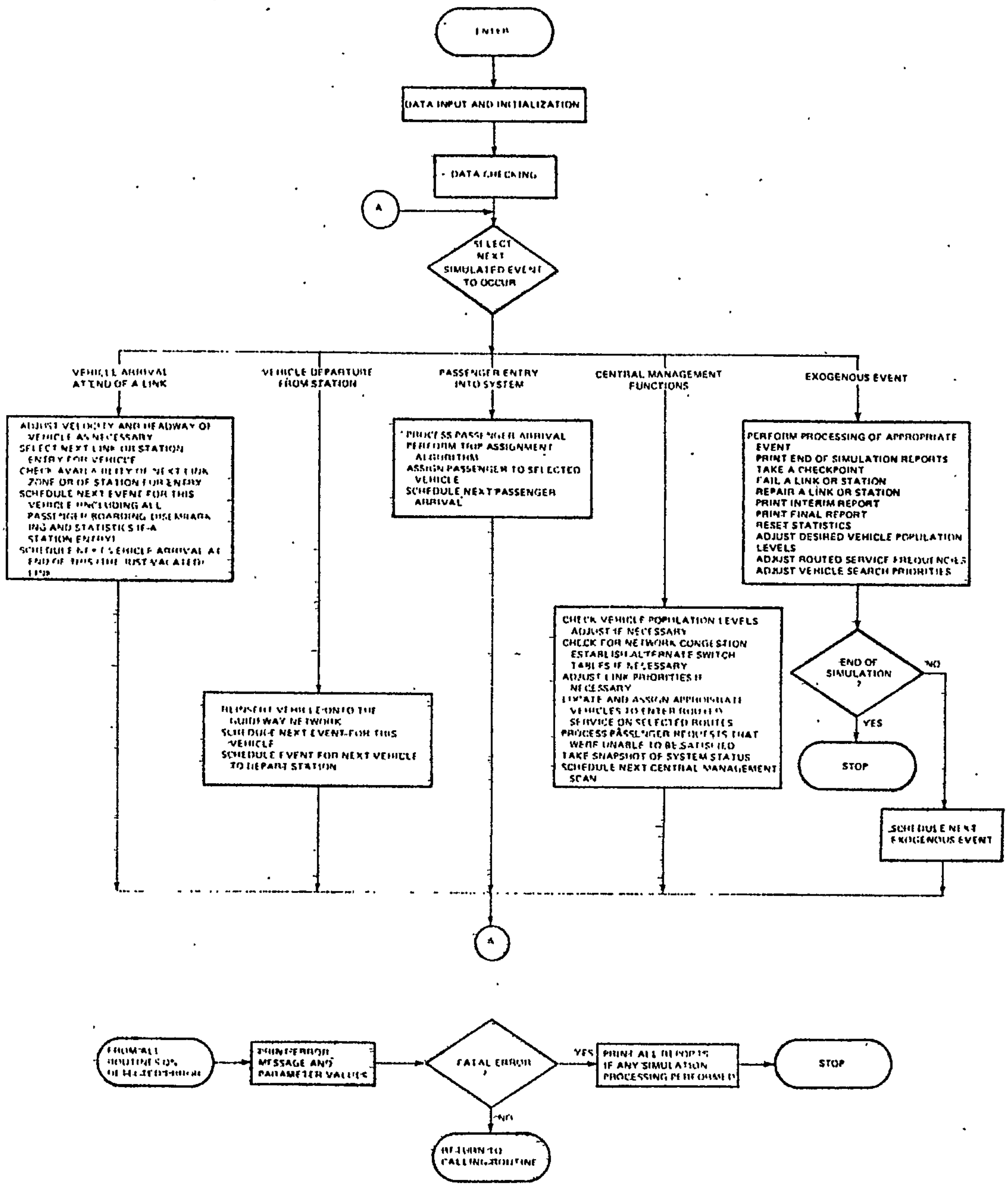


Figure 1. Flowchart of the Central Management System Simulation

TABLE 1

OVERVIEW OF THE PRINCIPAL MODELS OF THE CENTRAL MANAGEMENT SYSTEM FUNCTIONS

FUNCTIONAL MODEL	PURPOSE
1. STATION MODELS	
A. Passenger — Station Interface	To model the interface (interaction) between the passenger and the station.
B. Gate	To model the interface (interaction) between the boarding passengers and the vehicle at the station.
C. Vehicle — Station Interface	To model the interface between the station and the vehicle.
D. Station Dispatching	To determine when vehicles can enter a station or depart a station berth.
2. VEHICLE MANAGEMENT MODELS	
A. Trip Assignment	To model the assignment of vehicles to serve passenger trip requests.
B. Empty-Vehicle Distribution	To model the disposition of empty unassigned vehicles.
C. Routed Vehicle	To model the operation of routed vehicles.
D. Vehicle Training	To model the potential for vehicle training.
E. Zone Management	To model the effects of zone capacity limitations.
3. NETWORK MODELS	
A. Network Configuration	To describe and specify a network complete with links, switches, speed limits, and stations.
B. Network Status	To provide information on link, zone, and station loading for purposes of traffic flow management.
C. Central Scan	To model the central scan (periodically performed) functions of the central management system, as opposed to the "event-triggered" functions.
4. ALARM	To alert the vehicle management systems of the occurrence of, as well as the repair of, gross, system-level emergency situations which affect system operation.
5. CONGESTION MANAGEMENT	To model the strategies for dealing with link and zone congestion.
6. FAILURE MANAGEMENT	To model failures and repairs of vehicles, links, stations, or zones.
7. PERFORMANCE MEASURES AND STATISTICS GENERATION	To provide performance measures and statistics relative to the performance of the simulated network.

the present trip request will not create any route incompatibility or vehicle overloading problems and will not violate any specified constraints for maximum allowable stops of passengers already assigned to that vehicle. If route compatibility is assured and no stop constraints are violated, the vehicle becomes the best acceptable vehicle. If the vehicle is of the highest search priority, it is immediately assigned to the trip request. Otherwise, the search continues to the end of the search region, whereupon the most acceptable vehicle found in the region is assigned to the request. If no acceptable vehicle is found in the specified capture regions, an empty vehicle is called from an appropriate vehicle storage area. The flow diagram in Figure 2 gives further details of the trip assignment function.

B. Vehicle Control System Models

Each of the control models listed in Table 2 performs one of the basic vehicle control system functions.

The Longitudinal/Headway Control model has been selected to illustrate the vehicle control models because it demonstrates the simplified approach developed for modeling vehicle movements. Normally the accurate modeling of vehicle movements would require the maintenance and frequent (e.g., several times each simulated second) recalculation of vehicle velocities and accelerations. However, this level of computation, given the number of vehicles involved in an AGRT network, would cause the simulator to execute very slowly. As a result, it would be expensive to operate and would be considered ineffective in studying problems at the CMS level.

However, simplification is possible in our model, because the CMS algorithms require only the identification of the correct link (guideway section) on which the vehicle is located. Thus, the vehicle control model need only insure that the vehicle leaves each link at the proper time and with the proper velocity. It does this by means of calculations based upon the departure time of the previous vehicle to exit the link and a velocity-headway curve giving the required time separation between vehicles as a function of vehicle velocity. This process is illustrated in Figure 3.

A Vehicle V_A departing link 1 and entering link 2 will adjust speed (if necessary) to the civil speed limit in link 2 and proceed to traverse the link at the maximum permissible speed. It will continue at this velocity until a) it reaches the end of the link or b) it catches up with a slower vehicle, in which case it will decelerate and trail the other vehicle at a safe headway.

At the time a vehicle V_A actually departs link 1 and enters link 2, a tentative arrival time is calculated based upon the earliest time that vehicle V_A could arrive at the end of link 2. With the tentative scheduling of this vehicle, it is necessary to determine when the next vehicle V_B will arrive at the end of link 1. The arrival time of the next vehicle V_B will be the greater of a) the originally scheduled arrival time (the vehicle did not catch up with the preceding vehicle V_A), or b) the current time plus the appropriate operating headway (the vehicle did catch up with the preceding vehicle V_A and is following it at an operating headway's separation).

The calculation of the value of the operating headway to be used is based upon the vehicle flows on the link just traversed (link 1) and the next link to be traversed (link 2). The velocity for link 1 is estimated based upon the time that was actually required by the preceding vehicle V_A to traverse the link; the velocity for link 2 is estimated based upon the current vehicle density existing in that link. A velocity-headway curve of the form shown in Figure 4 is then used to determine the operating headways on each link. The headway that will be controlling at the junction between the two links will depend upon the link velocities and the relative values of the calculated headways.

Table 3 lists the conditions under which each link's calculated headway will control. For example, if the velocities on each link are greater than the minimum headway velocity v_c and the calculated headway for link 2 is greater than that for link 1, the link 1 headway will be controlling and will be used in calculating the possible arrival time of the next vehicle V_B at the end of link 1. That is to say, vehicles exiting link 1 will speed up in link 2. As they speed up, they will develop larger operating headways. However, this effect is a forward moving effect, so that vehicles can continue to cross the link 1 - link 2 boundary at the link 1 operating headway. (As vehicles continue to cross at this rate, however, velocity will decrease on link 2 due to increasing congestion, leading in time to a reduction of the link 2 headway to the link 1 headway value).

Once a vehicle arrives at the end of a link as scheduled by the above described calculations, it is potentially ready to enter the next link. However, other algorithms are also applied (e.g., merge control) that may result in further delays before the vehicle actually departs one link and enters the next.

V. Use of the CMS Simulator

The CMS simulator was used by transportation analysts at SRI and at Rohr to design an AGRT network and to develop a set of efficient CMS operating policies for that network. A basic environment was specified by UMTA, consisting of station locations and passenger trip demands over the course of a 24-hour day.

Operating iteratively with the simulator, network configurations (switches, turnarounds, vehicle storage locations) were developed and various CMS strategies were then developed for use with that network configuration. Figure 5 shows the configuration of the basic network which was used in the studies.

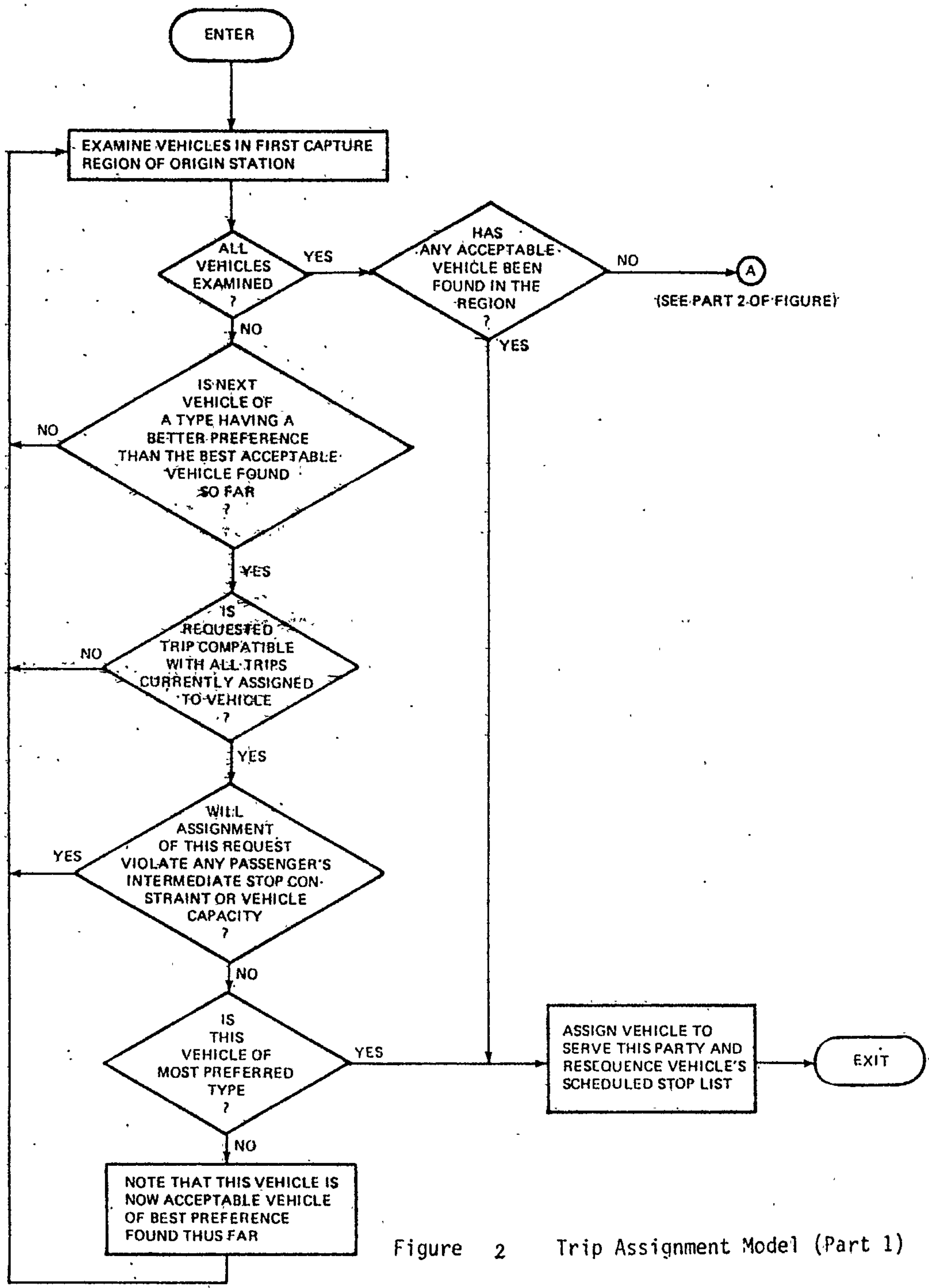


Figure 2 Trip Assignment Model (Part 1)

PERFORM FOR EACH TRIP REQUEST

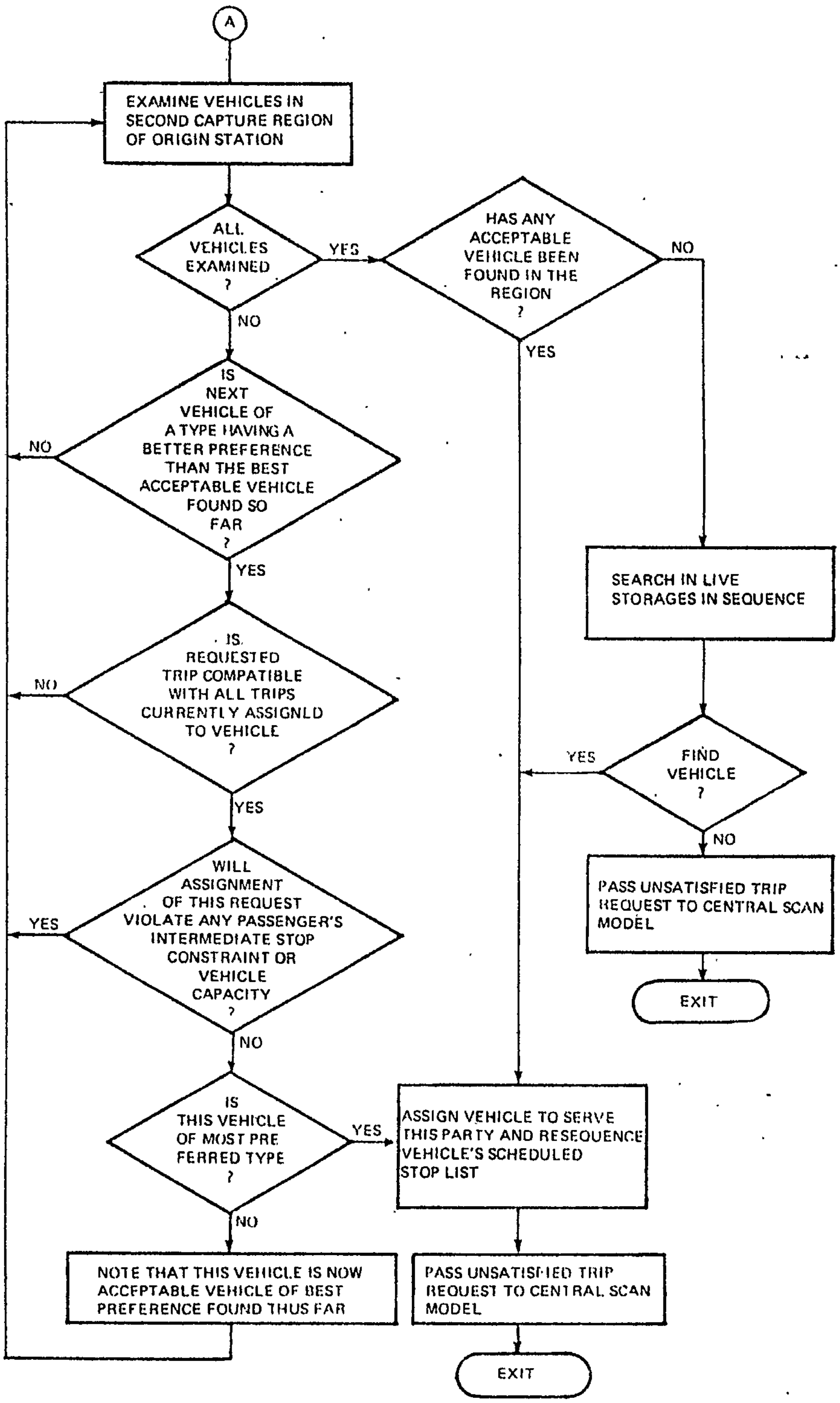


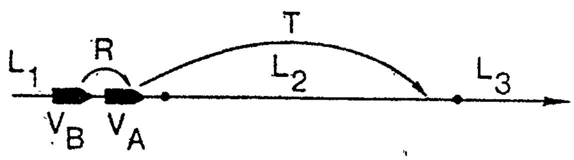
Figure 2 Trip Assignment Model (Part 2)

TABLE 2

OVERVIEW OF THE PRINCIPAL MODELS OF THE VEHICLE CONTROL SYSTEM FUNCTIONS

MODEL	PURPOSE
Longitudinal/Headway Control	To ensure that proper headway is maintained between vehicles on the guideway
Merge Switch Control	To control the merging of vehicles at switch points
Demerge Switch Control	To control the routing of vehicles through the system
Vehicle Position and Velocity	To maintain the link position and the scheduled link transit time for all vehicles

VEHICLE MOVEMENT - LINK



When vehicle V_A leaves link L_1 at time t:

V_A scheduled to arrive at end of L_2 at $t + T$

V_B rescheduled to arrive at end of L_1 at maximum ($t + R$, originally scheduled arrival time)

T = transit time = f (link length, link speed limit, vehicle velocity)

R = replacement time = f (vehicle velocities and headways on link L_1 & L_2)

Figure 3 Vehicle Movement in Links

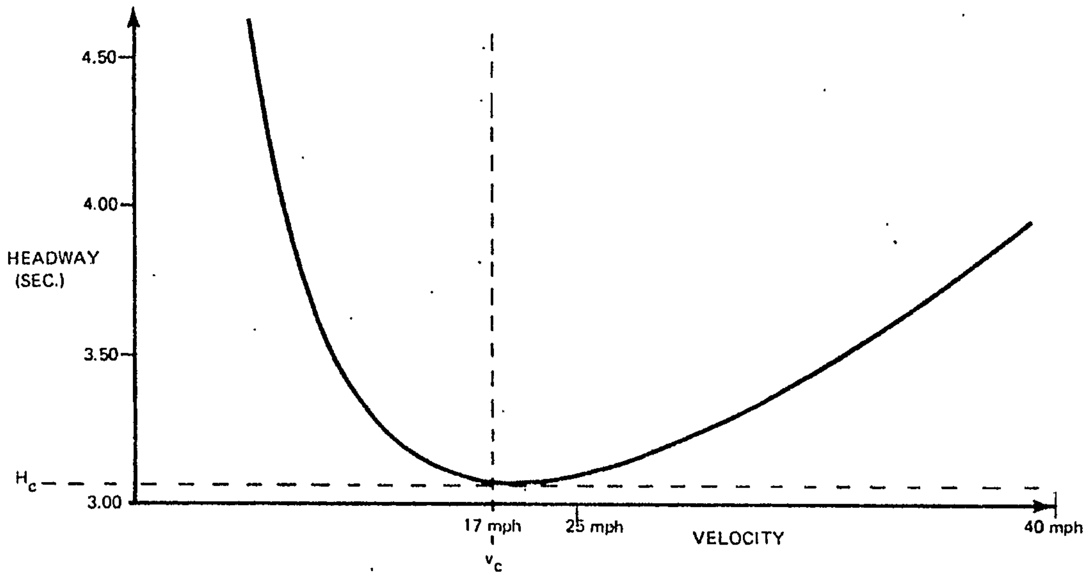


Figure 4 Typical Velocity - Headway Curve

TABLE 3
SELECTION OF CONTROLLING HEADWAY AT THE JUNCTION OF TWO LINKS

CONDITIONS	DIRECTION OF EFFECT	CONTROLLING HEADWAY
$(v_1, v_2) \geq v_c$, $H_1 \leq H_2$	FORWARD	H_1
$(v_1, v_2) \geq v_c$, $H_1 > H_2$	FORWARD	H_1
$(v_1, v_2) < v_c$, $H_1 \leq H_2$	BACKWARD	H_2
$(v_1, v_2) < v_c$, $H_1 > H_2$	BACKWARD	H_2
$(v_1 \leq v_c)$, $(v_2 \geq v_c)$, $H_1 \leq H_2$	FORWARD	H_c
$(v_1 \leq v_c)$, $(v_2 \geq v_c)$, $H_1 > H_2$	BACKWARD	H_c
$(v_1 > v_c)$, $(v_2 \leq v_c)$, $H_1 \leq H_2$	BACKWARD	H_2
$(v_1 > v_c)$, $(v_2 \leq v_c)$, $H_1 > H_2$	FORWARD	H_1

WHERE: V_C = MINIMUM HEADWAY VELOCITY
V_1 = VELOCITY ON LINK 1
V_2 = VELOCITY ON LINK 2
AND H_C = MINIMUM HEADWAY
H_1 = LINK 1 HEADWAY
H_2 = LINK 2 HEADWAY

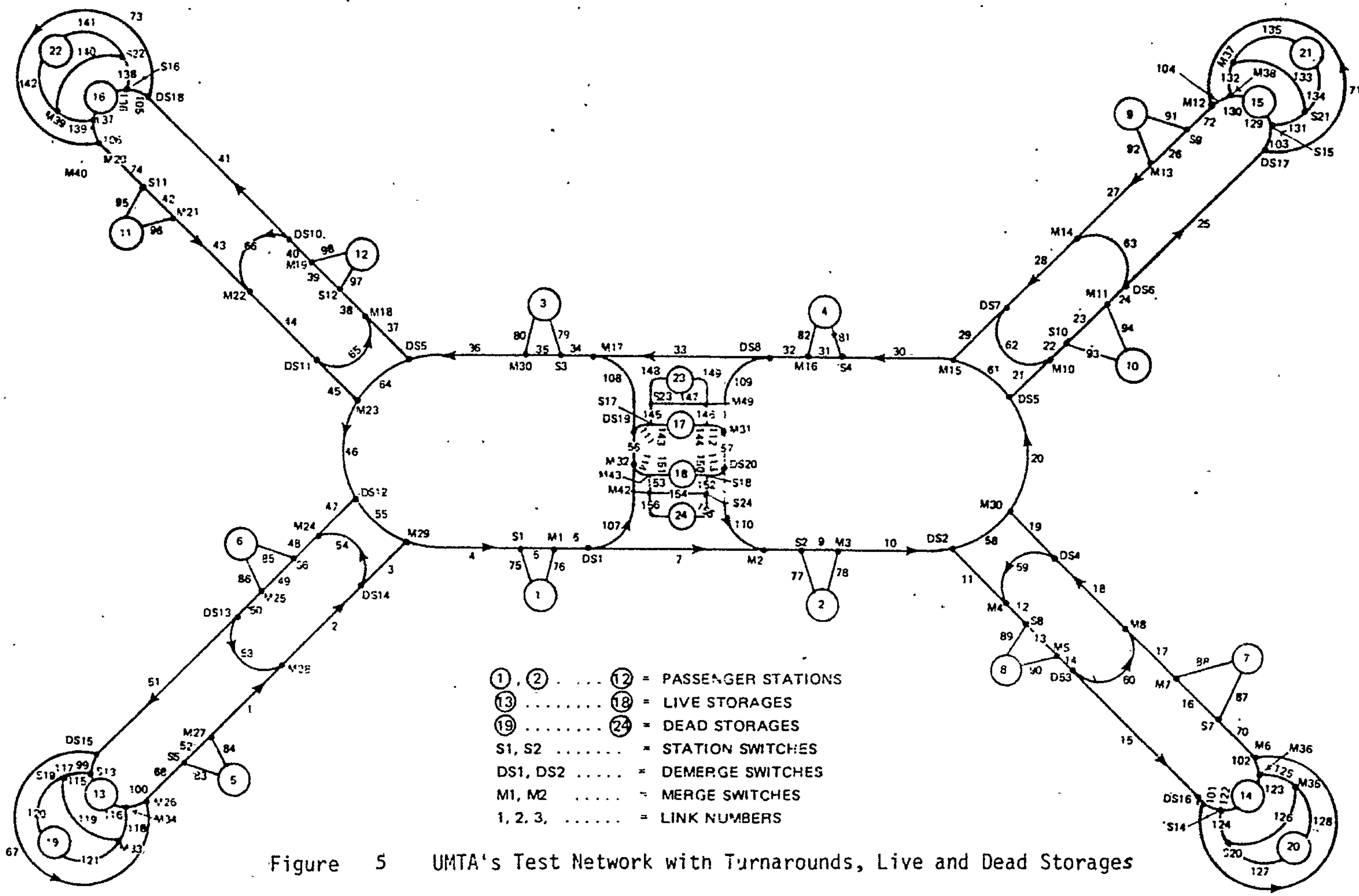


Figure 5 UMTA's Test Network with Turnarounds, Live and Dead Storages

The CMS strategy experimentation focused upon the specification of vehicle capture regions for each station, of vehicle search and assignment strategies, of permissible stops between various origin-destination pairs, and of vehicle routes and route service requirements. Experiments were also conducted to determine the effect of vehicle fleet size variations upon the strategies to be employed and upon the passenger service levels achieved. A more detailed discussion of the experiments conducted and the strategies developed, as well as of the passenger service and network performance levels achieved, has been described previously (5).

The model permitted a number of more general conclusions to be reached concerning AGRT networks. In particular:

- Demand responsive passenger-vehicle assignment strategies (as opposed to the scheduling of vehicles to transverse fixed runs at predetermined intervals) proved to be very effective.
- Significant demand increases can be accommodated by the system before serious degradation (due to vehicle congestion) results. Further, the system appears to degrade gracefully as demand is increased to higher and higher levels.
- Under normal operating conditions and with standard vehicle utilizations, most passengers can be served with a mean wait time of less than 5 minutes during periods of peak demand.
- A variety of trade-offs are possible between fleet size, passenger waiting time in the station, and passenger transit time on board a vehicle.

Although the AGRT design work performed by SRI was in connection with the test network shown in Figure 5, none of that network's specific characteristics were programmed or designed into the simulator. Network configuration and operating restrictions were all specified parametrically via input data. Thus, the simulator can be used without modification to investigate quite different network configurations.

The system designer also enjoys a great deal of flexibility in specifying CMS strategies, for these too are specified parametrically rather than via program changes. Service constraints, vehicle search priorities, search regions to be associated with stations, and origin-destination intermediate stops, among other considerations, are all specified as input data.

Thus, the simulator developed for this project is quite general, and may be used by other designers to assist them in their analysis of a variety of AGRT and AGRT-like systems.

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