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A simulation model for evaluating advanced dial-a-ride paratransit systems

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Abstract

This paper presents a simulation system that has been developed to model a variety of technology-oriented dial-a-ride paratransit systems operated in an urban environment. The latest advances in information technologies such as automatic vehicle location (AVL), digital telecommunication and computers have afforded a unique opportunity for public transit agencies to integrate these technologies in their paratransit systems for improved productivity and reliability. This opportunity has also prompted wide spread interest in quantifying the actual benefits that can be attained from such technological enhancement. The primary objective of the simulation model described in this paper was to facilitate the evaluation of the potential effects that these technologies may bring on a paratransit system. The paper discusses the general concepts, models and computational techniques applied in the simulation system, focusing on how various components are modeled and how they interact with each other in the overall simulation framework. The simulation system is applied to evaluate the potential operational improvement that may be attained from the application of automatic vehicle location technology.

1. Introduction

Dial-a-ride paratransit, also called demand responsive transit, plays a vital role in North America in providing equitable transportation service to a special group of population such as the elderly and handicapped who have difficulties to access regular public transit system (Cervero, 1997). Different from regular fixed-route transit, paratransit commonly uses small to medium sized vehicles to provide shared-ride, door-to-door services with flexible routes and schedules. Due to its taxi-like service approach with a fare scheme comparable to regular transit, most paratransit

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systems in North America rely heavily on subsidization. In the United States, the total operating expenses of paratransit service exceeded 1.2 billion dollars with only 173 million dollars collected in fares, as reported by the American Public Transit Association. According to the Canadian Urban Transit Association, the total operating expenses of 50 Canadian paratransit agencies in 1997 amounted to 146.5 million dollars, of which only 10% was recovered from fare revenues and the rest 90% was subsidized.

As an attempt to find a solution to mitigate this problem, many transit agencies are turning to advanced information technologies such as automatic vehicle location (AVL), digital telecommunication and computers. With the ability to track vehicle locations, communicate with drivers and clients, and access traffic information on a continuous basis, paratransit systems are expected to operate at a significantly improved level of productivity and reliability (Teal, 1993; Stone et al., 1993; Lave et al., 1996; Dial, 1995; Fu, 1999). However, many issues need to be addressed before such technologically enhanced service systems will be widely endorsed by paratransit agencies. How much increase in productivity can be expected from application of AVL? How effectively will these technologies be able to improve the quality of paratransit service? What dispatching strategies and policies can take advantage of real-time information?

In order to address these issues, it is required that performance of systems under alternative technological settings be predicted. Due to the dynamics of pick-up and delivery operations, the uncertainty of system environments, and the complexity of the underlying routing and scheduling problem, such prediction is often a forbidding task, defying utilization of traditional analytical models and field test methods (Roos, 1971; Wilson and Colvin, 1977; Hendrickson, 1979). For example, the operation of paratransit systems requires solving the problem of scheduling and dispatching available vehicles to service the travel requests. The underlying problems, generally called dial-a-ride problems (DARP), have been studied considerably over the past 30 years though optimal algorithms to problems of this type remain to be developed (Bodin et al., 1983; Psaraftis, 1983; Dumas et al., 1991; Toth and Vigo, 1995; Savelsberch and Sol, 1995). The lack of optimal algorithms means that comparisons of alternative operations have to rely on approximate solutions and heuristics. Conclusions from such comparisons are usually valid only under the particular operation settings as represented by the underlying service area, road network and travel patterns, under which the evaluation is conducted, and thus may defy generalization to other operating environments. This difficulty implies that field test may not be the ideal method to evaluate advanced paratransit systems since the experience obtained from one site may not be easily transferred to other sites (Hardin et al., 1996; Chira-Chavala and Venter, 1997). A computer simulation framework may effectively address these problems because of its potential to represent the underlying complex process and operating environments.

Despite the promise of the simulation method, there has been surprisingly scarce applications in the area of paratransit. To the author's knowledge, the only simulation model that is published in literature is a system developed by Wilson et al. (1970) for evaluating various heuristic routing rules and algorithms used in a computer-aided routing system. While many aspects of their simulation system are still valid to be applied for evaluating advanced paratransit systems conceived and/or deployed today, their system is limited in representation of road networks, and technology options and characteristics. In addition, their system was developed for mainframe computers and seems no longer available for use today.

This paper presents a simulation model that can be used as a virtual test bed to address some of the important technological and methodological questions that may arise in designing and evaluating technology-oriented paratransit. The paper first presents an overview of technological components of an advanced paratransit operation system (APOS) – the physical counterpart of the proposed simulation model. The principle components and structure of the simulation system are then introduced. Finally, an example is used to demonstrate the application of the simulation model.

2. Advanced paratransit: technology background

Paratransit operations require a set of interrelated managerial functions such as reservation, vehicle scheduling, real-time dispatching, billing and business reporting. With various technologies such as microcomputers, AVL and digital communication, these functions can be automated for potentially more cost-effective operations. This section presents an overview of a conceptualized system called APOS. The objective of this overview is to provide some operational and technological background of this envisioned APOS, which is the modeling target of the proposed simulation system.

In this hypothetical APOS, as shown in Fig. 1, the reservation system provides the connection between the operation center and the customers. It is responsible for recording information on each customer's request, including pick-up and delivery locations, desired time window, load to be picked up/delivered and their special requirements, and, in the case of service cancellation and

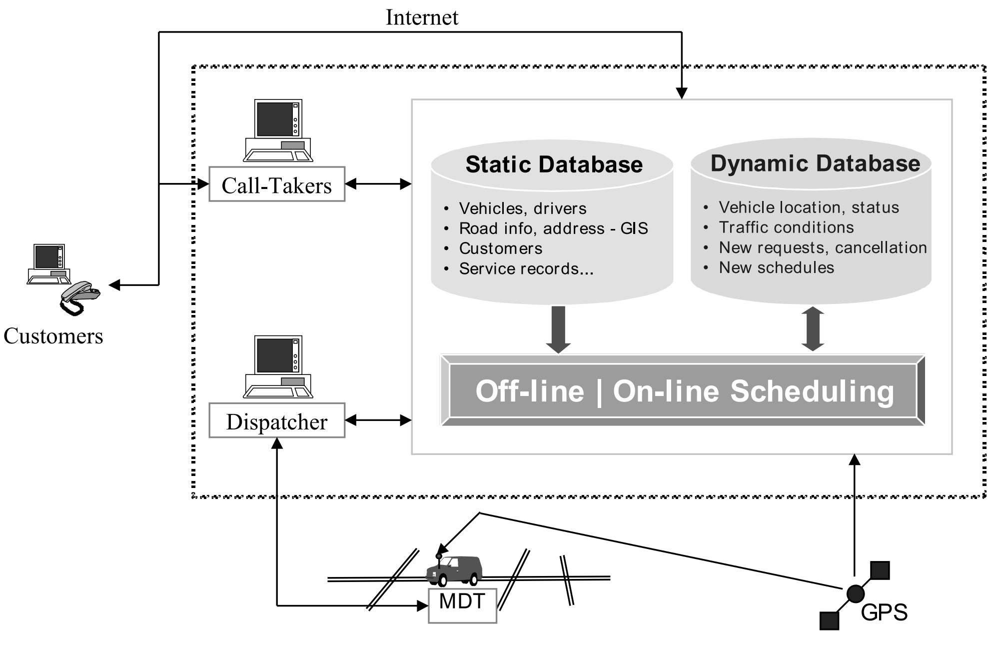

Fig. 1. Components of APOS.

change of service time, for updating request information. This procedure is usually performed by a reservation clerk who receives the information over the telephone and then manually enters it into the computer. During each reservation process, the clerk may inform the customer whether or not the service request can be accommodated. As another option, the reservation can be completed by an automated telephone system connected to a computer through a modem. Internet technology may be effectively applied to automate this function, whereby a dedicated web page is set up through which customers can make requests on-line.

The AVL system is used to locate and track vehicles. Several alternative technologies are available. These differ by positioning accuracy and updating frequency. Conversely the most popular technology is the global position system (GPS) which relies on signals from satellites to locate the vehicles. The location information can then be used for real-time monitoring and vehicle dispatching.

All related information is managed by a central database management system (DBMS) and a geographical information system (GIS) for effective data support to all associated functions. There commonly exist two categories of data that need to be treated differently. The first category of data, called static data, consists of those that are relatively stable and need not be updated frequently. Examples include road network topology, customer addresses, and fleet and drivers information. The second category includes data such as vehicle location, traffic conditions, new requests and cancellation, which often change during the time of day and need to be updated on a continuous basis.

The scheduling component provides both off-line and on-line scheduling capabilities. The off-line scheduling function is used to assign the trips that are requested in advance and known before operation starts while the on-line scheduling component is responsible for assigning the requests that arrive in real time and need to be serviced immediately.

The dispatcher monitors continuously any operational changes in the system such as vehicle breakdowns, service cancellations and new requests. These changes may justify modification of vehicle schedules such as diverting en-route an on-road vehicle to service a new request in vicinity or re-assigning trips from one vehicle to another. Once a change is verified, the modified schedules are sent to the drivers and displayed in their in-vehicle computers or mobile data terminals (MDT).

Finally, it should be noted that the diagram shown in Fig. 1 represents only the functional configuration of an APOS and should not be interpreted as a definite software or hardware setting. Such systems could take many configurations depending on the technologies used for collecting and communicating data and human interfaces. For example, individual components can be implemented on different computers, or combined into a single system; the vehicle location could be identified using AVL, or estimated approximately on the basis of vehicle routes and schedules stored in the computer; the system may use personal computers or workstations, which could be linked locally through a local area network (LAN) or globally through Internet.

3. The simulation system: models and structure

The simulation system SimParatransit has been developed primarily for evaluating APOS under a variety of technology options and operating strategies. This section first describes how various physical components in APOS are modeled, followed by an overview of the structure of the simulation system.

3.1. Principal models

The simulation system consists of nine principal models as described as follows.

3.1.1. Service area and road network model

It is assumed that the paratransit service to be modeled is located within an urban or suburban area covered by a road network. In order to realistically trace individual vehicles' movements in an urban traffic environment, the simulation system explicitly models the underlying road network as well as the temporal and stochastic variation of travel time in the network. This ability is important for modeling a service system in which most demands have tight pick-up and/or drop-off time windows and the total system cost is proportional to the service hours of individual vehicles. It is also important for the reason that a system with technology options such as AVL may be more advantageous in a highly varied operating environment than in a stable environment. In current implementation, a road network is represented by a set of nodes (intersections) and links (road segments). Each link is associated with a travel time vector, which represents the mean and standard deviation of travel times on the link as a function of the time of day, as shown in Fig. 2. Note that such link travel time data can be considered as information available from a traffic information center (TIC). If there is no real-time data available, average travel time based on historical data can be used. By using link-specific travel time or speed, it is possible to model the spatial variation of traffic congestion in the service area.

With the link travel time information, time-dependent shortest paths can be computed between any locations or stops (Fu and Rilett, 1998). It should be pointed out that the current model does not explicitly consider traffic flow in detail and delays at intersections, which are assumed to be already accounted for in link travel time.

During a simulation process, once a vehicle enters a link, a value representing the vehicle's travel time on that link is randomly selected from a log-normal distribution with the mean and

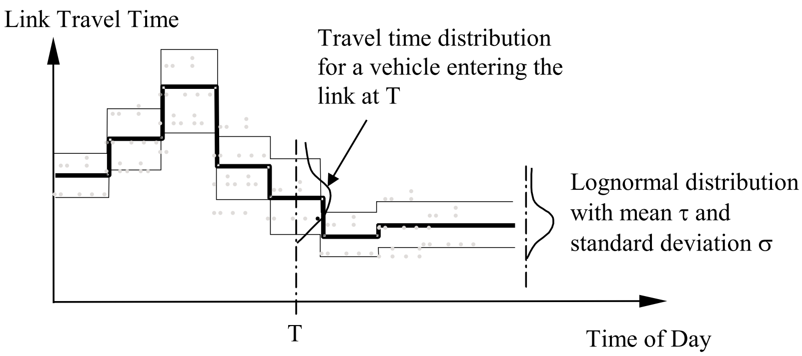

Fig. 2. Stochastic link travel time as a function of time of day.

standard deviation as functions of the time the vehicle enters the link. The vehicle moving speed is then back calculated on the basis of the link length and the generated travel time. The vehicle is assumed to travel at this speed for the entire link.

3.1.2. Trip model

A trip involves a passenger to be picked up at a given location (pick-up stop) and delivered to another location (delivery stop) in the service area. The simulation system considers two types of trips: advance reservation trips which are requested in advance, e.g., 24 h before service starts, and real-time trips which are requested after service starts and need to be serviced immediately. The common attributes of these two types of trips include: (a) seats required by up to three seating types, (b) desired pick-up and/or drop-off time, or request time for real-time trips, (c) pick-up and drop-off locations, (d) dwell time (boarding and alighting).

Since the dwell time may involve substantial variation and is therefore modeled as a random variable. While the mean dwell time is considered as trip-specific, the standard deviation to mean ratio (coefficient of variation) of the dwell time is assumed to be the same for all trips. It is important to note that, by explicitly modeling the magnitude and variation of dwell time, potential effects induced by some technological options such as AVL may be modeled. For example, suppose that, with the availability of AVL, customers are able to check the real-time location of the vehicles that are scheduled to pick them up, they could then get ready for their travel before the vehicles arrive. This means that the dwell time at pick-up stops may be reduced for a system with AVL.

During the simulation process, the system maintains the status of each trip, including (a) waiting to be picked up with expected lateness in minutes, (b) onboard, (c) delivered, (d) no-show, and (e) canceled. The expected lateness is determined based on the real-time status of its assigned vehicle and scheduled arrival time. This information is used as a basis by the dispatcher to decide whether or not it is necessary to assign another vehicle to the trip.

3.1.3. Vehicle model

Vehicles are mainly distinguished by their loading capacities of up to three types, the period that each vehicle is available for service and their depot locations as represented by coordinates. During simulation, the system tracks and updates vehicles' status which could be one of the following: (a) at garage waiting to start a service (ATGARAGE), (b) idling and waiting to start next shift (IDLE), (c) at stop picking up or dropping off a passenger or cargo (ATSTOP), (d) on road moving toward the next stop on its schedule (ONROAD), (e) done with its scheduled service (DONE). A vehicle's status changes when certain events occur. For example, a vehicle would change status from ONROAD to ATSTOP once it arrives at a stop to pick-up or drop-off a passenger. For each vehicle, the simulation system maintains a set of information on its assigned schedule and travel path, including a list of stops to visit, number of stops visited, street path for its assigned visits, current link (road segment) the vehicle is traveling on, current speed, current coordinates, and number of minutes that it is late behind its schedule. Note that the current coordinates are the exact values, which are different from the coordinates that would be reported by its AVL system (see Section 3.1.5) and used by the dispatcher (see Section 3.1.7).

3.1.4. Vehicle schedules

A vehicle schedule specifies the sequence and time that a vehicle is to follow when visiting assigned trips. As in real life operations, schedules must be prepared for the reservation trips before simulation starts. Two options are available in preparing schedules for simulation. One option is to create schedules outside the simulation system either by a scheduler or by a scheduling system and make them available for use in simulation. The other option is to generate schedules internally using the scheduling function included in the simulation system. During the simulation process, the pre-established schedules may be revised if changes occur in system states such as real-time requests, trip cancellation and unexpected vehicle delay.

3.1.5. AVL model

The fundamental functionality of AVL is the ability to pinpoint the coordinates of service vehicles at specific points of time. The simulation system models the AVL as the facility for a dispatcher (or dispatch center) to access the coordinates – longitudes and latitudes of equipped vehicles at a fixed time interval (or data acquisition interval as discussed in Section 3.1.6). Note that the use of fixed updating time may not be ideal to model non GPS-based AVL systems such as sign post technology, however, it is possible that, by properly selecting the time interval, a reasonable level of approximation can be achieved. In order to model the accuracy of a given AVL system, the longitude and latitude is generated from a probability distribution that is assumed to be obtainable from the exact coordinates of a vehicle and the positioning error of the AVL. The actual location of a vehicle is traced by simulation based on the vehicle's schedule, travel path, and realization of travel speeds on the individual links along the travel path. The positioning error of an AVL is represented by a parameter R – the maximum possible distance between the location identified by the AVL and the actual location.

Fig. 3 illustrates the methodology applied to generate these coordinates under two different circumstances. Two assumptions are made in this method. The first assumption is that the dispatch center is able to adjust a location identified by AVL (any point within the circular area) to a location on a nearby street, which is reasonable with the expected availability of GIS. The second assumption is that the vehicle's position that is possibly located by an AVL follows normal

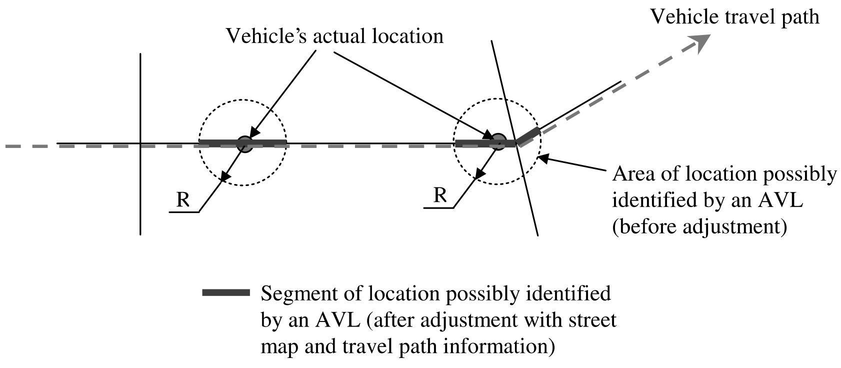

Fig. 3. AVL location model.

distribution over the street segment that is centered at the vehicle's actual location along the travel path with a standard deviation of R which represents the AVL positioning error.

As discussed in the preceding section, in a dynamic system, a change in system states may prompt the need to re-optimize vehicle schedules for a more efficient operation. When schedules are to be re-optimized, knowledge on vehicle location could then make difference. The major operational difference between a system with AVL and one without AVL is considered in the dynamic scheduling model detailed in Section 3.1.9.

3.1.6. Communication system model

An idealized model for a communication system would explicitly represent the information flows among three system components: dispatcher, vehicles (drivers) and customers, and the main characteristics of the communication system such as reliability of the communication network, delay in transmission of the information and updating frequency. Fig. 4 uses vehicle position information to illustrate the relationship between information acquisition, updating and its use. With most existing AVL systems, vehicle positions are obtained at discrete time of points and stored in an in-vehicle computer. These position data are then transmitted to dispatch center over a communication network. If a communication system can only allow transmission of information at specific frequency, the age or timeliness of information will depend mainly on the updating frequency. The higher the updating frequency, the higher the value of information for dispatching decisions. In the situation that information updating can be invoked by the dispatch center whenever a new event occurs, the age of information would depend mainly on the data acquisition frequency.

Since the main purpose of the simulation system is to evaluate the functional capabilities that have direct impact on real-time dispatching, a single parameter such as information updating time is sufficient to represent the combined capacity of the data acquisition and communication systems. In the simulation model, it is assumed that, at any point of time when an event calls for a dispatching decision, the decision would be made on the basis of the information obtained at the previous point of information updating time. For example, if the updating time is 1 min, the location information that the dispatcher can use could be as old as 1 min. By varying the updating

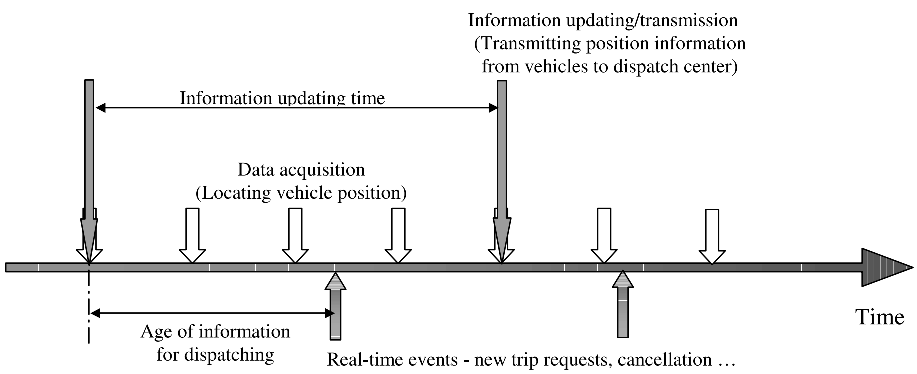

Fig. 4. Information collection, transmission and use.

time, a variety of communication systems may be simulated. For benchmarking, a zero updating time may be used to represent a perfect data acquisition and communication system – a system that can detect and update system states continuously and instantaneously.

3.1.7. Dispatcher model

The dispatcher model is the most critical component in the simulation system, responsible for undertaking dispatching actions under various real-time events. While the technology components such as AVL and communication systems make a large amount of real-time data available, it is this dispatcher model that actually makes use of these data to improve the system productivity, efficiency and responsiveness.

The simulation system includes two options: virtual dispatcher and human dispatcher. The virtual dispatcher is merely a set of dispatching strategies that can automate all dispatching tasks without any human interventions during the simulation process. For example, when a new request comes in, the dispatcher model automatically invokes the real-time scheduling algorithm to search for a vehicle that can best service the new trip. If there is no vehicle available to provide the required service, it would then set the trip request as rejected. However, if the service policy does not permit any rejection of real-time requests, the virtual dispatcher would automatically lower the pre-specified standards such as maximum allowable ride time and maximum allowable waiting time to make it feasible in order to insert the new trip into a vehicle.

The dispatching strategies define a set of rules that can be followed to respond to real-time operational events (see Section 3.1.8). Based on the type of responses, dispatching strategies are classified into two categories: immediate responses and responses with a time lag. The time lag is the amount of time that the system must wait before a further dispatching action can be taken after triggered by a real-time event. The underlying premise is that, by including an acceptable time lag (without letting customers wait too long), the system will be able to use more real-time information and minimize the negative consequence of a myopic optimization process. It is expected that an optimal time lag can be identified for a specific application through an extensive simulation analysis.

Dispatching strategies can be further classified by the type of actions as follows:

- *Re-scheduling* involves either inserting a new trip into, or modifying the arrival times and idle times of a given schedule under the assumption that the stop sequence on the schedule must be maintained.
- *Re-sequencing* modifies the sequence to visit trip stops on a given schedule.
- *Re-assignment* involves either assigning trips from one vehicle to another, or re-assigning all waiting trips.

Each dispatching strategy requires application of a scheduling algorithm to identify the best schedules under a given circumstance. Section 3.1.9 provides a further discussion on this subject.

The system also allows interactive simulation in which a human dispatcher is in the loop of simulation and responsible for handling all real-time situations – events generated by the simulator. Under this mode, once a new event occurs, the simulation system automatically 'slows down' by running under real-life clock and let the human dispatcher to make dispatch decisions in response to the event. After the modified schedules are updated, the system would then turn back into its original pace of simulation speed. This mode of simulation is expected to be useful for training purpose.

3.1.8. Real-time operational events

Real-time operational events that would trigger dispatching actions can be classified into three categories: customer-related events, vehicle-related events and dispatcher-related events. Customer-related events include real-time trip request (NEWREQUEST), and cancellation of trips after service starts (CANCELTRIP). The CANCELTRIP events are assumed to be Poisson processes because of their likely negligible interaction between individual events. The time interval between two consecutive events can be drawn from a negative exponential distribution once the associated distribution parameters are specified.

Vehicle-related events include breakdown of a vehicle during its service process (BREAKDOWN) and late behind schedule (LATE). The BREAKDOWN event is also assumed to follow Poisson's distribution for the same reason stated previously. The event LATE is an induced event that may be caused by excess travel times on some links (an indicator of traffic congestion) or long dwell time (unexpected long dwell time), therefore would automatically appear whenever a vehicle is late for an amount of time exceeding a pre-specified threshold.

Dispatcher-related events involve periodical requests made by dispatcher to re-optimize schedules (REOPTIMIZE). The underlying assumption is that, as the time unfolds, vehicles' status may change and deviate substantially from the conditions that are assumed when schedules are prepared or dispatching actions are performed. By re-optimizing schedules periodically, the productivity and reliability of the service system may be improved.

3.1.9. On-line dynamic scheduling component

The dispatcher model discussed previously relies on an on-line algorithm to solve the dynamic (or real-time) version of the DARP. The primary objective of a dynamic scheduling algorithm is to determine the assignment of real-time trips to vehicles that are already in service with a given set of schedules. Depending on what strategy is used, the algorithm may also be used to reschedule trips that have been assigned to certain vehicles. In the current model, the dynamic scheduling algorithm is extended from the algorithm for the static DARP with a set of modified objective functions and constraints (Fu and Teply, 1999). The major modifications are outlined as follows:

- The objective (cost) function is defined as a combination of total service time and total disutility caused to the customers because of the modification. The customers' disutility is measured in terms of waiting time and/or excessive ride time. For trips already on schedule (mostly advance reservation trips), waiting time is defined as the difference between the expected arrival times before and after the modification. For real-time trips, it is defined as the difference between the request time and the scheduled time. The excess ride time is defined as the extra ride time as compared to a customer's direct ride time (without any diversion to service other customers).
- The operational constraints which must be satisfied during the routing and scheduling process include seating requirements, vehicle available service period, and trip pick-up/drop-off time windows. For the validity of a schedule, the scheduling process guarantees that the load on each vehicle does not exceed the vehicle loading capacity of each type at each stop along the route. The pick-up/drop-off time window is defined differently for advance reservation trips and real-time trips. For real-time trips, the time window is simply determined based on their request time and maximum allowable waiting time, while for advance reservation trips, their absolute latest pick-up/drop-off times need to be considered.

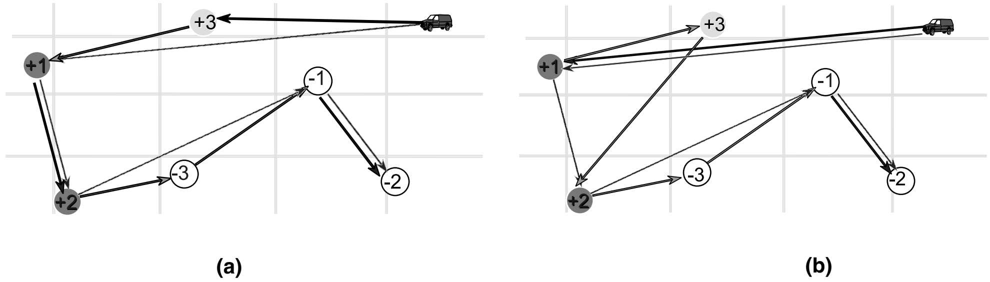

Fig. 5. Dynamic scheduling: (a) with AVL; (b) without AVL (Trips 1 and 2: advance reservation trips; Trip 3: real-time trip).

In the dynamic scheduling model, a system with AVL is modeled differently from one without AVL based on the following two operational assumptions, similar to Wilson et al. (1971):

- In a system with AVL (Fig. 5(a)), each vehicle that is currently traveling toward to the next stop according to its schedule may be diverted en-route by the dispatcher to a new stop if such diversion is efficient and at the same time is not expected to jeopardize the service to existing customers.
- Conversely in a system without AVL (Fig. 5(b)), the location of each vehicle is not always known to the dispatching center. It is therefore assumed that a vehicle is not to be diverted from its immediate destination for a new customer. However, diversion is allowed after the first stop of a vehicle, as the location of that stop is known to the dispatching center. It should be noted that under this non-AVL scenario, some type of communication system is assumed to be available so that a dispatcher can relay modified schedules to on-road vehicles.

3.2. Program structure

The simulation system includes two essential program components: the main module and the event-processing module, as shown in Fig. 6. The main module (Fig. 6(a)) includes a loop over the event-processing module that is invoked whenever a new event occurs, and a sub-module that performs the tasks of updating system states at an interval of information updating time. This module follows time-based simulation logic and integrates the functionality needed for system animation.

The event-processing module (Fig. 6(b)) consists of a set of actions that are driven by various real-time operational events described previously. The module is invoked by the occurrence time of next event from the event queue. Once activated by an event, this module first updates the positions of individual vehicles if AVL is used. Otherwise, the projected time that each vehicle will arrive at its immediate stop is updated. This information is subsequently used in the dynamic scheduling process. For each specific type of event, corresponding dispatch strategies are applied by the virtual dispatcher to find the optimal dispatching actions in response to the given event. Schedules are subsequently modified and updated. This modification has an immediate effect on the main module, which will simulate the system based on the modified schedules.

The simulation starts with loading all needed data from a database, including vehicle data, advance reservation trip data, road network data, and schedules for the advance reservation trips.

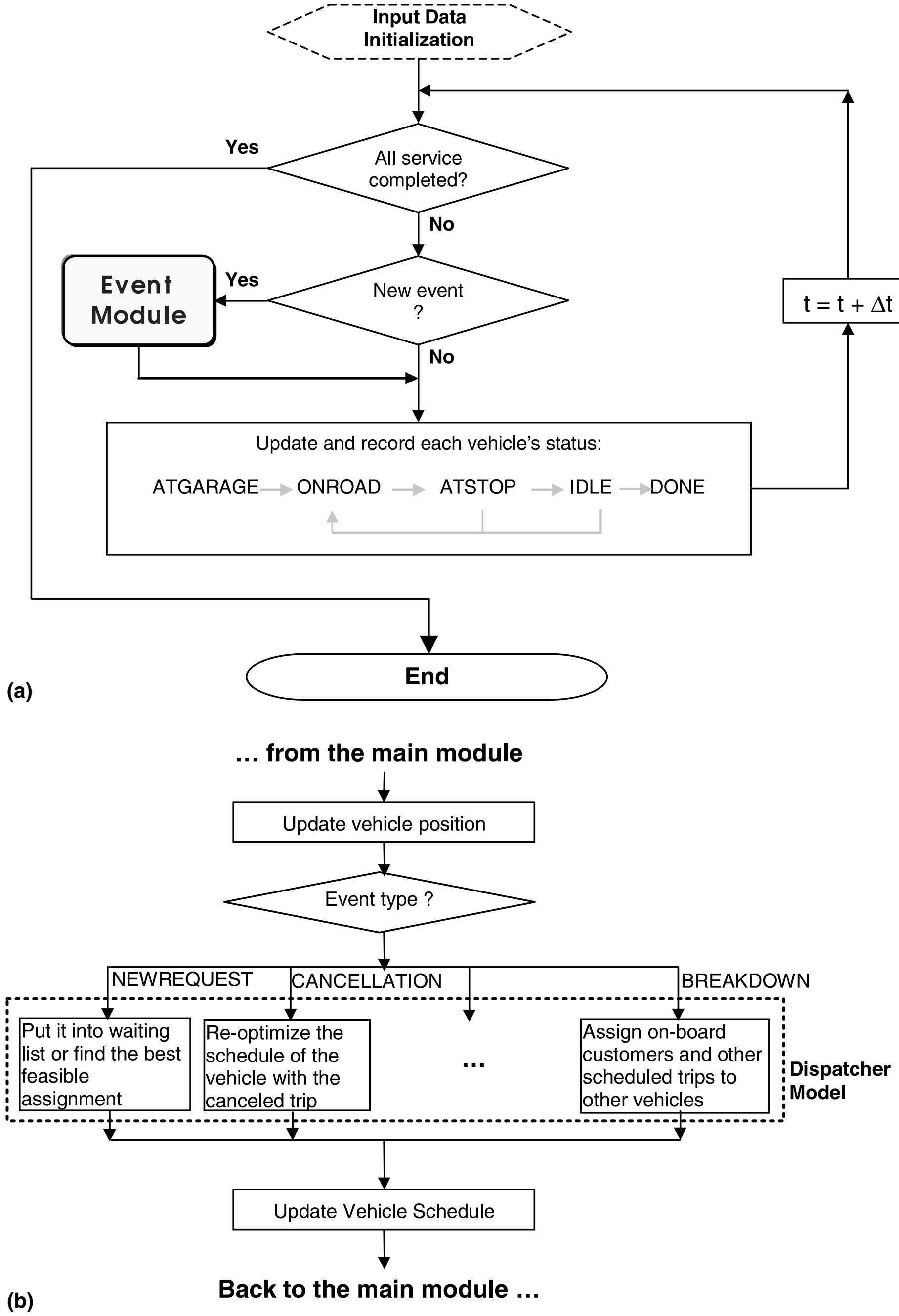

Fig. 6. SimParatransit simulation logic: (a) the main module; (b) the event-processing module.

After all data are prepared and parameters are set, the simulation can then be activated. During the simulation process, the system logs the detailed service records of each vehicle, including arrival time, dwell time and leave time, at each stop. This information, combined with trip data, is used to generate all simulation statistics. The simulation process continues until all vehicles complete their service and the event queue is exhausted.

4. System implementation

SimParatransit is written in C++ using object-oriented programming (OOP) technique which provides the flexibility to easily modify and extend the program as the system is continuously validated and enhanced. The program is compiled as a 32 bit program run on Microsoft Windows platforms. The size of problems to be simulated (e.g., number of trips and vehicles) are not restricted in the program but by the available computer memory.

A GIS interface is used to display all system status data including trips, vehicles, travel time, scheduling parameters, schedules and various measures of effectiveness (MOE). SimParatransit allows importing and exporting data using the ODBC database engine, which usually requires much less data preparation effort. Although most of the data are prepared outside of the program and input from a database, an interface is set so that the user can easily modify the data if necessary.

5. Simulation experiments and results

To demonstrate the application of the developed simulation system, the system is applied to simulate the operations of a dial-a-ride paratransit. The objective of this simulation study is to investigate the differences in operational performance between a paratransit system using AVL and one without AVL under the assumption that a system with AVL has an increased flexibility in dynamic scheduling as described in the preceding section.

The experiments were first performed on a set of hypothetical cases generated within a geographic area of 10×10 km^2. The area is covered by a uniform grid road network with a link length of 500 m and a link speed 30 km/h. Three levels of demand with trip densities of 0.5, 1.0 and 1.5 trips/h/km^2 (corresponding to a total of 100, 200 and 300 trips, respectively) were considered with percentage of real-time demand trips of 10%, 30% and 50%. At each demand level, five random sets of trips were generated to represent the variation in trip distribution. Each trip was assumed to have a pick-up/drop-off dwell time of 1 min. A total of 45 ($3 \times 3 \times 5$) cases were therefore included. To limit the scope of our analysis, we did not consider any stochastic variations in both network conditions (link travel times) and trip dwell times. Under these controlled environments, a total of 54 replications were found sufficient to reveal the difference between systems with and without AVL. Each case was simulated twice: one with AVL and the other without AVL, and the resulting statistics were collected for further analysis.

It was assumed that the routing and scheduling objective is to minimize the total travel time. A maximum ride time of 90 min and a maximum service time deviation of 30 min were used in scheduling the reservation trips. In real-time dynamic scheduling, the maximum waiting time was 30 min for demand trips and 10 min for reservation trips. These constraints define the minimum level of service that must be guaranteed in the test cases. The comparative analysis then focused on the difference in vehicle productivity between individual scenarios.

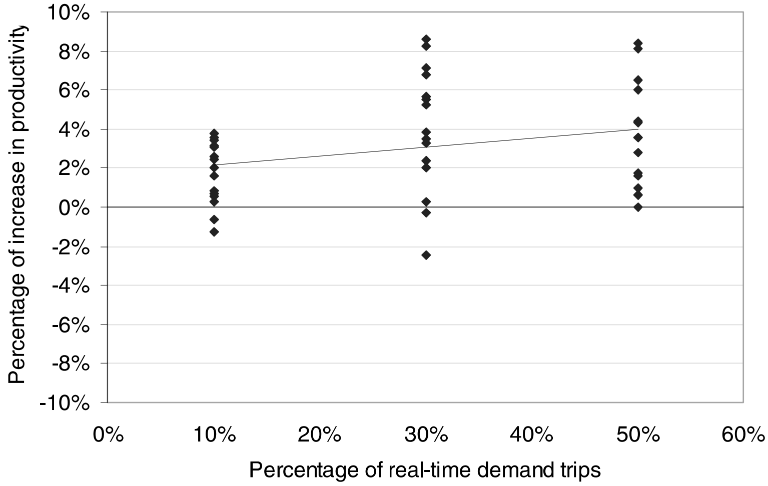

Fig. 7. Relationship between productivity improvement and proportion of real-time trips (hypothetical cases with trip density = 0.5–1.5 trips/h/km^2).

Fig. 7 shows the relationship between the percentage of increase in productivity due to AVL and the percentage of real-time demand trips. Several observations can be made from these results. First, systems with AVL have a clear advantage over ones without AVL in terms of vehicle productivity. The average increase in vehicle productivity due to AVL ranges from 2.0% to 4.0%, with the highest observed increase of 8.8%.

Second, the relative increase in productivity appears to be an increasing function of the proportion of real-time demand trips, with an approximate 1% improvement in productivity in average for every 20% increase in demand trips. This relationship is somehow expected, as the higher is the real-time demand in a system, the more opportunities exists for en-route diversion and thus the more advantageous is it for a system with AVL.

Third, the actual benefit is highly case-dependent with productivity improvement varying from negative gaining (−2.5%) to as high as 8.8%. For the cases with negative gaining (4 out of 54), it means that decreases in productivity were observed, indicating that using AVL had in fact worsen the system performance in these cases. Such performance variation is, however, expected as the relative advantage of an AVL system depends on the formation and location of the active routes and the real-time trips; some combinations present better potential than others in terms of travel time saving that can be obtained through en-route diversion. Furthermore, in a dynamic system, a decision made in the present affects the future state of the system. As a result, whereas a dynamic assignment solution is always advantageous to a system with AVL under the current system condition, it may turn out to be less desirable in the future when other real-time trips arrive.

Experiments were then performed on a modified real-life example from the disabled adult transportation system (DATS) in the City of Edmonton, Alberta. The problem instance consists of a weekday off-peak service (11:00 am–1:00 pm), including 460 advance reservation trips. In order to model real-time demand trips, the original list of trips was divided into two groups according to a given percentage: one was used as reservation trips and the other as real-time demand trips. The original trip database did not include the dwell time required at each trip stop,

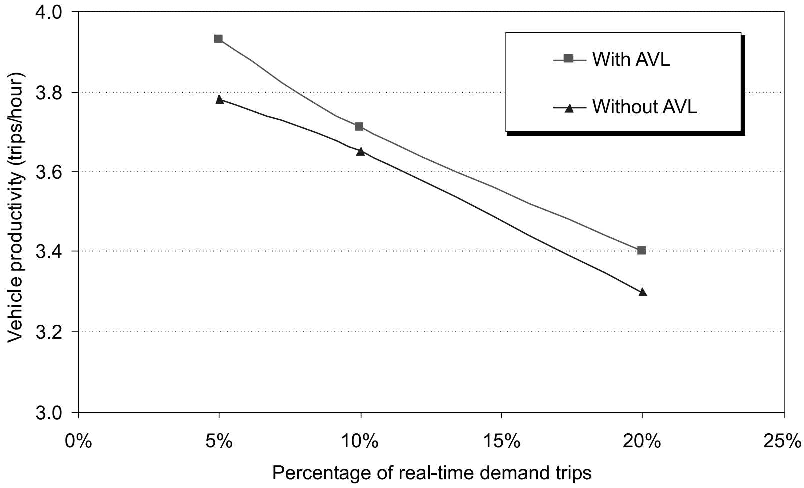

Fig. 8. Relationship between productivity improvement and proportion of real-time demand trips (Edmonton case, trip density = 0.45 trips/h/km^2).

therefore a dwell time of 1 min was added to each pick-up and drop-off stop. A fleet of vehicles with a capacity of 10 seats is assumed to provide the service. Travel times between stops used in scheduling are estimated based on Euclidean distance and an average travel speed of 30 km/h. Travel time on each link in the network was assumed to be deterministic and determined on the basis of the posted speed limit associated with the link. We note that while the hypothetical scenario assumes a uniform distribution of trips over a service area, the Edmonton cases represent more realistic situations in which trip clustering is taken into account. The productivity improvement was also observed in this real-life problem under three hypothetical proportions of real-time trips, as shown in Fig. 8. The average increase in productivity was between 2% and 4%.

It should be noted that our results are somewhat different from the results obtained by Wilson et al. (1971) who observed an average of 10% increase in productivity due to AVL. This discrepancy is likely due to the differences in the assumed operating conditions. For example, in the analysis performed by Wilson et al., all trips were assumed to be real-time requests with an average trip density of as high as 5.0 trips per square kilometer per hour. These assumptions are, however, no longer realistic in representing most existing paratransit service systems.

6. Summary and future research

This paper presented an overview of the concepts, models and computational technologies applied in a new simulation system called SimParatransit, which has been developed as a virtual test bed for evaluating advanced paratransit systems. The simulation system has the following unique features:

- It explicitly models the functionality of the important APOS hardware components such as AVL and communication systems. This ability opens the possibility to evaluate the cost-effectiveness of these technologies without field experiments.

- It allows realistic representation of the underlying road network in a service area and explicit consideration of time-dependent, stochastic traffic patterns. In addition, it is able to model the availability of real-time link travel time data.
- It allows use of various important dispatching strategies that may be applicable for responding to common real-time operational events such as new trip requests, trip cancellation and vehicle breakdown. The on-line scheduling system is efficient enough to handle these dispatching tasks of different computational intensities, such as re-sequencing, re-assignment and re-scheduling.
- A user-friendly GIS interface and a database-oriented data input–output scheme are used so that data preparation and use of the program are considerably easier.

The simulation system was applied to evaluate the potential operational improvement that may be attained from the application of AVL. A series of simulation experiments were performed on a set of hypothetical cases and a realistic example. The simulation results have shown that AVL benefit due to increased flexibility in dynamic scheduling is highly case-dependent. The observed productivity gain ranged from −2.5% (loss of productivity) to +8.8% with an average productivity increase of 2–4%. It should be stressed that the simulation study presented in this paper is still limited in representativeness. Further research is needed for a more complete sensitivity analysis with respect to area size, demand distribution, operating policies, dispatching strategies and variation in travel time.

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