ANALYSIS OF DEMAND-RESPONSIVE TRANSPORT SERVICES: A MICROSIMULATION APPROACH

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SUMMARY

Demand-Responsive Transport Services (DRTS) are an attempt to improve the efficiency of public transport when demand is sporadic. The DRT service simulator that we have developed analyses most of the random events, such as traffic congestion and the arrival time of passengers at their pickup points, which ultimately affect the quality of the service. We assume that vehicles are moving within the traffic flow on the network, and a microscopic traffic simulator was therefore used to observe the dynamics of congestion.

INTRODUCTION

This paper deals with Demand-Responsive Transport Services (DRTS), a facility which could well provide an answer to the problem, inherent in all traditional public transport systems, of below-capacity loading of vehicles when demand is low. Conventional scheduled services, based as they are on a system of set routes and timetables and pre-determined bus stops, planned in advance on the basis of average data, may leave vehicles virtually empty at certain periods. DRTS aims to supply a service for individual requests by using vehicles that collect passengers along the route. The service can be coordinated by a Travel Dispatch Centre (TDC) (1) (2) and differs from a taxi service in that a DRTS allows passengers bound for various destinations to share the same vehicle. An innovative alternative to the problem of management of DRTS is that proposed by Dial (3) for a “many to few” service, which succeeds in avoiding the use of a TDC and a central management. In this case each vehicle’s computer communicates with the driver and with other computers to exchange data and to decide on the best solution for any passenger request. When a customer places a call, a computer on board one vehicle, automatically selected by a centralised call distribution system, answers the call and begins to process the request.

But whichever system is used, travel requests made by individual users are gathered together and combined, so that a solution may be found, for example by using an algorithm based on the Dial-a-Ride Problem with Time Windows (4). This does imply, however, a certain elasticity on the part of passengers who would have to be flexible about the time they arrived at their destination, and might also have to cover a greater distance - to enable the driver to pick up other passengers, for example - than they otherwise would.

Not only is DRT service governed by the service regulator, it also relies heavily on vehicles and passengers arriving punctually at stops (or other pick-up points). The punctual arrival at stops of DRTS vehicles may of course be affected by traffic conditions. It is by no means easy to make a realistic estimate of the speed at which a given distance is covered, and any error made here may affect the quality of the service. In order to improve the performance of the service, a version of the Dial a Ride Problem has recently been presented (5), with time-varying and stochastic travel times. This model is helpful during the planning phase for long vehicle journeys on wide networks, which are influenced by the changes in traffic conditions over the course of a day.

Any change in the planned journey may adversely affect the quality of the service. Passengers already on board a vehicle may not appreciate having to linger at stops if their vehicle arrives ahead of schedule. Conversely if it is running behind schedule, passengers waiting at stops will be inconvenienced, and those waiting to leave the vehicle will arrive at their destination later than anticipated.

It is the service operator who determines the price and the quality of service offered, and both of these will naturally be related to what can realistically be achieved on that particular network. It will clearly be useful, therefore, to carry out a series of detailed analyses, which take all these real-life aspects into account, to ensure that the promised quality of the service is guaranteed. When DRTS journeys are planned, it is virtually impossible to take into account all the various factors which actually come into play in real life: variations in journey time and passengers arriving late at stops, for example. It is, however, possible to ascertain how well the system performs, by observing what happens on the network, during simulation, when different conditions occur.

An interesting tool for the analysis of public transport systems by means of an integrated simulator of DRTS and other different transport modes over a wide area is LITRES-2 (6). The environment LITRES-2 uses O/D matrixes to generate individual travel requests which are managed by a travel broker, whose task it is to choose the best alternative, in each situation, by comparing all the available modes for that particular request. The aim is to model the interactions among the various modes available to users on the same network, rather than to describe accurately the congestion on the network.

Another simulation model has also been proposed (7) to evaluate the use of information technologies in DRTS in order to improve their productivity and reliability. An Automatic Vehicle Location (AVL) system, for example, can be used to locate and track vehicles and enables an on-line updating of the scheduled plans in order to adjust them to changes caused by network conditions or passenger requests. In this simulation model, vehicles move into a network based on time-dependent and stochastic travel time, assuming that a traffic information centre can estimate these values.

It is often the case that traffic congestion is only a sporadic occurrence in a given location and it will almost certainly vary according to the time of day. In these conditions we cannot simply make rough estimates regarding the speed at which various parts of the network are covered. In real life, vehicle speed is affected by congestion on the network or by isolated occurrences, such as bottlenecks at congested intersections. In our work, we used a microscopic traffic simulator to give an accurate description of traffic phenomena in order to provide a realistic simulation of the flow of vehicles on road networks and to observe the dynamics of time-dependent traffic phenomena. Various micro-simulation tools are already available for the analysis of the most common transport systems (8), such as conventional public transport and private cars, but not as yet for all of the innovative transport systems. In this research, therefore, we have developed a *DRT service simulator* by implementing an established model, described below, within a traffic micro-simulator. We used AIMSUN (9) (10), which enable the user to access internal data on line by means of the GETRAM extensions. By activating a number of elementary functions, new vehicles may be fed into the network, at each step of the simulation, and their various parameters (position, speed, acceleration) may be controlled. The whole model gives a much more realistic representation of the road network and traffic conditions and therefore provides a more effective evaluation of the performance parameters of the service than its predecessor (11) (12) developed by using ARENA.

ANALYSIS OF A DRT SERVICE

This study, whose purpose is to investigate the performance of a DRT service, looks at three different aspects:

- *The Generation of Travel Requests,* which predicts individual travel requests on the network (during the day), on the basis of socio-economic factors obtained through statistical data concerning population and taking into account companies established in the area;
- *Trip Planning,* which draws up travel plans and timetables for vehicles and passengers, using the ADARTW (*Advanced Dial-A-Ride with Time Windows*) heuristic algorithm (4);
- *DRT Service Simulation* to evaluate how the DRTS behaviour is affected by uncertain factors, such as passenger and vehicle arrival time at stops; the next section examines this issue more closely.

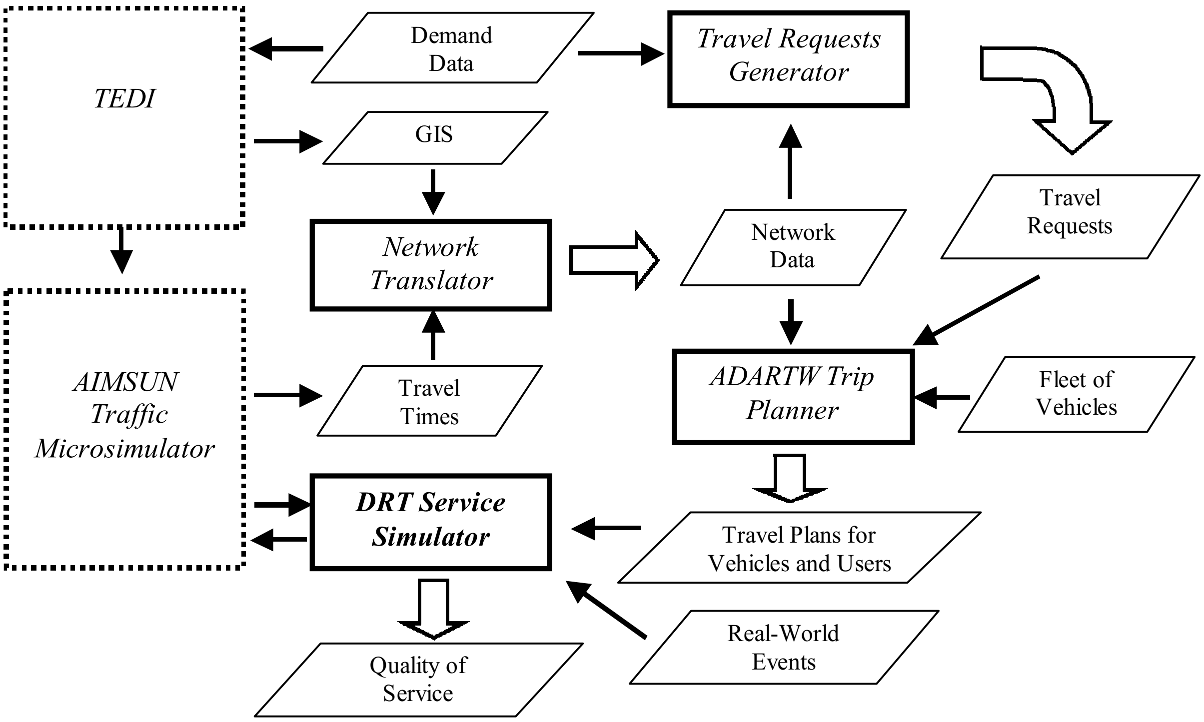

Figure 1 - The simulation framework for DRT systems.

The simulation system does not reproduce the operations of a Travel Dispatch Center, but models the different components of the system in order to analyze the effects of the various different alternatives the service operator might take, during the planning of the journeys. For this reason accident and vehicle breakdowns are not simulated and neither are cancelled journeys.

In order to allow the exchange of data between the modules described above, a *Network Translator* was developed for the purpose of converting the network from the Geographical Information Systems (GIS) exported by TEDI (10) to the format used for the *Travel Requests Generator* and the *Trip Planner* modules. In addition, it elaborates dynamic speed data captured from the AIMSUN micro-simulator to build a static database of travel times on the road network (Figure 1).

The Generation of Travel Requests

A simulation approach was used to represent travel demand, individual travel requests being positioned at nodes of the network and at specific times. Each node of the network can be considered as a stop for DRTS vehicles, and homogeneous nodes can be grouped in zones, so that information concerning the different parts can be put to use over the area as a whole.

The simulation is based on data collected within the area thus might be, by means of surveys, performed in homes and in the workplace, whose purpose is to gauge to what extent each zone will generate and attract DRTS journeys. Travel requests on the network can also be generated by using socio-economic variables related to the world of employment, such as the number of employed people within each zone. Information on the shortest length of the DRTS journeys and the available transport modes between zones are also used to correct the sample generated and to obtain more realistic results.

Trip Planning

The *ADARTW Trip Planner* is the module that codes in C^{++} the *Advanced Dial-A-Ride with Time Windows* algorithm and elaborates the requests obtained through the first module. The algorithm uses a heuristic constructive procedure based on the insertion technique. It gives as results route plans and time schedules, for each vehicle activated and each request accepted by the system. In our investigations all of the requests are known in advance and, during the planning of the journeys, travel times on the network are assumed constant over time, and deterministic.

This paper does not deal with the abilities of the algorithm to solve a set of travel requests with appropriate plans; it focuses, rather, on the "*Service Simulator*" and its aptitude in evaluating real-world aspects which can affect system performance. It is also possible to evaluate travel plans whose elaboration is based on different hypotheses, for example, stochastic and time-varying travel times (5).

DRT Service Simulation

In previous works the service simulation module was built with ARENA (13), a simulation software package based on a discrete, flow-oriented, modelling language known as *Siman*. The logic of this simulation model is divided into different sub-models; each of these simulates a specific component of the system: the network, the time of departure of the vehicle from its depot, passenger arrival times at stops, vehicle journeys, passenger pick-up and drop-off at stops. A more detailed description of the simulation system built by means of ARENA can be found in previous papers (11) (12). The service simulator allows the observation of most of the real-world aspects related to the DRTS, such as the propagation effect of passenger and vehicle delays upon the actual journey. Both passengers and vehicles may actually arrive later than planned, and this can adversely affect the quality of the service supplied. Unfortunately traffic congestion is not easy to implement realistically, within a simulation tool such as Arena. For this reason a micro-simulation approach was chosen to analyse the service.

It should be pointed out that it is far from easy to build an analytical model designed to describe vehicle journeys on the network, capable of taking into account all the possible uncertainties. In general terms, the random distribution of events, for example, the departure time of vehicles from stops, might not be a known statistical distribution. It should combine both the movement between stops, affected by traffic conditions, and the waiting at stops, affected by passenger behaviour.

THE MICROSIMULATION ENVIROMENT

Network model

The representation of the network used by the Trip Planning module, composed of nodes, as intersection points, and links as stretches of road between intersections, is not detailed enough for the microscopic model. We therefore built a network model using TEDI. In this environment the network is represented mainly by *sections* and *junctions*: these are the basic elements, which allow us to model almost all of the various different configurations of the road network. Consecutive sections are linked by *joins*, which connect them together on the network model. Turning manoeuvres are modelled by means of junctions that represent all of the directions a vehicle is permitted to take wherever more than two sections meet. If traffic lights are present at the intersection, for example, all of the data related to turnings can be stored in the Signal Groups folder and used during simulation.

The *Network Translator,* then, further elaborates the database of the GIS (exported with TEDI), to provide a network model which uses links to represent both sections and turning manoeuvres at intersections. Nodes are used as connection points between consecutive links. Each node can be a potential DRTS stop, and nodes also represent traditional bus stops, so that any section which contains a bus stop is split into two links.

Traffic congestion

Demand data related to the study area are represented by Origin - Destination matrixes. An O/D matrix describes the total number of vehicles of to each vehicle type, loading the network during each time slice over the whole simulation period. Vehicles leaving from a point of Origin (departure) bound for a certain Destination could be randomly generated: the distance between two consecutive vehicle arrivals may be sampled, for example, as an exponential, uniform or normal distribution. However the distance can be kept constant during each slice.

The simulation is based on O/D matrices and routes (*Route-Based* simulation model). In this model, vehicles are introduced into the network according to the O/D matrix and they drive along the network following a certain path to reach their destination. For the sake of simplicity in our simulations, the *Fixed Routes Mode* was adopted: the shortest path trees are computed from any section to every destination at the beginning of the simulation. Therefore, all vehicles always follow the shortest path, from which they cannot deviate during the journey. Vehicles can also be introduced externally into any section, through the GETRAM Extension, when a particular transport system or specific vehicles are to be modelled.

Demand data, path choice model and detailed network geometry (intersections, signals, steep roads, PT stops) allow the description of local traffic congestion, such as bottleneck phenomena, which can arise even in small parts of the network, but produce consequences over a wider area.

DRTS vehicles

DRTS vehicles are introduced into the network as a specific vehicle type. For any activated vehicle, the route plan computed by the ADARTW trip planner provides the estimated time the vehicle will take to touch each node and, if the node is involved in travel requests, the names of the passengers to be picked up or dropped off. During the trip, various random events can arise and modify the desired plan. The journey performed by the vehicle can be modelled by dividing it into different phases, which are described below and depicted in Figure 2.

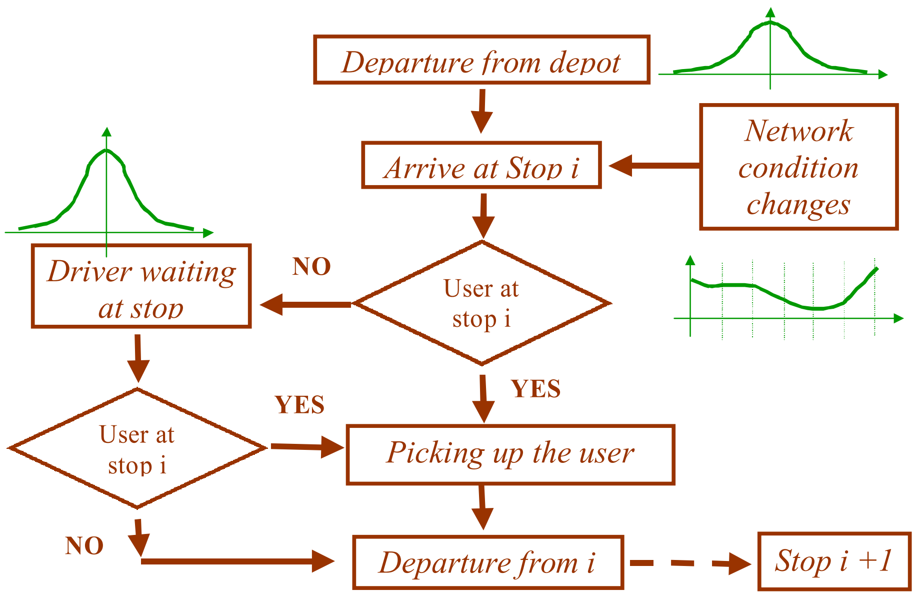

Figure 2. Scheme of vehicle behaviour

<u>PHASES OF THE VEHICLE'S JOURNEY</u>

Departure from the depot

The actual time of departure from the depot cannot be accurate as in the estimated plan. A random distribution was therefore assumed for the simulation of the time difference between the actual departure time and the estimated one. If we suppose that the drivers' clocks are all synchronized, we can imagine an Average Delay for Vehicles at Departure (ADVD) equal to 0, whereas, to describe the randomness of the starting event, the Standard Deviation of Delay for Vehicles at Departure (SDDVD) was fixed at a value other than zero (the experiments were performed with normal distributions and SDDVD equal to 20 seconds).

Running

During the vehicles' journey, road speed limits or vehicle performance and, when congestion occurs, traffic speed or delays at intersections affect the speed of DRTS vehicle. The path of the vehicle is traced out by communicating, before any intersection, the outgoing section to be followed as established by the estimated plan. In this case, the Trip Planning module, by means of the Dijkstra Short Path Tree algorithm, selects the best path for each vehicle. In a further step of the research, a different kind of vehicle routing procedure might be activated: the vehicle is free to follow the best path, suggested by the micro – simulator, on the base of a DRG (Dynamic Route Guidance) algorithm which, however, permits the connection of consecutive DRTS stops.

Approaching Stops

When the vehicle is arriving at a DRTS stop, an approaching manoeuvre is performed in order to avoid simulation problems and to make the process more realistic. If we know the distance the vehicle has to cover in order to reach the stops and assume a straightforward uniform deceleration, we should set the speed so as to avoid missing a stop. When the vehicle is closer to the *Stop Point*, it tries to move into the right-hand lane, if there is one. If the stop point is after an intersection, the vehicle can be stopped only when it has fully entered the section following the turning. When the vehicle has to stop along a section or in a node connecting two sections or a turning proceeded by a section, the vehicle will have to draw up slightly before the stop, for reasons of safety.

Waiting at stops

A number of rules were established to regulate the behaviour of the vehicle (or the driver) during the waiting time at stops. When the vehicle arrives at each active stop, the first check concerns the passengers who want to alight at the stop. After all passengers have been dropped off, the pick-up phase can start:

- if passengers are already at stop, they can board the vehicle;
- if even one of the passengers has not yet arrived, the driver has to wait for him until the maximum waiting time, as established by the service operator, has elapsed; after this time the vehicle can leave the stop without picking up the late passenger.

Leaving a stop

The departure from the stop occurs when all of the passengers have already boarded or alighted from the vehicle. In same cases, the vehicle can also leave the stop without picking up passengers, because it is running late and passengers have already left the stop or, in the situation described above, passengers reach the stop too late.

OBSERVING VEHICLE BEHAVIOR

Statistical values are collected during simulation experiments to observe DRTS journeys, since the vehicle is obviously not the sole user of the road network; its behaviour may be affected by a number of different events, caused both by passengers and other traffic. It is not easy to predict how these random events may alter the schedule, and how severe the effects on the punctuality of the vehicle or other service parameters may be. Simulation experiments are therefore used to assess these effects, by means of a number of replications in suitable conditions. For each vehicle the average value and the standard deviation (or the frequency histogram) can be calculated to describe statistical distributions.

Delay of travel plans

In order to check service regularity, the difference between the *Simulated* and the *Estimated (or Planned)* Stop Arriving Time can be monitored ($SAT_S - SAT_P$). In this case, the vehicle situation was observed only in those particular nodes of the travel plan where an event (pick-up or drop-off) occurs. The more accurate the prediction regarding traffic and passenger delays, the closer the simulated situation will be to the estimated one.

Waiting at stops

The actual waiting time for vehicles at stops can also be observed, to verify how long vehicles stay at stops waiting for passengers. For each stop, differences between the simulated values of the Departure from the Stop and the Arrival at the same Stop ($DS_S - AS_S$) were gathered. This parameter is affected mainly by passengers arriving late, although traffic conditions can modify vehicle speed and therefore vehicle arrival time at stops.

DRTS passengers

The travel plan also establishes the time by which each passenger has to get to his pick-up point so as not to miss the DRTS vehicle. The moment when the passenger actually boards the vehicle can be considered as random for a number of reasons; watches may be slow o fast, for example, or passengers may arrive late at that or at previous stops.
In order to reduce the waiting time at stop for vehicles, the service operator may give passengers a pick-up time which is slightly earlier than the scheduled time, although this might mean passengers having to wait slightly longer at stops. It was necessary therefore to carry out further investigations to find a satisfactory compromise here.

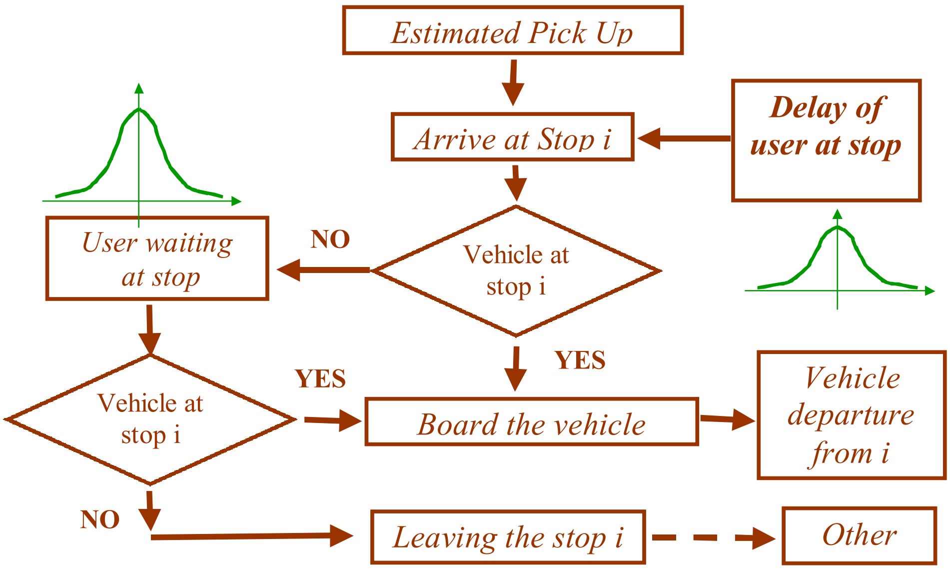

Figure 3. Scheme of passenger behaviour at stops

PHASES OF PASSENGER BEHAVIOR

Arriving at stop

Passengers are introduced within the model at stops, on the basis of the Estimated Pick up Time, as calculated by the Trip Planner module. The actual arrival time of the passenger is assumed as a random event, and can also be shifted over time to take into account modified times which the operator communicates to passengers, in order to reduce the waiting time for drivers at stops. The model developed assumes a normal distribution and the following parameters have to be set:

– Average Delay (or advance) for Passengers at Stops [s] (for example, -60 s means that, on average, passengers arrive at stops 1 minute before the Pick up Time planned);
– Standard Deviation of Delay for Passengers at Stops [s], (60 s was assumed as dispersion measure).

Waiting at stop - leaving the stop

In the model, passengers at stops usually wait for vehicles, but sometimes traffic congestion, or other factors, can delay the schedule, so that passengers have to decide whether to leave the stop or continue to wait for the vehicle. To represent this aspect a Maximum Waiting Time for Passengers [s] has to be set. After this waiting time the passenger will leave the stop to adopt another means of transport. If we suppose that the system operator provides passengers with information about the position of their vehicle, passengers do not have to wait until their maximum waiting time has elapsed, if the vehicle has already left the stop before the passengers' arrival. Otherwise, passengers would have to wait for the vehicle even if it had already passed their stop.

Boarding the vehicle

When the vehicle arrives at stop and any passenger whishing to alight have done so, waiting passengers can board and if there are several of them, the order of boarding is governed in the model by a FIFO queue.

OBSERVING THE QUALITY OF THE SERVICE PROVIDED TO PASSENGERS

Waiting at stop

This parameter attempts to assess how long passengers wait at stops for vehicles, taking into account all the factors that can affect the waiting phase (traffic congestion, late arrival of other passengers at previous stops, early arrival of passengers at stops). For each passenger, the waiting time is arrived at by calculating the difference between the Simulated Pick up Time and the Simulated Arrival Time ($PT_S – AT_S$), so that an average delay can be estimated for all the vehicle journeys, for passengers who have actually boarded their vehicles.

Journey length

Another consequence of random events concerns the duration of the journey, which should not vary significantly from that communicated, if a certain quality of service is to be maintained. For each passenger, the difference between the Simulated Delivery Time and the Simulated Pick up Time ($DT_S – PT_S$) is calculated. These values can then be compared with the Actual Ride Time and the Maximum Ride Time planned, to ascertain the real standard of service.

Arrival at destination

One of the constraints of the trip planning procedure is that all the passengers must be delivered to their destinations before the Desired Delivery Time. During simulation, though, various events can affect the plan and some passengers may be delivered later than DDT. In other cases, passengers can also be delivered to their destination too early, resulting in a longer Waiting State time, if the arrival is before the Actual Delivery Time planned. Besides estimating the Waiting State planned ($WS_P = DDT_P – ADT_P$) the following parameters can also be collected during simulation:

- Simulated Delay of Arrival at Destination $DAD_S = ADT_S – ADT_P$
- Simulated Waiting State $WS_S = DDT_P – ADT_S$

The former is a measure of the delay compared with the planned time, the latter can be used to ascertain if all passengers are always taken to their destination before their Desired (or Latest) Delivery Time.

Number of passengers who do not board

Finally it is useful to compute the number of passengers who are not taken on board, because they are late arriving at stops or because the vehicle is behind schedule and passengers have already left the stop for other means of transport. For each vehicle journey, the following indicators can be estimated:

- Number of Passengers Leaving the Stop - NPLS
- Number of Passengers Missing the Vehicle - NPMV

APPLICATION OF THE MODEL TO A SMALL AREA

Network

In order to analyse the service simulator within the micro-simulation environment a network model was built, using the TEDI network editor, to represent part of a mountain valley (Valchiusella), located about 100 Km from Turin, in the north of Italy. This is a suitable environment in which to test the DRT service simulator, with the assumed hypotheses, where on-line travel times are not available (here a traffic information centre is unusual) and congestion may arise and remain very localized.

The GIS exported from TEDI, which describes the network by means of 632 sections and 206 turns, has been converted into a graph of 752 nodes and 841 unidirectional links, for a total extension of travelling distances of 20 Km. It is a small network but it enables us to observe the performance of the service simulator more closely.

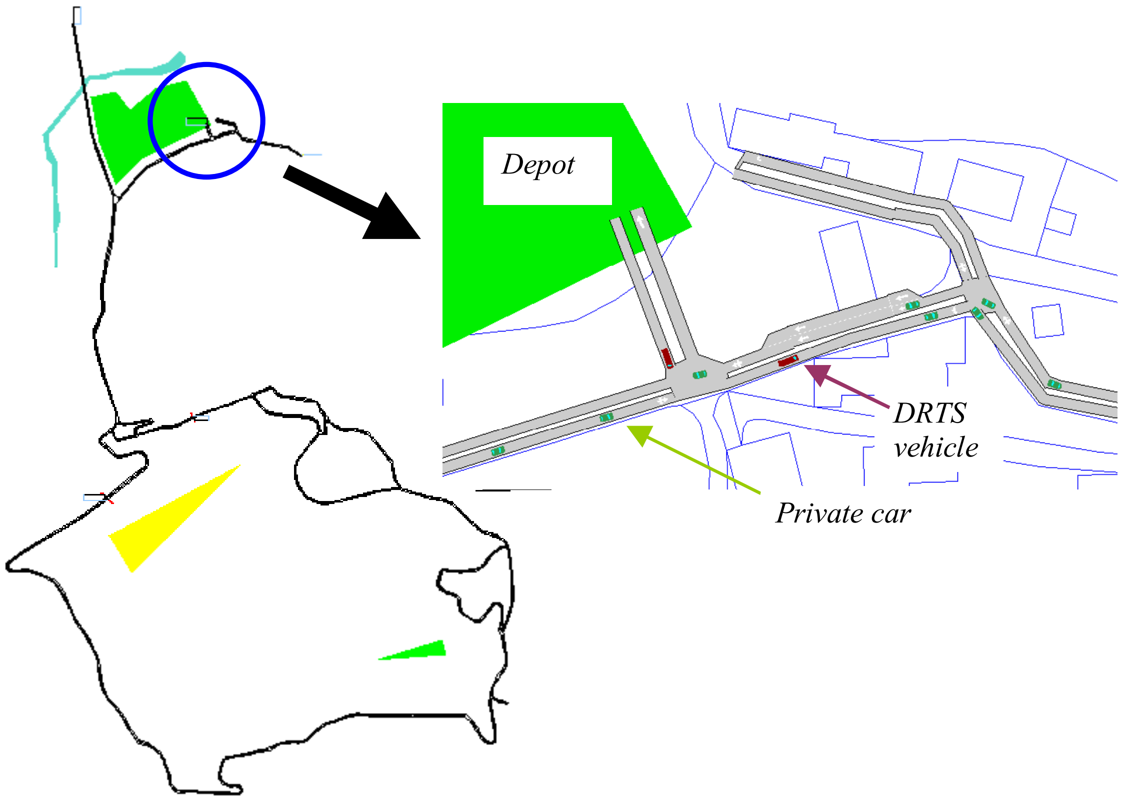

Figure 4. The road network and a detailed part near the depot

For each section of the network, data on variable speed are collected during simulation slices with the AIMSUN model, so that different travel time data can be used for the whole simulation period (not congested, minimum and maximum travel time) in the trip-planning module. In the service simulation module, however, changes in traffic conditions over time are the consequence of the O/D matrix variability and the interaction of vehicles on the network. Speed variability on the network was therefore the result of the micro-simulation approach.

Demand

During the simulation period (8:00 - 9:00), four O/D matrixes for the private car system were built to represent the dynamic evolution of traffic congestion on the network. Each of these covers a 15-minute slice and centroid nodes were introduced only in the north part of the network to simulate unhomogeneous congestion phenomena. The aim is to reproduce heavy congestion, though this is located only in certain intersections and for short periods. For the sake of simplicity only one vehicle type was used.

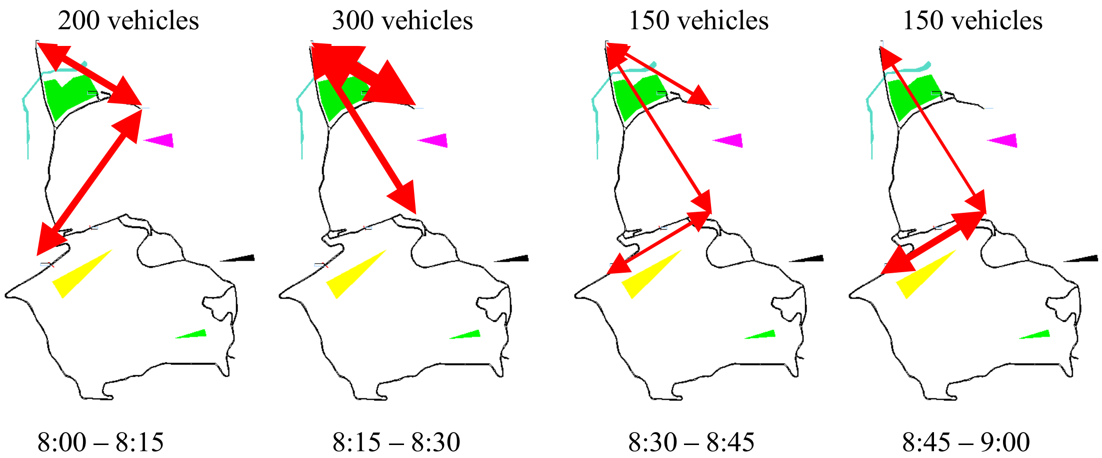

Figure 5. The demand assumed to reproduce traffic congestion on the network

We hypothesized 100 DRTS journeys with a *Desired Delivery Time* within the simulation period, and generated travel requests accordingly. In order to examine concentration phenomena over short periods, the total number of requests were divided up as follows:

- 60% between 8:30 and 8:45;
- 40% between 8:45 and 9:00.

	Destination		
Origin	3	4	
1	**9**	**26**	*35*
2	**-**	**30**	*30*
5	**16**	**-**	*16*
6	**6**	**13**	*19*
	31	*69*	***100***

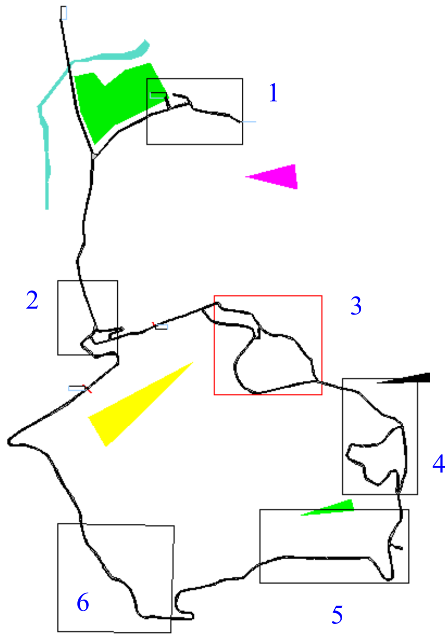

Figure 6. The O/D matrix of DRTS travel requests

The nodes of the network where travel requests are feasible have been grouped into 6 zones to control the spatial dimension of DRTS demand. The O/D matrix in Figure 6 describes the relation between zones.

Experimental scenarios

In order to test the micro-simulation model developed and its ability to assess the feasibility of a policy proposed by the DRTS operator, various scenarios were investigated. During experiments we looked at the following factors:

1. Traffic variability with respect to the situation used for trip planning;
2. Patience of drivers in waiting for late passengers at stops;
3. Punctuality of passengers at stops.

The first two are related to the policy of the DRTS operator, which has to organize the service in such a way as to achieve maximum efficiency, whilst maintaining the promised quality of the service supplied to passengers, whereas the third factor involves passenger behaviour. Nevertheless, the service operator can also influence the punctuality of passengers, if a modified pick-up time is communicated during booking. The patience of passengers in waiting for late vehicles was assumed fixed in these experiments, and a high value was chosen: the Maximum Waiting Time for Passengers was set at 30 minutes. After this time, passengers will leave stops to look for other transport systems.

Effects of traffic changes over time, due to congestion on the network, can be taken into account as early as the trip-planning phase, if detailed traffic information is available. In our experiments, for the same set of travel requests, three different travel plans were drawn up, by assuming the following hypotheses:

1. uncongested link travel times (N);
2. for each link of the network, the travel time is equal to the maximum value observed during the simulation period, when only private cars are present on the network (M);
3. a predictive situation which estimates, for each link of the network, the travel time as the maximum value observed during the simulation period, when also DRTS vehicles are on the network (P); in this case travel times are related to those particular vehicles, which follow paths planned using hypothesis n.2.

For all of the cases, a reference scenario was built (N0, M0 and P0), by assuming that passengers arrive on time at stops (on average) and vehicles leave every stop without waiting for late passengers. To provide a comparison, an elementary scenario (E0) was also built, with the purpose of simulating the DRTS journeys without traffic on the network, in order to exclude the influence of congestion on simulated travel plans.

Three additional simulation scenarios were investigated for the predictive estimation of travel times (scenarios P - hypothesis n.3), increasing the maximum waiting time for drivers at stops and hypothesizing earlier passenger arrival time at stops. The different values of variables for these scenarios are shown in the table below.

		Scenarios			
		P0	**P1**	**P2**	**P3**
Congestion	*Link travel time used for Trip Planning*	Hypothesis n.3			
Patience of drivers	*Maximum Waiting Time for Vehicles MWTV [s]*	0	60	0	60
Punctuality of passengers	*Average Delay for Passengers at Stops [s]*	0	0	-60	-60

Results of Travel planning

All of the vehicles leave one depot, located in the north of the area (Figure 4), and travel plans were drawn up by hypothesizing the following service features:

- *Wait State* (WS), the maximum time the passenger can wait at destination before his *Desired Delivery Time* (DDT), is equal to 10 minutes;
- *Maximum Ride Time* (MRT) for any passenger is 3 minutes plus 30% of his individual *Direct Ride Time* (DRT).

In attempt to satisfy the entire travel demand using 8-seater vehicles, the *ADARTW Trip Planner* activated 7 vehicles for the uncongested hypothesis "N" and only 6 vehicles for the "M" scenarios. In this case, slightly higher values of link travel times may allow better integration of the various travel requests. The most significant data emerging from the planning phase can be seen in the following table.

Scenario	**N**	**M**	**P**
Number of vehicles	**7**	**6**	**9**
Global DRT – Direct Ride Time [h]	3.7	3.9	6.4
Global VTT – Vehicle Travel Time [h]	2.6	2.7	4.6
Index DRT/VTT	1.43	1.44	1.38
Average DRT – Direct Ride Time [s]	134	140	230
Average ART - Actual Ride Time [s]	229	239	329
Average MRT - Maximum Ride Time [s]	354	361	479

Table 1. Travel Planning Results

For the "P" scenario, where a more accurate estimation of link travel times for the DRT system was attempted, 9 vehicles were activated and higher values of Direct Ride Time can be observed. The efficiency of these plans and the degree of dispersion of travel requests can be assessed if we consider the ratio between the sum of the DRT for the entire demand and the global Vehicle Travel Time (VTT), which includes the time spent travelling from and back to the depot. In these cases, the average degree of efficiency (DRT/VTT) is almost the same and is equal to 1.4.

Results of the Simulation

A number of replications simulate each scenario with different random drawings from the same distribution. At the end of the series of replications, the expected values of performance indicators can be calculated. In this study, in order to reduce the computation time, only 10

replications per scenario were processed. Nevertheless, the 95% confidence interval for the average DTP (Delay of Travel Plan) in the N0 scenario, for example, is [405-13, 405+13], 3% of the mean value, which is an acceptable result.
The average data set out in the table below show the influence of the choice of link travel times on the actual travel plans and, as a consequence, on the quality of DRT service. The first performance indicator gives the Delay of Travel Plans, with respect to the planned situation [DTP]. Even if the service operator estimates congested travel times (hypothesis n.2) and allows for this factor when planning journeys, simulated travel plans are delayed with respect those estimated (by an average of 6 minutes – scenario "M0").

100 Requests		**Scenario**			
	Average values (10 replications)	**E0**	**N0**	**M0**	**P0**
	Number of vehicles	**7**	**7**	**6**	**9**
Vehicle	**DTP [s]**	383	403	386	28
	WAS [s]	7	7	7	8
	NPMV	10	10	10	35
	NPLS	0	0	0	0
Passenger	**WAS (waiting at stops) [s]**	337	354	343	58
	JL (journey length) [s]	395	397	389	363
	DAD_S [s]	496	516	487	47
	WS_S [s]	-225	-245	-209	274

Table 2. Global results for the scenarios to investigate travel time estimation

Negative values of WS_S mean that passengers are delivered after the *Latest Delivery Time* (on average more than 3 minutes later). It should be pointed out, however, that the congestion simulated on the network is rather heavy. Nevertheless, delays are due not only to congestion, but also – and predominantly – to the fact that DRTS vehicles behave differently from private cars. In scenario "E0", however, where DRTS vehicles run in the absence of other traffic, there is still a significant delay (on average about 6 minutes). These results show that the assessment of travel time on the network needs to consider the specific behavior of DRTS.
In scenario "P0", where plans are based on "predictive" travel times estimated for DRTS vehicles, simulated journeys are much closer to those estimated (the average DTP is only 28 seconds and the DAD is 47 seconds). The journey length simulated (JL) is much closer to the planned one (ART is about 5.5 minutes), and shorter than others simulated. For scenarios "N0" and "M0", on the other hand, the simulated values are about 6.5 minutes, whereas planning results estimate less than 4 minutes. In scenario "P0", on average, passengers are delivered earlier than the *Latest Delivery Time* (the mean value of WS_S is equal to about 5 minutes). Unfortunately, in this case, many passengers miss the vehicle (35), because drivers are fairly punctual and do not wait for late passengers. On the other hand, every passenger who has been able to use the service will have waited at his stop less than 1 minute.

In the following table the results of the other "P" scenarios are presented. In all cases, there is no significant difference in waiting time at stops (WAS) for vehicles, although the delay with respect to the planned schedule (DTP) increases when drivers have to wait for late passengers (scenarios “P1” and “P3”).

100 Requests	Number of vehicles = 10	Scenario			
	Average values (10 replications)	**P0**	**P1**	**P2**	**P3**
Vehicle	**DTP [s]**	28	79	33	57
	WAS [s]	8	9	8	8
	NPMV	35	11	9	3
	NPLS	0	0	0	0
Passenger	**WAS (waiting at stops) [s]**	58	81	95	109
	JL (journey length) [s]	363	377	370	376
	DAD_S [s]	47	106	55	80
	WS_S [s]	274	217	269	243

Table 3. Global results for the ‘P’ scenarios

As expected, fewer passengers miss the vehicle (NPMV) if the service operator decides to wait for late passengers for 1 minute (scenario “P1”) or to communicate an earlier pick-up time (1 minute earlier than that scheduled) to passengers (scenario “P2”); the latter strategy seems to be more effective. In scenario P3 both actions were applied, and an average of only 3 passengers miss vehicles. These actions have the opposite effect on passenger waiting time at stops (WAS), which increases slightly, because passengers arrive early, or because vehicles wait for late passengers and this delay affects the remaining part of the journey. In this scenario passengers wait at stops for an average of 30% of their journey length. The number of passengers leaving the stop is always equal to zero during simulations, because a high value (30 minutes) was assumed for the Maximum Waiting Time for Passengers. The promised delivery time is delayed in all the scenarios, even if the delay of arrival at destination (DAD) is somewhat lower. However, in these cases the values of WS_S are always positive (e.g. 4 minutes, scenario “P3”).

A further analysis of simulation results concerning scenario “P3” is given below to show how certain performance indices vary for the various vehicles and passengers. Figure 7 gives the mean values of Passenger Waiting Time at Stops (WAS) for the various vehicles, and also shows, for purposes of comparison, the passenger Journey Length (JL) for each vehicle. The worst case occurs for passengers who take vehicle 3 (15 passengers); they wait 2.5 minutes for a journey that lasts less than 6 minutes. The 9 passengers in vehicle 8 enjoy the best quality of service in this respect: they wait only 1 minute to travel for about 8 minutes.

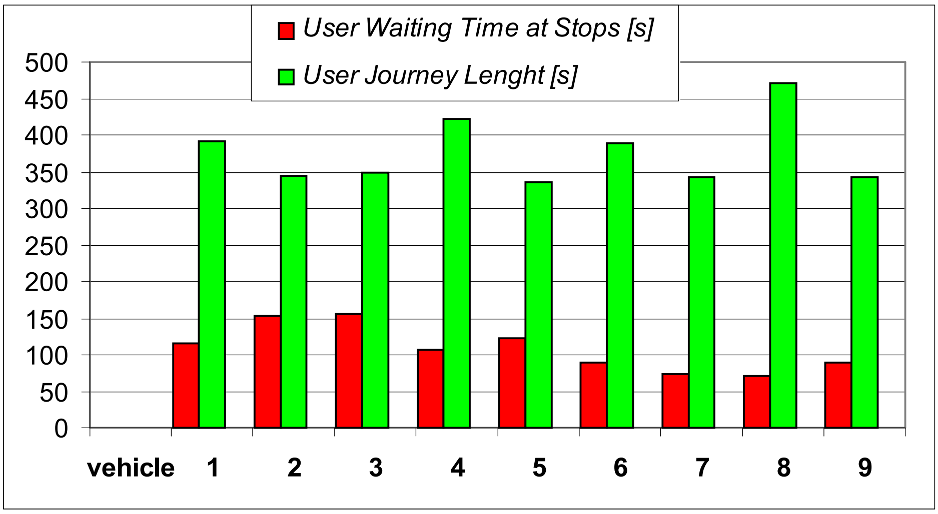

Figure 7. Comparison between waiting and travel times among vehicles

The variability of the waiting time at stops for all passengers in scenario P3 is shown in Figure 8, which gives the simulation results of 10 replications. Although the mean value is less than 2 minutes, it can be observed that in 1% of cases do passengers wait longer than 6 minutes and in 14% of cases longer than 4 minutes.

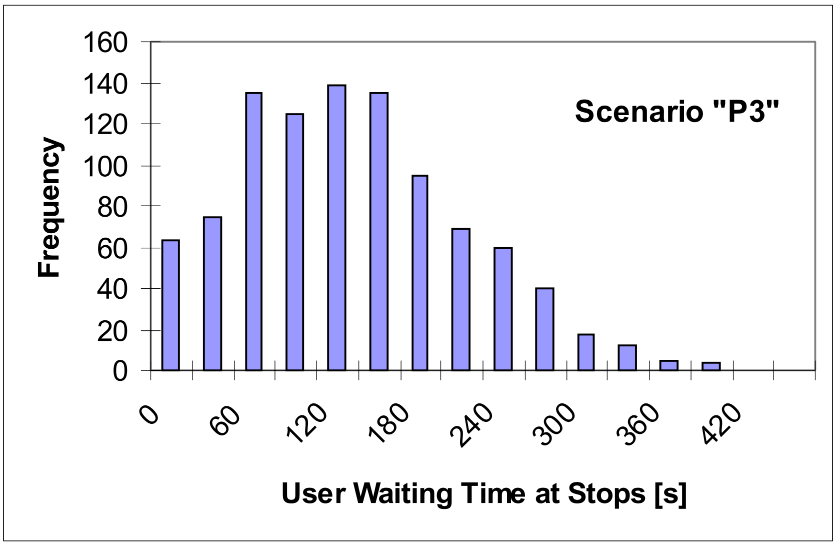

Figure 8. Variability of passenger waiting time at Stops for scenario "P3"

For purpose of comparison, Figure 9 shows a similar histogram for scenario "M", where the estimation of travel times on the network for DRTS vehicles is not accurate. In this case, although the average value of the waiting time at stops is less than 6 minutes, in 6% of cases passengers wait longer than 20 minutes and in 15% of cases longer than 15 minutes. These results demonstrate how important it is to evaluate travel times on the network correctly, and show the useful role played by the simulation tool developed to estimate appropriate travel times for DRTS vehicles.

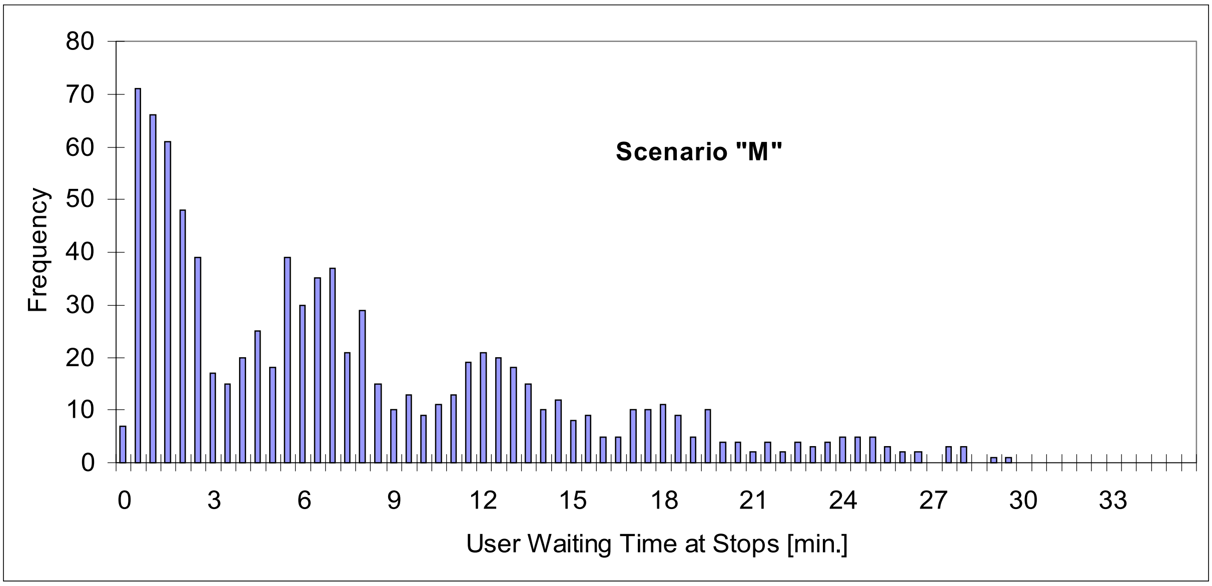

Figure 9. Variability of passenger waiting time at Stops for scenario "M"

CONCLUSIONS

At this phase of the research, the simulation system proposed is able to assess the effects of certain policies of a DRTS operator on the quality of a service, which accepts only requests made in advance. The *DRT Service Simulator*, developed within a microscopic traffic simulator, takes into account most of the possible uncertainties, such as the arrival time of passengers at their pickup points, the travel time on network links, or the driver's patience in waiting for late users. Other real-time operational events (passengers making new requests or cancelling journeys, vehicles breaking down, …) can affect the performance of the systems, but at this stage of the research they are not taken into account.

The service simulator was previously implemented by using the ARENA simulation tool, which does not permit accurate representation of traffic congestion. Thus, speed variability was modelled only approximately by multiplying all link travel times used for trip planning by a coefficient which varied during simulation. In this paper, on the other hand, the DRT service simulator takes into account the fact that vehicles are moving within the traffic flow on the network, the microscopic traffic simulator was therefore used to observe the dynamics of traffic congestion, by means of on-line data exchanges.

One very important function of the simulation tool is to provide an accurate estimation of travel times throughout the network. Operators will then be able to draw up a timetable which corresponds as closely as possible to actual vehicle journey times on a particular network, and thus to guarantee the quality of the service; they will not find themselves in the position of making promises they are unable to keep.

In real life of course there are a number of imponderable factors, which play a crucial role; such as a driver's patience and a passenger's punctuality. The simulation findings show to what extent these aspects affect service operations and the quality of a DRTS. It will therefore be useful to perform detailed investigations to select suitable values of parameters for the regulation of service operations. For this purpose, it would be necessary an adequate calibration phase concerning both the microscopic traffic model and the passenger and driver behaviour of DRTS.

Although in our investigations we applied a trip planning algorithm that uses deterministic and constant travel time on the network, the DRT service simulator can be applied to ascertain the performance of more complex algorithms, if they are available, and further research might proceed along this line.

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