Determining the Viability of a Demand Responsive Transport System

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***Abstract*— Demand responsive transport systems providing a flexible point-to-point service based on casual requests are becoming more feasible due to developments in information and communication technologies such as mobile phones, global position systems as well as advances in optimization methods. Since they promise to address some challenges of existing transport systems the question of their financial viability arises. This paper describes a model developed for investigating the financial viability of implementing a demand responsive transport system. This involves determining whether such a system can provide acceptable level of performance at reasonable cost.**

I. Introduction

DEMAND responsive public transport systems (DRTS) providing a flexible point-to-point service based on booking or casual requests are becoming more feasible due to developments in information and communication technologies [9], [23] as well as advances in optimization methods [12], [2], [11].

DRTS are a hybrid form of traditional public transport, combining elements of both buses and taxis and can include a broad spectrum of transport services ranging from informal community based transport through to urban wide networks [14], [17]. DRTS have the potential to improve accessibility and personal security at a more reasonable cost to the user than taxis [25], [8], but with similar flexibility and short-term response-to-demand. In this market segment, DRTS can solve several challenges of existing transport systems. In particular, DRTS promise to address the challenges of public transport in low density urban areas as well as of the short distance pickup and delivery problem [21], and the challenge of reducing the general dependency on private cars. In addition, DRTS can be used to support people with mobility disadvantage, such as teenagers, the elderly, and disabled persons [7], [24], [1].

With all these advantages and the emerging technical feasibility of ad-hoc response the question of the financial viability of DRTS becomes more urgent. Viability, the operator's interest, is in conflict with usability, the customer's interest: the more vehicles are loaded the longer the detours for each individual passenger. The parameters to be studied in this context are average and maximum waiting times, travel times and vehicle occupancy. Accordingly, this paper describes the development and application of a model for determining the financial viability of implementing a demand responsive public transport system, complementing [16] which focuses on usability. The DRTS investigated in this paper involves vehicles transporting persons between any two locations within an urban traffic network (free routing), and ad-hoc response to transport demand (real-time route planning).

The results of this study are important in multiple ways. The simulation of a DRTS allows for testing a variety of parameters, or model assumptions, for comparison. It also allows adapting to different urban environments, demand patterns, vehicle types, or optimization policies. We will present results demonstrating the overall viability of DRTS for particular parameter combinations.

II. Background

Societal factors such as ageing communities, protection of the environment, problems associated with social isolation, increased need for access and mobility and regional economic growth are affecting thinking about public transport worldwide [15]. New challenges for public transport administrators and service providers include maintaining the quality of life and economic sustainability of outer urban and regional areas, making traditional public transport relevant to people's needs, addressing regulatory restrictions that impede responsiveness to community needs, changing the culture of public transportation organisations to embrace change, improving the quality of customer service on public transportation and more effectively using technology to maximise efficiency and market penetration [10], [18]. DRTS have been identified as being an important element in future public transport systems in low density cities [3].

There is growing pressure for higher levels of service from transport systems in urban areas as congestion levels rise and fuel prices continue to increase. Cars offer flexibility and convenience but are costly, inefficient due to their effect on road congestion and their need for parking space. Cars also create substantial environmental problems due to emissions and fuel consumption and create social problems in terms of road safety. Buses, trams and trains

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tend to operate to fixed schedules that are often infrequent, and on fixed routes that frequently do not match the traveller's route. Trams and trains require also extensive purpose-specific infrastructure that is expensive to build and maintain and usually not available in low density urban areas. Taxis are expensive for the user and may not be available when required.

DRTS have the potential to the address these problems. They reduce the dependency on private cars, can operate without schedules and by flexibly choosing routes, share existing infrastructure, and since they offer shared transport their fares should be cheap.

DRTS exist in many cities; however, these often involve fixed origins or destinations, or fixed routes, or some form of pre-booking. In this paper we are interested in true demand response: a DRTS that involves vehicles transporting persons between any two locations within an urban traffic network, and that responds to expressed transport demand in an ad-hoc manner.

Ad-hoc response to demand is a computational challenge; the underlying problem is NP-hard. A large number of computational heuristics were developed, e.g., [6], [13], [5]. It is also a challenge for quality of service since plans cannot be made ahead, and hence, cannot be guaranteed. Especially for large numbers of vehicles a decentralized planning approach has been studied recently [23]. In a decentralized service design, customers negotiate directly with nearby vehicles. With appropriate optimization strategies, in particular passengers changing vehicles during their trip, it was shown that this service design can solve the multi-commodity-flow-over-time problem [2]. The service design was also adopted to utilize taxi empty cruising time for solving the short-distance pickup and delivery problem [21]. The present paper's model is still based on central planning; computational complexity did not play a role in the agent-based simulation. It is also based on the assumption of a fix number of vehicles, and typically a small number.

III. Model Development

DRTS involve assigning vehicles to satisfy demands from a set of customers who request operators to pick them up from specific locations and deliver them to specific destinations. Additionally they have the characteristics of a shared taxi service where several customers may be in the vehicle at the same time. This implies that vehicles may not travel directly between a customer's origin and destination since the vehicle maybe servicing a number of other customers' trips. Such systems typically involve service constraints relating to the maximum waiting time at the origin as well as the maximum amount of time taken to reach the destination [12]. They have many similarities to courier operations in urban areas [19], [22].

DRTS are complex systems that have a number of goals, constraints and decision variables. Vehicles have a fixed capacity in terms of the number of persons that can occupy a vehicle at any time. With demand arising any time, route plans of vehicles have to be updated during travel, which implies that travel times cannot be guaranteed for any customer. Instead, travelers experience waiting times to be picked up, detours on their trip of variable length, and if particular arrival times were requested also possible delays of delivery. Early arrival is possible as well, but typically not considered a disadvantage. A common goal is to minimize the number of vehicles required as well as their total travel distance travelled. Constraints are often represented by service requirements, specified as time windows (earliest and latest pick-up times) and maximum travel time for customers, and the decision variables are the order of stops (pick-up or drop-off locations) for each vehicle in operation [5]. These constraints can be modeled as hard constraints or by penalties.

Due to their dynamic nature DRTS are generally modeled using multi-agent simulation that includes optimization procedures associated with customer-vehicle allocation and route determination [4], [20]. For this paper, a number of software tools including traffic micro-simulation and multi-agent simulation packages were evaluated for representing the DRTS. However, no existing traffic simulation system was able to easily represent the dynamic demand and random pick-up and drop-off trip patterns. Although several multi-agent simulation packages evaluated allowed the dynamic aspects of a DRTS to be considered they had difficulty incorporating a traffic network. Similarly to [2], [23] and others, we finally decided to develop our own simulation model. The model is implemented in Delphi, which provided a flexible development environment that allowed both the dynamic travel demand and traffic network elements to be integrated. However, this required considerable effort in developing procedures and limited the level of animation.

A. *Customer Demand Generation*

Procedures were developed to generate the demand information of customers using the system. These details were determined before running the simulation model and used as input. Although there are several types of requests that customers could have in a demand responsive transport system only ad-hoc requests to pick-up as soon as possible were considered. Thus pre-booked requests were not included.

The total number of customers, temporal distribution of requests (proportion of requests in each operating hour) and the proportion of short (1-5km) and long (5-10km) trips are specified as global parameters. Using these details, the requested times and origin and destination nodes were randomly generated.

B. *Customer Allocation*

The simulation model's time clock was updated at discrete time intervals. The customer demand file was checked to determine whether a new request was received during the previous time interval. The customer's request time is determined in advance by the customer demand generation procedure. If a customer request falls within the previous time interval, the customer is allocated to a vehicle.

Customers are allocated to a vehicle. Vehicle's have an itinerary of customers already allocated to them. This is a list of ordered customer pickups and drop-offs. The customer allocation procedure determines the best position to insert the customer's request in each vehicles itinerary. The customer is allocated to the vehicle that has the least additional travel and penalty cost. This accounts for the vehicles' existing itinerary and their current location in the network.

Penalty costs are calculated for all customers in a vehicle's itinerary according to the formula presented in Appendix A. This involves a travel time ratio for each passenger, i.e., the ratio of the planned travel time over the direct travel time. A quadratic travel time ratio relationship was used to calculate the penalty cost.

C. Cost Determination

Costs for each passenger were determined after the simulation model was run. The costs associated with providing the service were derived and assigned to each customer. A relationship incorporating both fixed costs as well as the customers trip's distance was used according to the formula presented in Appendix B. Fixed costs were determined by the average fixed cost per passenger. A distance rate, based on the total variable costs, the total distance travelled by all vehicles and the distance of the passenger's trip was used.

D. Performance Measures

For each simulation run a number of statistics were determined for both customers and vehicles. The average number of passengers, distance travelled, waiting time and occupancy were calculated for vehicles. The distribution of journey times expressed as a ratio of direct times as well as the distribution of costs for customers were also estimated.

IV. Model Application

The model was used to investigate the viability and levels of service for customers of the DRTS. A hypothetical urban grid traffic network was used in the model's application. This was comprised of a 6km by 6km grid network (Fig. 1). A grid of arterial roads 1km apart (dark lines) defined cells or local areas. Three densities of local streets were created, low in the outer areas, medium in middle areas and high in the inner areas. Travel speeds on the arterial roads were assumed to be 50 km/h, and 30 km/h on the other streets.

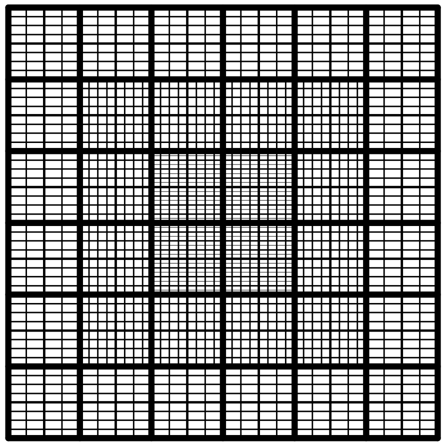

Fig. 1: Grid traffic network

Customer requests were generated for short trips uniformly distributed over a five hour period. The model was run until the last customer was dropped off. All vehicles had a seating capacity of ten passengers.

Results were generated for investigating the performance of the systems under a variety of conditions, including:

(i) Number of vehicles (20 to 35)
(ii) Number of customers (1500 to 3000)
(iii) Penalty quadratic coefficient (0 to 2)

The DRTS represented here only involved ad-hoc requests, where customers request to be picked up as soon as possible. The requested times were generated using Monte-Carlo simulation based on a uniform distribution over the entire five hour period.

The effect of the total number of customers requesting the service on the costs for a fixed number of operating buses was investigated. For each run, a distribution of costs was estimated. Fig. 2 presents the costs when 35 buses were available for operation. Decreasing costs per customer were estimated as the total number of customers increased. At the higher demand levels the costs appear to be reasonable approaching that of traditional public transport services.

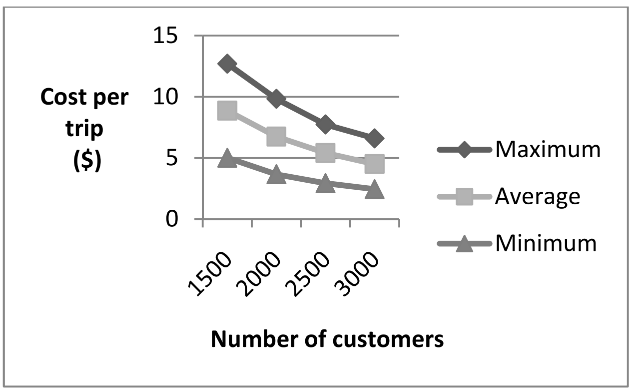

Fig. 2: Service costs and demand levels

The model allowed levels of service in terms of travel time and waiting time to also be estimated. The travel time ratio, defined as the ratio of the actual journey time to the travel time if the most direct route was travelled was used to investigate the performance for users of the system (Fig. 3). As expected the percentage of persons experiencing longer travel times increases as the number of customers increases.

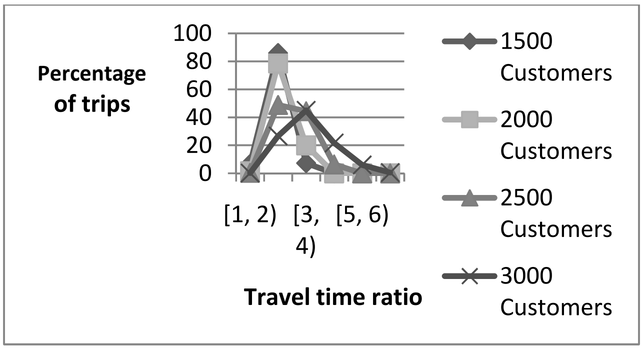

Fig. 3: Travel times and number of customers

Customers are assumed to be sensitive to the time between when the service was requested and the time the vehicle arrived to pick them up. Average waiting times decreased as the number of customer increased due to the increased likelihood of customers in the same areas requesting travel at a similar time (Fig. 4).

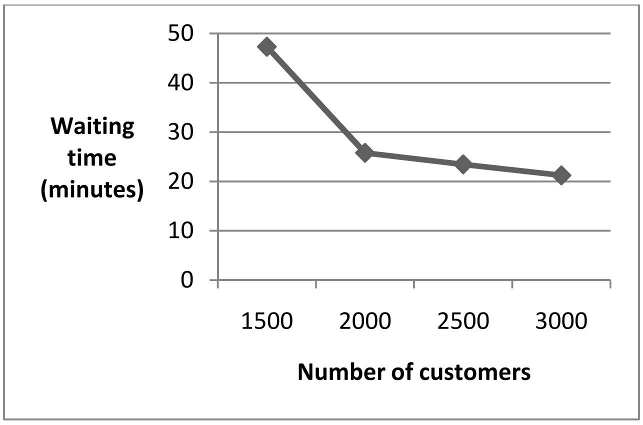

Fig. 4: Waiting times

The relationship between the number of vehicles in service and the average costs was also investigated. As expected the number of vehicles used increased as the average cost per trip increases (Fig. 5). Lower costs per trip were estimated when a larger number of customers requested travel.

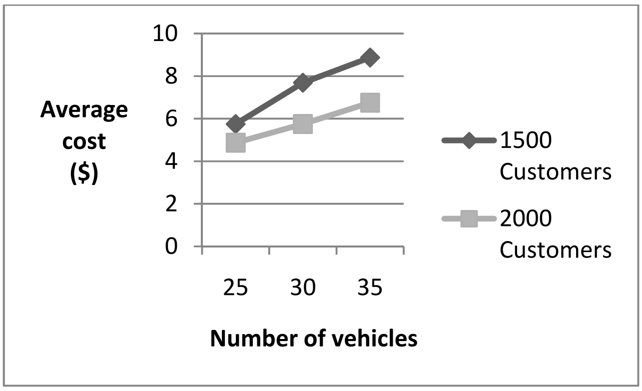

Fig. 5: Number of vehicles and costs

V. Conclusions

DRTS are becoming more becoming more feasible with developments in information technology. They offer a means for increasing mobility for example in low density urban areas, or in integrated public transport systems. This way, DRTS could provide alternative or complementary, environmentally and socially more sustainable forms of transport than traditional forms of urban public transport.

This paper has described the development and application of a model designed to investigate the viability of a DRTS for ad-hoc requests for point-to-point transport within a city. The model's results suggest that DRTS can provide reasonable levels of service for reasonable costs.

The model could be adapted to investigate a variety of further design alternatives or parameters, among them different types of requests such as booking trips in advance, or networks that include the use of transfer hubs that would provide higher levels of utilization and reduced operating costs.

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APPENDIX

A. Penalty costs

$PC_i = TTR_i + \beta TTR_i^2$

where,

$PC_i =$ penalty cost for passenger i

$TTR_i =$ travel time ratio for passenger i

$$= \frac{PTT_i}{DTT_i}$$

$PTT_i =$ planned travel time for passenger i (minutes)

$DTT_i =$ direct travel time for passenger i (minutes)

$\beta =$ quadratic coefficient

B. Passenger cost

$C_i =$ cost for passenger i $(i = 1, \ldots, P)$

$= \alpha FC + (1-\alpha) x_i DR$

where,

$P =$ number of passengers in a daily period

$\alpha =$ fixed cost proportion $(0 \le \alpha \le 1)$

$FC =$ fixed cost passenger charge ($)

$$= \sum_{\mathrm{j}=1}^{\mathrm{N}} fc_{\mathrm{j}} / P$$

$fc_{\mathrm{j}} =$ fixed cost for vehicle j ($ per day)$(\mathrm{j} = 1, \ldots, \mathrm{N})$

$\mathrm{N} =$ number of vehicles operating in a daily period

$x_i =$ direct trip distance for passenger i (km)

$DR =$ Distance Rate

$$= \mathrm{VC}/\mathrm{X}$$

$\mathrm{VC} =$ total variable cost of vehicles ($)

$$= \sum_{\mathrm{j}=1}^{\mathrm{N}} OC_{\mathrm{j}} \times \mathrm{t_j}$$

$OC_{\mathrm{j}} =$ operating cost for vehicle j ($ per hour)

$\mathrm{t_j} =$ time vehicle j is operating (hrs per day)

$\mathrm{X} =$ total direct trip distances for all passengers (km)

$$= \sum_{i=1}^{P} x_i$$