Optimizing the fleet size of a Personal Rapid Transit system: A case study in port of Rotterdam

Li Jie, Chen Yu Sen, Li Hao, Ingmar Andreasson, Henk van Zuylen

Abstract—Cost issues have been an important concern in the development of Personal Rapid Transit (PRT) since the concept was developed several decades ago. The lightweight, computer-guided electric vehicles operating the PRT system are generally a major part of the capital cost of the system, especially in larger network with high demand. A sufficient number of empty vehicles are needed to be moved to the stations where passengers are waiting or demand is expected. Generally a larger fleet size leads to a reduction in waiting time of passengers and thus a higher level of service given a specific demand, but an increased investment cost including capital cost per vehicle and additional operation and maintenance. So it requires a compromise between user cost (in terms of passenger waiting times) and operator cost (in terms of fleet size-dependent capital cost and operating/maintenance costs). There should be an optimal fleet size so that the sum of these two costs can be minimized while an expected level of service is achieved. This paper presents first the way to obtain the PRT demand, and then a prescription to determine the optimal fleet size using a cost-effectiveness analysis with traffic simulation. This prescription identifies the set of activities that are necessary to perform the optimization task. Each activity is regarded as a component in our general framework and this framework is illustrated by a case study in the Waal/Eemshaven harbor area in the Port of Rotterdam.

I. INTRODUCTION

A Personal Rapid Transit (PRT) system provides an automated on-demand, non-stop transportation service with small sized, computer-guided vehicles for 4 to 6 passengers running on a dedicated network of guide-ways. Rather than in bus or train systems, where people have to wait for transit vehicles, normally a few empty PRT vehicles are waiting at stations for passengers or circulating on the network to serve the requests of passengers as soon as they arrive. The flexible service by many small vehicles can provide much lower waiting time for passengers at stations than mass transit like bus and metro, and is rather independent of the number of passengers. This is one of the main appealing features of PRT compared with conventional public transit. If the fleet size is sufficiently large, passengers arriving at stops always find empty vehicles available. This gives zero waiting times. However, in practice, for high peak demand, the fleet size is subject to financial constraints and will not be so large that all passengers can have zero waiting time. The PRT vehicles are still rather expensive at this moment and contribute significantly to the total investment costs of a PRT system. For example, the PRT vehicles that are built for the track at Heathrow airport cost about €140,000 each. This makes about 10% of the total investment costs of a PRT system. Similarly it is reported that the initial vehicle cost estimate for Sky Loop system in Ohio [1] are $18,321,406 (24% of total). Therefore, optimization of the fleet size of a PRT network becomes a necessary task in PRT planning in order to make a trade-off between the level of service in terms of expected waiting-times or maximum waiting-times for the entire network and the whole day. The implementation costs consist of the capital cost of vehicles and the operating/maintenance costs. The infrastructure costs are not taken into account in the optimization, since they are independent on the number of vehicles. A case study has been made to analyze the balance between waiting-time of passengers and the investment and operation costs. The case study is done for a part of the port of Rotterdam, a harbor area close to the city with many working places and some public transport at a distance. The optimum fleet size is determined by optimizing the total costs, including the value of waiting times. This is done by simulation of the PRT system for different number of vehicles.

The fleet size required to serve the demands on a specific PRT network depends on several factors:

1. Network topology. A preliminary design of the PRT network for the case study is shown in Section 2 along with a brief explanation of it.
2. Spatial distribution of demand. The demand pattern has to be analyzed: how many people will use the PRT system and from which stations they start their trips and to which stations they travel. A web-based Stated Preference (SP) survey has been carried out to investigate the traveler’s attitudes towards the innovative transport mode-PRT, and the traveler’s

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preferences versus other modes such as the automobile, conventional public transit including bus, train and metro. Section 3 will describe the survey and the successive modeling. This results also in the station-to-station Origin Destination (OD) matrix, which is one of the most important inputs for the simulation of PRT operation. After estimating the OD demand on the preliminary PRT network, we explore the relationship between the fleet size operating on the network and waiting-times that passengers experience at stations. Both costs are explicitly expressed in terms of Euros in a total cost function developed in Section 4. Then the economical analysis immediately results in an optimal fleet size.

3. Empty Vehicle Redistribution (EVR): Vehicles are normally waiting for passengers at stations ready to depart. But because the number of vehicles requested from a station need not equal the vehicles ending there or the vehicle may be blocking the way for other vehicles, some empty vehicles need to be sent to balance the flow and to mitigate congestion. Several EVR algorithms are proposed by Irving [2], Anderson [3], Bell and Wong [4]. Andréasson [3] refines the allocation of empty vehicles into three stages. The first stage is a sequential allocation. In the second stage, waiting passengers are allocated to the nearest vehicle on the basis of waiting time. In the third stage, the remaining empty vehicles en route are reallocated on the basis of minimum running distance. This algorithm was in the simulation program PRTsim developed by Andréasson [6] that we used in the case study.

In addition to these three factors, several others should be considered, like line speed in the simulation and the possibility to have ride-sharing when several travellers use the same vehicle [7]. Summarizing the discussion above results in a prescription for optimizing the fleet size, which is shown in Figure 1. The illustration of the components with the case study in the Port of Rotterdam, The Netherlands makes up the body of the paper.

Figure 1 Framework of optimization of fleet size for PRT

II. PROJECT DESCRIPTION AND NETWORK DESIGN

The case study of the Port of Rotterdam was initiated to investigate the possibilities to improve the accessibility of parts of the port area by means of cost-effective public transport. At present public transport plays a minor role, partly because the demand for transport is very diffuse in time and space. During the peak hours, passenger car traffic causes congestion and long delay. There is some collective transport organized by companies in the port area to serve their employees working in shifts. However, most of the workers in the port area travel by car, alone or with ride sharing.

The case study is aimed at assessing the feasibility of an innovative transport system that improves the accessibility, strengthens the existing transport facilities and facilitates the further development of the economic activities in the area. One particular area was chosen, two older harbors close to the urban region of the city, the Waalhaven and Eemhaven. After an inventory of the challenges and of the most promising innovative transport systems, PRT was chosen as the most suited extension of the present transport system. The design steps of the PRT network are intuitive: First, we defined places (nodes) to connect based on the functional, spatial and demographic analysis of the area and the objectives of the case study: to find ways to improve the accessibility of the area. The existing public transport stations are defined as entrance points of the network. Second, the nodes are connected as directly as possible. Single nodes on a larger distance have been removed from the network. This resulted in the network shown in Figure 2.
III. DEMAND ANALYSIS AND SIMULATION

The objective of demand estimation is two-fold. The first objective is to verify that the designed system will attract sufficient travelers to make it worthwhile. The second is to serve as input for a simulation model to get output for cost-effectiveness analysis.

The methodology follows the well-known demand Pivot method [7]. This is done by a transport model containing the information on network infrastructure and multi-modal demands covering the entire Netherlands. The data is developed for the whole country and integrated in a multi-modal traffic planning package Omnitrans[9].

This multi-modal model contains only existing major modes, without PRT. A new Stated Preference (SP) Survey was necessary to assess how travelers would switch their mode, based on the new hypothetical situation in which PRT is available.

The SP survey contains three parts. The first part is about the current behavior of the respondents: their departure time/place, travel mode, arrival time/place. The second part is a stated preference experiment where questionnaires present alternatives with their attributes, in order to determine the weight of each attribute (such as waiting time; free flow travel time – for PT this is the in-vehicle time; waiting time – for car passengers the congestion delay; walking time, out-of-pocket costs) for the different alternatives (car, bicycle, public transport including bus, metro, and tram, and PRT) presented to the respondents. The third part of the survey is their social-economic characteristics.

The details of the SP survey, the analysis and the resulting model are described in [10].

Fig. 3 gives an example of a question in the online SP survey. A conjoint Revealed Preference (RP) and SP approach has been followed. The current modal share is taken into account as prior knowledge and the SP survey provides the input for a new calculation of modal choice. Applying a multinomial Logit model, we immediately obtain the OD matrix for PRT in the port area. It was implemented in the Regional Traffic Model Rotterdam (RVMK) and transformed to the station to station demand matrix [9].

Then the station to station trip-making was simulated in PRTsim with the proposed PRT network by specifying parameters reflecting the system characteristics, such as travel speed, boarding and alighting time, station dimension etc...By varying the fleet size for a given demand and running the simulation several times (15 times in our case) for each level of fleet size so that the statistical reliability is guaranteed, we can get the corresponding average waiting-time and the longest waiting-time.

<table>
<thead>
<tr>
<th>Weather</th>
<th>Raining</th>
<th>Raining</th>
<th>Raining</th>
<th>Raining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free flow travel time</td>
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<td>24 min.</td>
<td>17 min.</td>
<td>30 min.</td>
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<tr>
<td>Waiting time</td>
<td>5 min.</td>
<td>5 min.</td>
<td>15 min.</td>
<td>--</td>
</tr>
<tr>
<td>Walking time</td>
<td>8 min.</td>
<td>4 min.</td>
<td>4 min.</td>
<td>--</td>
</tr>
<tr>
<td>Cost</td>
<td>€1.30</td>
<td>€2.50</td>
<td>€2.30</td>
<td>--</td>
</tr>
</tbody>
</table>

**Figure 3 Table of SP survey questionnaire**

**Figure 4 Waiting time versus Fleet size**

Fig. 4 presents the average waiting-time and maximum waiting-time of passengers for different fleet sizes. The waiting-time is on the horizontal to match the following analysis of the optimal fleet size. E.g. to meet a requirement of an average waiting-time less than 1 minute, at least 190 vehicles are needed. As is shown in Fig. 4, both maximum and average waiting-time decrease steeply as the fleet size increases from 100 to 200. But afterwards they decline slightly and level off with an average of 0.7 min and maximum of 3.8 min.

In the calculation the demand was assumed to be fixed, based on the OD model with an average waiting-time of 2 minutes. Of course, the demand would become less if the waiting time would become longer than 2 minutes, which would lower the waiting time for small fleet size compared with Figure 4. However, since we wanted to find an optimum
fleet size for relatively short waiting times, we did not have to put the OD model in the optimization loop.

IV. COST EFFECTIVENESS ANALYSIS

We determined the optimal fleet size by integrating two perspectives: the user perspective and the perspective of the operator / system owner. For both perspectives the costs and benefits are expressed in monetary values.

A. User perspective

We assume that cost perceived by the user’s is composed of two parts: Fare and travel time. The travel time can be converted to monetary cost by multiplying the estimated value of time (VOT). Practically speaking the impact of fleet size on the price of ticket can be neglected because in The Netherlands the public transit fare system is determined by the national public transit policy which depends more on social and environmental benefits than the capital and operating cost. This will especially apply to an innovative transit system like PRT.

Riding-time (in-vehicle time) is barely affected by fleet size as long as no congestion occurs in the case of an overloaded network.

Access and egress are not influenced by fleet size as well, so the only user cost component related to fleet size is the waiting-time. Thus the total user cost relevant to fleet size can be expressed in following way as a function of average waiting time:

$$C_{\text{user}} \text{ / yr} = \alpha_w \ast T_w \ast N$$

(1)

In eq. (1) \( T_w \) denotes the average waiting-time and \( \alpha_w \) is the monetary value of unit waiting time at a station. In our study we use the value for \( \alpha_w \) that was obtained from the Stated Preference questionnaire: 10 € /hr. \( N \) is the number of the PRT trips during one year. The demand analysis as described in [6] gives 4000 trips for 2 hours in the morning peak but in this case we do not know exactly what the demand profile (the demand variation during the day) looks like. For practical consideration, the demand is assume to be 10000 trips per work day for 300 work days per year.

B. Operator perspective

The term “operator” refers to the companies and agencies that are responsible for the financing, construction and operation of the PRT system. Adding a vehicle to the fleet does not only cost the price of the vehicle itself, but also the operation and maintenance costs. These costs are summarized and defined as “operator cost”. The values that are assumed have been derived from data provided by PRT developers and given by the following equation:

$$C_{\text{operator}} \text{ / yr} = C_{v} + C_{e} + C_{o\&m}$$

(2)

In eq. (2) the symbols have the following meaning:

- \( C_v \):-vehicle annuities (ME/yr):
  $$C_{v} = C_{v} \ast A_{i} = C_{v} \ast \frac{i}{1-(1+i)^{-n}}$$

where \( i \) is the interest rate and \( n \) is the life expectancy of the vehicle. In this study they are 4% and 15 years respectively. \( A_{i} \) is the amortization factor.

- \( C_{e} \):-annual electricity consumption (ME/yr), estimated by multiplying the cost per hour with running hours. In our calculation each vehicle is supposed to work 9 hours per day and 300 days per year, if unit electricity cost per vehicle per hour is 1.54 €, then total energy cost is 0.187 ME/(yr*veh).

- \( C_{o\&m} \):-annual cost for cleaning and fixing vehicles, supposed to be 5% of the vehicle cost \( C_{v} \). These costs are all proportional to the number of vehicles.

Figure 5 depicts the annual cost for the operator as a function of the fleet size.

C. System costs

The total costs \( C \) to be optimized are:

$$C \text{ / yr} = C_{\text{user}} \text{ / yr} + C_{\text{operator}} \text{ / yr}$$

(3)
Figure 6 Costs vs. Fleet size

Figure 6 plots each cost component and the total cost versus the fleet size. The optimal fleet size minimizes the total system cost. For the case study 150 vehicles is the optimum fleet size. The minimum is locally stable since the total cost appears to be not very sensitive to a small increase or decrease in the fleet size around optimum. The calculation followed does not take into account that if the number of vehicles increases and the waiting-time decreases, the number of passengers will increase and consequently the incomes from fares. The reason is simply the robustness of the optimum: changing the fleet size around the optimum only slightly changes the waiting times and does not have much influence of the modal choice. Irving [2] suggested that beside the maximum and average value, the distribution of waiting time is also very important when examining the quality of service. This is plotted in Figure 7. For the recommended fleet size of 150 it is shown that 86% and 55% of waits will be less than 2 minutes and 1 minute respectively.

Figure 7 Distribution of the passenger waiting time

For comparison, the analysis has been extended by considering two alternative fleet size 200 vehicles and 250 vehicles. As can be seen in Figure 7, adding 50 (100) more vehicles will increase the percentage of waiting times less than 1 min and 2 min by 2 % (4%) and 12 % (15%) respectively. It would increase the investment costs considerably. It is obvious that a fleet size of 150 vehicles is already adequate to handle the estimated demand at a low waiting time level. A fleet size of 200 or even 250 vehicles would give an oversized system.

V. CONCLUSION

This paper presents a framework for optimizing the fleet size for a PRT system. The framework considers major components such as the network design, the OD demand, a simulation of the operation of the PRT system, and a calculation of the cost-effectiveness from both user’s and operator’s perspectives. The implementation of this methodology is illustrated by a case study for the Port of Rotterdam. The methodology is generic and can be applied or transferred to other locations. This work provides an open reference for a cost-effectiveness analysis to determine of the fleet size of PRT system.

REFERENCES