A choice-driven framework for an integrated demand responsive mobility system

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1 Introduction

In Demand Responsive Transport (DRT) people can make use of more personalised public transport in which they are transported in smaller vehicles, possibly taking a slight detour to serve other requests at the same time. Traditionally, DRT systems were created for elderly and disabled people to abide to government regulations that required accessibility for these groups where Fixed Line and Schedule (FLS) transport services could not offer this service (Nelson et al., 2010). In low demand areas, FLS transport can however be inefficient due to the low number of passengers using the service. Therefore, introducing DRT systems as a complement to and/or partially replace FLS transport could be of interest (Alonso-González et al., 2018). Besides potentially increasing the profit to the company, other potential benefits exists. One potential benefit is increased customer satisfaction due to the more personalised public transport. Furthermore, as this might prevent large busses from driving to serve a small amount of people, using DRT could lower the emissions and road congestion.

The aim of this study is to evaluate the effect of using DRT systems in combination with existing FLS transport. Here, we assume DRT services to be offered from and to bus stops in the existing FLS transportation system and hence the decision to be made is whether a bus stop will remain a stop in the current bus lines, whether it will serve as a DRT system stop, or both. To evaluate the effect of the addition of DRT services on customer decisions, a customer choice model is used as input for the problem. We propose an Adaptive Large Neighbourhood to solve this problem. This method is tested on a case study from a public transport company in The Netherlands.

2 Choice Driven Optimisation Framework

To determine the optimal trade-off between DRT services and FLS transport, it should be known how many people will commute between the different stops. With the help of utility maximisation theory, a utility function is dedicated to different possible alternatives namely: using DRT, using FLS, or not using public transport at all, depending on the offered options. A trip could solely include DRT, FLS, or DRT and FLS. To find the utility of the (potential) customers, the approach is similar to the case introduced by Atasoy et al. (2015). Parameters that influence the utility for a trip are price, in-vehicle travel time, waiting time outside the vehicle, and number of transfers (Atasoy et al., 2015; Robenek et al., 2016).

Given the output from the choice model, a Mixed Integer Linear Problem (MILP) can be constructed to model the decision regarding the FLS and DRT trade-off as to maximise the profit. We will use decision variables x_s denoting whether bus stop $s \in \mathcal{S}$ is part of the DRT network, and y_{bs} denoting whether bus line $b \in \mathcal{B}$ stops at stop $s \in \mathcal{S}$, for $\mathcal{S}$ the set of bus stops and $\mathcal{B}$ the set of bus lines. To compute the profit, we need to determine the number of trips between the different stops using DRT and FLS, $\vartheta_{od}^{\mathrm{DRT}}$ and $\vartheta_{od}^{\mathrm{FLS}}$ respectively. In order to compute this, we need to define some more variables. For the following variables, let $o \in \mathcal{S}$ and $d \in \mathcal{S}$. First, let α_{od} be 1 if DRT is required for trip (o, d), that is, when at least one of o and d is not part of the FLS network, 0 otherwise. Second, let β_{od} be 1 if choice option 1: {DRT} is offered, that is, when stops o and d are both part of the DRT network and at least one of o and d is not part of the FLS network, 0 otherwise. Next, let γ_{od} be 1 if choice option 3: {DRT, FLS} is offered, that is, when both stop o and d are part of the DRT and FLS network, 0 otherwise. Finally, let δ_{od} be 1 if choice option 2: {FLS} is offered, that is, when both stop o and d are part of the FLS network but at least one of o and d is not part of the DRT network, 0 otherwise.

Using the number of customers that want to travel from $o \in \mathcal{S}$ to $d \in \mathcal{S}$ (qt_{od}), $\vartheta_{od}^{\text{DRT}}$ and $\vartheta_{od}^{\text{FLS}}$ can be computed using equalities (1)-(6). Here, $p1_{od}^{\text{DRT}}$ and $p3_{od}^{\text{DRT}}$ represent that probability that a customer chooses DRT to travel from o to d when either alternative {DRT} or {DRT, FLS} is offered, respectively. Similarly, $p2_{od}^{\text{FLS}}$ and $p3_{od}^{\text{FLS}}$ represent the probability that a customer chooses FLS to travel from o to d when alternative {FLS} or {DRT, FLS} is offered, respectively. Using the number of trips between two stops, the revenue (r_{od}) between theses stops can be computed using the fixed and variable prices for the DRT and FLS tickets.

$$\alpha_{od} = 1 - \min\Big\{1, \sum_{b \in \mathcal{B}} y_{bo}, \sum_{b \in \mathcal{B}} y_{bd}\Big\} \qquad \forall o, d \in \mathcal{S} \qquad (1)$$

$$\beta_{od} = \min\{x_o, x_d, \alpha_{od}\} \qquad \forall o, d \in \mathcal{S} \qquad (2)$$

$$\gamma_{od} = \min\{x_o, x_d, 1 - \alpha_{od}\} \qquad \forall o, d \in \mathcal{S} \qquad (3)$$

$$\delta_{od} = 1 - \max\{\alpha_{od}, \gamma_{od}\} \qquad \forall o, d \in \mathcal{S} \qquad (4)$$

$$\vartheta_{od}^{\text{DRT}} = qt_{od}\big(p1_{od}^{\text{DRT}} \times \beta_{od} + p2_{od}^{\text{FLS}}(\alpha_{od} - \beta_{od}) + p3_{od}^{\text{DRT}} \times \gamma_{od}\big) \qquad \forall o, d \in \mathcal{S} \qquad (5)$$

$$\vartheta_{od}^{\text{FLS}} = qt_{od}\big(p2^{\text{FLS}} \times \delta_{od} + p3_{od}^{\text{FLS}} \times \gamma_{od}\big) \qquad \forall o, d \in \mathcal{S} \qquad (6)$$

The total distance driven by DRT vehicles and FLS vehicles can be computed as in (7) and (8) respectively, with di_{od} the distance between bus stop o and d, c a multiplication factor to account for detours taken on DRT trips, f_{O_b} the frequency of bus line b n the initial FLS roster, and l_b the length of bus line b computed as the sum of distances between the consecutive bus stop in the bus line.

$$d^{\text{DRT}} = c \sum_{o \in \mathcal{S}} \sum_{d \in \mathcal{S}} di_{od} \times \vartheta_{od}^{\text{DRT}} \qquad (7)$$

$$d^{\text{FLS}} = \sum_{b \in \mathcal{B}} fo_b \times \ell_b \qquad (8)$$

To compute the profit (Π) of the network per time unit (9), we use the salary of drivers cs, the number of drivers used for the DRT vehicles w, the fuel and maintenance price per distance unit per DRT and FLS vehicles (cd^{DRT} and cd^{FLS} respectively), the number of DRT vehicles needed (b^{DRT}), and the write-off cost per time unit per DRT vehicle. For the number of DRT vehicles required to serve the customers, we use simulation results from the public transport company that has provided us with the case study. As DRT can only be used for a limited number of trips per hour, we assume the number of FLS vehicles in the integrated model to be equal to the number of FLS vehicles in the original setting. Hence, these costs are excluded as they can be considered as parameters.

$$(\Pi) : \max \quad \sum_{o \in \mathcal{S}} \sum_{d \in \mathcal{S}} r_{od} - \Big(cs \times w \ + \ cd^{\text{DRT}} \times d^{\text{DRT}} + \ cd^{\text{FLS}} \times d^{\text{FLS}} + \ cw^{\text{DRT}} \times b^{\text{DRT}}\Big) \qquad (9)$$

A bus line can only stop at a bus stop if it is part of the bus line in the current situation. Furthermore, each bus stop should be served by FLS and/or DRT. For small instances, the problem can be solved using the MILP to find the optimal combination of DRT and FLS stops in the transportation network. However, as the number of variables in the MILP is in the order of magnitude of $2|\mathcal{S}|^2$ and the number of constraints is in the order of magnitude of $(|\mathcal{B}|+18)|\mathcal{S}|^2+|\mathcal{B}|^2|\mathcal{S}|$, the size of the service area has a crucial impact on the running time. Therefore, a heuristic is required to solve the problem for larger instances.

3 Adaptive Large Neighbourhood Search

To solve this problem, we have chosen to use an Adaptive Large Neighbourhood Search (ALNS). In an ALNS, a solution is destroyed using a destroy heuristic and consequently repaired using another heuristic (Gendreau & Potvin, 2010). By using different destroy and repair heuristics that are chosen with a probability based on their performance and incorporating meta heuristic methods such as simulated annealing, the aim is to find a good solution in terms of its quality and computational time and try and prevent getting stuck in local optima. An ALNS has been successfully applied to various types of problems such as the Vehicle Routing Problem (Ropke & Pisinger, 2006).

In the ALNS, we start with the solution in which all bus stops operate on the bus lines that could also potentially serve as a DRT stop. The number of trips that can be executed by DRT vehicles is taken from a simulation study. A penalty is imposed when the number of DRT trips exceeds the maximum number of trips served by the DRT vehicles. Then, using a destroy heuristic various bus stops will not operate on a bus line and/or will not serve as a DRT stop anymore. Consequently, for these bus stops it is decided what travel options should be offered at that bus stop.

We use different destroy heuristics that aim to diversify or intensify the solution. Some general heuristics are used such as a random removal and a historical removal based on former solutions with low objective values. Furthermore, a heuristic is used that removes a bus stop from all bus lines. Finally, a heuristic is used in which the high demand stops are removed from the DRT network and low demand stops are removed from the FLS network. The intuition behind the latter heuristic is that if there are many customers, it is worthwhile for a large bus to stop at that bus stop compared to stopping at a bus stop with low expected number of customers. To repair the solution, we make use of a greedy repair as well as a historical repair based on the best solutions found so far. Detailed explanation are provided in the final paper. In the next section, we present some of the main results.

4 Results

To evaluate the quality of the ALNS, it is first applied to a small instance consisting of two bus lines and compared to the optimal solution of this instance. The fixed price of a DRT service is set to €1.5 and a variable price for the ticket of €0.3. These prices are taken from the case study as they are representative for DRT ticket prices in The Netherlands. The gap between the optimal solution and the solution found using the ALNS is 4.5%. As the ALNS was able to retrieve this solution within 20 minutes, while the MILP used a couple of hours, we can conclude that the ALNS is able to find good solution in terms of its quality and running time.

The case study concerns the region around a medium-sized city in The Netherlands with population density ranging from 500 to over 2,500 inhabitants per square kilometre. The bus lines connect the small villages with the city as well as to Amsterdam.

The ALNS is applied to the case study using different pricing combinations to evaluate the effect of changes on profit. Here, we have taken the fixed price (p^{DRT}_{fixed}) to be €1.5, €2.0 or €2.5 and the variable price (p^{DRT}_{dist}) €0.3 or €0.5 per kilometre. Table 1 reports the current profit using only FLS transport (Π^{FLS}) and the solution characteristics of the result of the combined FLS and DRT network. Here, Π^{DRT} is the profit obtained when DRT is added to the FLS network and d^{DRT} and d^{FLS} represent the distance travelled by DRT and FLS vehicles, respectively. n^{DRT} and n^{FLS} represent the number of DRT and FLS customers served, respectively. The number of dropouts, i.e. the number of customers that do not use public transport, is presented by n^0.

Table 1: Results of the ALNS for different time windows and pricing combinations for DRT tickets

Time Window	FLS			DRT						
	Π^{FLS}	n^{FLS}	n^0	p^{DRT}_{fixed}	p^{DRT}_{dist}	T (min.)	Π^{DRT}	n^{DRT}	n^{FLS}	n^0
Weekdays 7-17 & Saturday 10-16	396.34	455.38	21.62	1.5	0.3	26.80	406.31	23.52	433.67	19.82
					0.5	23.93	428.50	24.96	432.19	19.85
				2.0	0.3	22.23	412.51	24.65	432.57	19.77
					0.5	23.30	436.07	24.82	432.60	19.59
				2.5	0.3	24.21	430.95	24.99	431.34	20.67
					0.5	23.80	457.25	24.99	431.89	20.13
All days 19-22	-129.96	94.65	4.35	1.5	0.3	25.14	-113.08	24.77	73.36	0.87
					0.5	23.01	-91.37	24.93	72.45	1.62
				2.0	0.3	20.43	-100.67	24.99	72.37	1.64
					0.5	22.28	-78.05	24.99	72.30	1.72
				2.5	0.3	22.98	-98.77	24.99	73.20	0.81
					0.5	23.81	-67.96	24.91	73.07	1.02
Sundays 11-17	234.47	285.63	14.37	1.5	0.3	23.64	243.29	24.95	262.39	12.66
					0.5	25.35	265.25	24.88	262.33	12.78
				2.0	0.3	27.28	252.85	24.55	262.83	12.62
					0.5	25.12	277.53	24.95	261.54	13.51
				2.5	0.3	25.62	266.75	24.78	261.60	13.61
					0.5	30.96	292.46	24.97	261.40	13.63

Table 1 shows that adding DRT to the network leads to more revenue compared to using solely FLS transport. Furthermore, the service level is increased as more customers are served. The extent to which the revenue is increased depends on the time window in which it is applied as well as the price of the DRT tickets used. We see that, although profit remains negative due to governmental subsidies, especially during the evening hours adding DRT to the system is beneficial. A possible explanation for this is the lower number of customers that use public transport during this time frame. The resulting transportation networks consists for the majority of bus stops that are operated by bus lines, however there are bus stops at which the option to travel by DRT is available as well as bus stops that solely have the DRT option.

It is likely that the type of geographical region has an impact on the resulting solution. Furthermore, the sensitivity of the customers to the price, travel time and number of transfers is likely to affect the degree of Demand Responsive Transport in the network.

In this case study, we have taken the choice model as input in a static way. Hence, the number of customers that want to travel from one bus stop to another is fixed. However, when changes are made to the transportation network, customers reconsider their travel options. This does not only affect the total number of customers in the system, but also shifts the demand for transport between the different stops as one might decide to travel from and/or to a different stop if the travel options at the bus stops change. Not taking this into account is a limitation of this model and it would thus be of interest in order to evaluate the effect of changes to the transportation network on the travel decisions made by customers.

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