Development of a Simulation Model to Combine Schedule-based and Demand Responsive Modes and Economical Evaluation of such a System

Jonas Henken and Simon Jedelhauser

Abstract

Resent technological advance lay the foundation for new transport system. This paper proposes combining traditional line- and schedule-based public transport with a demand responsive service in an urban setting. While common buses operate on the main arteria, a fleet of automated vehicles provides the first- and last-mile accessibility. The goal of this system is to reduce the cost for the owner by reducing unused capacity and to increase the comfort for the user by offering an integrated door-to-door transport service.

Previous research focuses on the replacement of a complete line-based transport system with a demand responsive transport (DRT). For this approach, different simulation models were developed and case studies done to show its potential. However, the combined system as suggested here, has received little research attention.

Based on the agent-based transport simulation framework MATSim a model was developed which allows simulating the desired system behavior. Even though the implementation does not correctly represent every aspect of the suggested processes, it allows producing preliminary results.

A case study was set up based on a real network taken from a part of the city of Zürich and using an artificially created population.

Simulations with this setup show, that the developed model approximate the desired behavior. Further, the results allow evaluating the economic feasibility. Based on cost estimates for all system components, a potential yearly saving of 6% is possible without causing considerable loss of quality for the user.

1 Introduction

Emerging technologies bring potential for new transport systems. With these technologies, urban public-transport can possibly be improved for all parties involved by utilizing the potential of new vehicles and software. This project introduces a new way of combining traditional line- and schedule-based public transport and a demand-responsive system with the goal to strengthen the arteria while replacing underutilized buses by a fleet of autonomously operating electric shuttles. This concept promises to reduce costs for the operator while maintaining or possibly improving the service quality for the user.

This project seeks to analyze the feasibility of the suggested system based on a simulation study. Since this concept has not yet received much research attention, a simulation model which allows representing the desired behavior must first be developed. This model can be tested in a carefully designed case study. The results allow a preliminary estimate of potential economic implications.

The model was built in the multi-agent simulation framework, MATSim, since this approach allows to realistically estimate the change in the utility for the users. This open source, community-based framework facilitates extending the core modules to allow including demand responsive transport services. In order to observe the desired interaction between schedule-based public-transport and DRT the parameters must be adjusted carefully.

A case study was designed in order to test the developed model and to produce results to estimate the economic feasibility. This study is based on selected perimeter in the north of Zürich.

This report will firstly review existing literature to gain a theoretical background and to put the analyzed model into context. Secondly, the suggested public transport system is described in all detail and relevant terminology is defined and explained. It follows the development and description of the methodology and software used and the encountered challenges. Finally, the case study is designed with all required inputs and specifications. The last chapters document the simulation scenarios designed, the results and their interpretation.

2 Literature review

The definition of the concept of demand responsive transport (DRT) is very variable depending on the goal of the proposed system. Ryley et al. define demand responsive transport as an “intermediate form of public transport, somewhere between a regular service route that uses small low floor buses and variably routed highly personalized transport services offered by taxis” [1]. This could be rephrased to describe a reliable form of transport where the operation perimeter and times are clearly defined just as it is the case in traditional, route- and schedule-based public transport, but where no defined routes or timetables exist.

Various case studies look at a demand responsive transport offer in rural areas where operation of a classical public transport system is not profitable (such as [2, 1, 3]). Apart of limiting the service to rural areas, they suggest that the demand responsive service should be designed for and offered exclusively to very specific client groups such as patients on non-emergency hospital visits. As in these areas public transport is not lucrative, and most people are likely to use private vehicles, the demand is limited to those, who cannot drive, or do not own a vehicle. This especially happens to be the elderly, children and sick people. While Mounce et al. focus on hospital access [2], Ryley et al. wanted to find out in which cases a DRT system might be economically feasible by investigating six well-defined user groups or trip purposes, including transfer offers to airports or shopping centers [1]. Additionally, they considered a demand responsive transport system providing commuter access to rural train stations. This study is based on 400 face-to-face surveys. The results show that only the airport shuttle and station-access promise an economically attractive market share. While these studies focus on rural areas, Rahimi et al. suggests DRT to serve similar client groups in large urban areas [4].

Other authors suggest replacing local bus systems in small cities or suburban settings with DRT (such as [5, 6]). Navidi et al. conclude based on a simulation study on artificial and real networks that “replacing conventional public transport with demand responsive transport will improve the mobility by decreasing the perceived travel time by passengers without any extra cost under certain circumstances.” [6] Barrilero et al. conducted a case study for Schorndorf, a 40’000 inhabitants city in Germany, replacing all bus lines with DRT [5]. An ant colony optimization process was carried out which finds the shortest way for each DRT vehicle. The automated vehicles are shared, what can cause detours for passengers already aboard. In order to quantify that, a so-called Direct Route Factor was defined as the ratio of maximum time window size and direct travel time if the car would not be shared. Barrilero et al. make clear how important the development of optimal routing algorithms is in order to solve the so called “travelling salesman problem”.

Indeed, the dispatcher faces a great challenge when trying to manage the fleet of DRT vehicles in the best possible way, minimizing user delay and wait time while not violating the constraints given especially by vehicle availability. As stated by Maciejewski and Nagel “the Vehicle Routing Problem (VRP) is among the most complex and fundamental components of modern fleet management.” [7] Maciejewski further analyzed how this problem can be addressed within the MATSim framework.

The before mentioned studies consequently assume replacing the classical public-transport completely by DRT. Narayan et al. suggest a system in which both systems coexist, and users can freely choose between one and the other [8]. Perera et al. goes a step further, suggesting a system in which DRT is combined with traditional public-transport as an integral service offer. The interaction is considered in a way that classic line- and schedule-based modes serve most of the distance whereas DRT ensures convenient access to public transport infrastructure – serving the first- and last-mile [9]. A mathematical model was developed to evaluate the behavior of such a system. The authors point out that the total passenger travel time consisting of waiting time and riding time has to be minimized .

The combination of a conventional system and more flexible public-transport modes within one integrated offer as suggested by Perera et al. is a new approach, which did not yet receive much attention.

3 Introduction to the suggested system

The analysis of past research on demand responsive transport systems shows, that in most cases the DRT seeks to replace the existing public transport completely. The system proposed in this study tries to combine both, schedule based and demand responsive public transport, into one integral system. In an urban setting low occupancy bus lines are removed, and a fleet of demand-responsively operating vehicles is introduced instead. The DRT is designed to serve on the first and last mile only.

The idea is that the user searches the possible transport option in an online application for the desired trip by defining his current location and the final destination. If no bus stop is close by, or if the overall trip time can be considerably reduced by using a different stop, the application offers the possibility of using DRT to access the bus stop and calculates the estimated waiting time based on the current fleet occupation. Based on this information the user can decide to accept this suggestion or walk anyway. If he accepts the DRT route, a vehicle is requested and sent to pick up the user in time for him to arrive at the bus stop before the departure time of the bus. The user is informed on the planned arrival time of the DRT at his location and is expected to wait on the sidewalk to avoid delays. The same procedure can be applied on the egress leg where the DRT vehicle will be waiting at the bus stop to take the user to his final destination. Clearly, this system requires a certain buffer time as requested vehicles must be deviated from their previous route to pick up a new passenger. Depending on the size of the perimeter and the current distribution of the vehicles, this planning horizon can limit the flexibility of the user, as he must request the ride with sufficient anticipation. However, this lack of flexibility is compensated by reducing the required walking distance.

The implementation of the complete dispatching algorithm is beyond the scope of this project. Therefore, a simplified version of this model is developed where DRT is available as an access- and egress-mode for schedule based public transport. The request is however still done exactly at the desired departure time and the dispatcher has no possibility to match the DRT routes to the timetable of the traditional public transport lines.

4 Specifications and parameters in the system

The new public transport system including traditional line-based service and DRT contains many uncertainties that are described in this section. Unfortunately, the number of factors exceeds the scope of this project, and not all of them can be considered. This section is divided into two main parts of which the first is a collection of parameters that have an influence on the operator's side and the second is the collection of parameters on the user's side.

4.1 Parameter for the operator's side

The cost for the owner consists of the investment into the fleet of busses and DRT, operations cost including fuel, and wages for drivers. The price of busses is assumed to be CHF 330'000 for common diesel- and CHF 1.6 million for double-articulated trolley-busses [10, 11]. To reflect the uncertainty in prices of automated vehicles, based on different sources three different values (namely CHF 50'000, 75'000 and 100'000) are used [12, 13]. The operation cost contains maintenance of the vehicles and energy and was estimated at CHF 1.45/km for diesel- and CHF 1.99/km for trolley-busses [10]. Based on various estimates, the operation cost for the DRT vehicles is set to CHF 0.30/km [12, 14]. Based on information from the local public transport operator, the wages for drivers were estimated at CHF 58 per hour [15].

The number of vehicles is part of an optimization process. Having a too small fleet results in a higher rejection rate and waiting times for the users. On the other hand, a very large fleet makes the whole system unprofitable for the owner due to excessive investment cost. This dilemma is especially difficult to solve as the demand is unpredictable in time and space. The number of vehicles is part of the sensitivity analysis in section 0.

As DRT is designed to serve on the first-/last-mile only, the distance covered in DRT must not exceed a certain limit. The maximal allowed distance by DRT is chosen in such a way that every resident within the perimeter can reach a bus stop (1400m) and the minimal distance is set to a distance which is still walkable (500m).

4.2 Parameter on the user's side

The user wants the highest possible quality of service and therefore a reliable, fast and comfortable transport offer. In the proposed system, the reliability can suffer if the rejection rate is too high as this leaves users in uncertainty whether the agent can execute his daily plan as desired. The travel time can be controlled by the acceptable detour parameter of the DRT dispatcher. Both of these arguments require a trade-off between higher investment cost for the owner and higher quality for the user.

5 Methodology and software

In the core modules of MATSim, each agent optimizes his plan from one iteration to the next. This so-called day-to-day planning does not allow for any "live-optimization" of the chosen plan during the execution. This means that before each iteration, the agent decides on exactly what route to take and even if it turns out to be closed, he does not divert from it. This works well for classical transportation modes such as cars and traditional public transport where by iterating, every agent can find his ideal route. However, a dynamically routed service such as DRT, cannot be simulated using this approach as the demand is not known in advance. It is necessary for the dispatcher to have the possibility to react to requests received and modify the route of each vehicle in real time.

This is commonly known as the "dynamic vehicle routing problem" and a solution is implemented in the *MATSim.contrib* module "*DVRP*" [7]. This is the basis for the DRT module, which implements a dispatching algorithm for demand responsive transport services allowing for sharing and many-to-many routing. Upon receiving a request from a user, the dispatcher tries to find the vehicle which can serve this request with the smallest additional penalty. A maximum travel time is defined which limits the delay each passenger can suffer. Additionally, the defined maximal wait time for the user requesting a ride must not be exceeded. If no vehicle can be found, the request is rejected. A rejected agent stops executing his plan in this moment as he does not have the possibility to choose an alternative way of traveling. To represent real behavior, these rejections would need to be handled differently.

A MATSim module developed by the Swiss federal railways (SwissRailRaptor (SRR)) [16] allows to define freely which mode an agent can use to access the public transport stop. This module is used to define DRT as possible access-/egress-mode next to the default option 'walk'. However, this setup does not allow the agent to choose his preferred access-mode freely since he only decides to use public transport and gets a route assigned by SSR. This brings certain problems since the fastest way is always chosen. DRT is faster than walking which leads to abusive use of this service. Even with an additional filter allowing DRT usage only for trips above 500m this behavior prevailed.

6 Case study

A perimeter was carefully chosen in the north of Zürich where the topography and current transport system promise successful operation of the suggested system. While the road network could simply be extracted from OSM [17] the network for buses is manually created and linked at each stop to the road network to allow passenger exchange between the DRT vehicles and busses. This perimeter contains three public transport nodes that bundle large demands. Most passengers continue from these stops to their final destination using traditional public transport. To reproduce this behavior additional long distance stops were added which are not accessible by DRT.

Two different timetables were implemented, one representing the current system (schedule full) and the other describing a reduced offer with only three lines and a reduced number of stops (schedule DRT2).

The population was created based on passenger counts from the local public transport operator. This was done based on the assumption that the same people will use public transport and therefore neglecting demand elasticity. Further, this approach did not allow analyzing the physical interaction of the public transport vehicles with private vehicles on the roads. A similar approach was chosen by Navidi et al. [6]. Each of the 25'000 agents in the created population had a simple initial plan with two activities: home and work.

7 Simulation and results

A set of parameter combinations was designed to explore the effect of different adjustments to both, the software model and the case study elements. Each simulation was run for at least 100 iterations allowing agents changing the mode choice, the timing and the route.

The primary values extracted from received outputs are the average best scores of all agents, the mode-share, the DRT-ride count and the rejection rate. The DRT-ride count and rejection rate allow evaluating whether the offered service (e.g. number of vehicles) is sufficient for the given demand and whether the offer is attractive. The quality of DRT is alternatively quantified by the mode share as those users which still walk, seem to not profit from the DRT service. The average maximum score allows preliminary evaluation of the utility for the user.

Based on the DRT usage statistics and the cost estimated before, the total owner cost could be estimated for each scenario. In Table 1 the costs were calculated for the benchmark scenario 40 and three alternative parameter combinations of the combined system.

Table 1: Calculation of the cost of the combined system of schedule based public transport and DRT based on three different price assumptions for DRT vehicles (a,b,c).

Scenario		**40**	**31.02**	**31.03**	**31.04**
average Best Score		135.93	133.83	134.79	134.98
a	**total yearly cost [CHF]**	2'972'500	2'980'000	2'786'000	2'900'000
	difference to benchmark		7'500	-186'500	-72'500
b	**total yearly cost [CHF]**	2'972'500	3'190'000	2'899'000	3'070'000
	difference to benchmark		217'500	-73'500	97'500
c	**total yearly cost [CHF]**	2'972'500	3'400'000	3'012'000	3'240'000
	difference to benchmark		427'500	39'500	267'500

8 Discussion

Based on the collected results, the importance of different parameters is evaluated.

Two scenario pairs compare a system with full bus service to one with the same service but added DRT. Surprisingly, both sets show a significant loss of utility (from 136.7 to 130.8 and from 135.9 to 133.5) when making DRT available. As still all bus lines are operating, no agent would need to use the new service as everyone has a bus stop in walking range, but still they do. This suggests that the access-/egress-mode choice of the agents is not sufficiently well implemented.

The goal of introducing a DRT system is to replace various bus lines, which today are not used as intensely as others are. Comparing the score of a system with full timetable and DRT to one with reduced bus service and DRT shows that the output values do change only by very little (e.g. score: 130.8-130.6). These observations suggest that in a system with available DRT, removing bus lines and stops does not reduce the quality for the user.

The envisioned transport system is based on shuttles, which can transport multiple passengers at a time. When a user requests a ride, the dispatcher looks for the DRT vehicle, which can serve this request with the smallest additional penalty and without violating the maximal acceptable detour of any passenger inside the vehicle. From the user's perspective reducing the acceptable detour optimizes the quality of the service, while for the operator this is likely to imply that more vehicles are required to serve the same demand. The output of different scenarios shows, that reducing the acceptable detour considerably increases the required fleet size and reduces the share of shared vehicles. Similarly, the maximally acceptable wait time can provoke rejections if no vehicle is currently in the proximity of the user. These two aspects can especially affect agents from the periphery of the perimeter.

The stopping duration of DRT vehicles when picking-up or dropping-off a passenger proved to have a considerable impact on the required fleet size and user comfort. In different runs, the wait time was reduced from 60 to 5 seconds. With this measure, the required fleet size could be decreased by 96 vehicles (from 210 to 114)

The previous observation focus on the quality of the developed simulation model. Additionally, the economic feasibility of the proposed system was analyzed. The cost estimates summarized before, show, that depending on the simulation parameters and the cost estimated for DRT vehicles, it is possible for the operator to save yearly up to 6.25% (CHF 186'500) compared to the benchmark scenario.

9 Conclusion

The goal of this project was to find a way to model an alternative public transport system in an agent-based simulation framework and to give a preliminary estimate on the economic feasibility of such a system. The suggested system seeks to combine schedule-based services with a demand responsive service of driver-less shuttles operating principally between bus stops and the activity locations of the passengers in order to eliminate underutilized bus lines and therefore to minimize the cost for the operator while maintaining the same service quality for the user.

The simulations were done using MATSim with its DRT module and the rail-raptor extension developed by the Swiss federal railways. This combination allows offering DRT as an access-/egress-mode for public transport trips. However, the mode choice does not always satisfy the expectations causing inefficiently long or unnecessary DRT trips. The behavior was improved by modifying the SRR code slightly, but further improvement is required to reproduce the envisioned system behavior. Such improvements promise higher overall scores and reduced operator costs since the efficiency of the mode choice and routing would be improved.

The results of the agent-based simulation show that a yearly saving of up to CHF 186'500 is possible while the average best score reached by the user indicates nearly equivalent service quality. However, the calculated total cost is very sensitive to the procurement cost of the DRT vehicles which cannot be determined reliably as the technology is not yet fully developed. Further, the expenses for the dispatching software and the maintenance personal are hard to quantify.

In conclusion, a model was found which promises to allow detailed implementation of the suggested combined transport system. This project, however, is limited to identifying points of improvement based on a preliminary analysis. Nevertheless, these first estimates allow approximating the cost of such a system. Based on the numbers used, saving of up to 6% is possible, motivating further analysis to

References

[1] T. J. Ryley, P. A. Stanley, M. P. Enoch, A. M. Zanni und M. A. Quddus, «Investigating the contribution of Demand Responsive Transport to a sustainable local public transport System,» Elsevier Ltd., 2014, pp. 364-372.

[2] R. Mounce, S. Wright, C. D. Emele, C. Zeng und J. D. Nelson, A tool to aid redesign of flexible transport services to increase efficiency in rural transport service provision, Journal of Intelligent Transportation Systems, 2018.

[3] N. Ronald, R. G. Thompson und S. Winter, «Comparison of Constrained and Ad Hoc Demand-Responsive Transportation Systems,» *Transportation Research Record: Journal of the Transportation Research Board,* pp. 44-51, 2015.

[4] M. Rahimi, M. Amirgholy und E. J. Gonzales, «System modeling of demand responsive transportation services: Evaluating cost efficiency of service and coordinated taxi usage,» *Transportation Research Part E,* pp. 66-83, 2018.

[5] M. Barrilero, A. Sauerländer-Bibel, A. Sohr and T. Hesse, "Development of a Demand Responsive Transport system with improvement analysis on conventional public transport: A Case Study for Schorndorf, Germany," in *2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*, Naples, 2017.

[6] Z. Navidi, N. Ronald und S. Winter, Comparison between ad-hoc demand responsive and conventional transit: a simulation study, Springer-Verlag GmbH Germany, 2017.

[7] M. Maciejewski und K. Nagel, «Towards Multi-Agent Simulation of the Dynamic Vehicle Routing Problem in MATSim,» 2014.

[8] J. Narayan, O. Cats, N. van Oort und S. Hoogendoorn, «Performance assessment of fixed and flexible public transport in a multi agent simulation framework,» *Transportation Research Procedia,* pp. 109-116, 2017.

[9] T. Perera, A. Prakash, C. N. Gamage und T. Srikathan, Hybrid Genetic Algorithm for an On-Demand First Mile Transit System Using Electric Vehicles, Springer International Publishing AG, 2018.

[10] Ernst Basler+Partner, «Systemvergleich Trolley-, Diesel- und (Bio-)Gasbus,» Zollikon, 2002.

[11] J. Meier, «VBZ kaufen Doppelgelenkbus,» NZZ, 30 3 2006. [Online]. Available: https://www.nzz.ch/articleDPM9D-1.22100. [Zugriff am 14 12 2018].

[12] D. Chen, K. Kockelman und J. Hanna, «Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions,» *Transportation Research Part A,* pp. 243-254, 28 09 2016.

[13] A. Nussbaum und M. Mawad, «This $290,000 'Robo-Taxi' Is France's Answer to Waymo,» blomberg, 07 11 2017. [Online]. Available: https://www.bloomberg.com/news/articles/2017-11-07/a-290-000-robot-car-is-french-startup-s-answer-to-gm-waymo. [Zugriff am 14 12 2018].

[14] Strategy&, «Studie: Betriebskosten von Elektroautos langfristig am günstigsten,» ecomento, 02 10 2018. [Online]. Available: https://ecomento.de/2018/10/02/studie-kraftstoffkosten-fuer-elektroautos-am-guenstigsten/. [Zugriff am 14 12 2018].

[15] VBZ, «https://www.stadt-zuerich.ch/vbz/de/index/die_vbz/portraet/zahlen_fakten.html,» VBZ, 31 12 2017. [Online]. Available: https://www.stadt-zuerich.ch/vbz/de/index/die_vbz/portraet/zahlen_fakten.html. [Zugriff am 14 12 2018].

[16] SBB, «MATSim-Extensions by SBB,» [Online]. Available: https://github.com/SchweizerischeBundesbahnen/matsim-sbb-extensions. [Zugriff am 26 11 2018].

[17] OpenStreetMap, «www.openstreetmap.org,» [Online]. Available: https://www.openstreetmap.org. [Zugriff am 14 10 2018].