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Performance assessment of fixed and flexible public transport in a multi agent simulation framework

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Abstract

The emergence of innovative mobility solutions that offer flexible transport services, is changing the way urban public transport systems will be designed. Such mobility solutions offer on demand transport services and hence can solve the problems inherent with traditional line based and schedule based public transport systems. It is essential to understand the dynamics of this new demand-supply market with co-existing and competing fixed and flexible public transport. However, the performance of the system comprising of users and transit services and the factors influencing them, have received limited attention in literature. In this paper a model is developed to analyse the system performance when the modes of fixed public transport and flexible public transport operate in competition. The model is implemented in the multi-agent simulation framework MATSim with dynamic assignment in which the users optimise their travel plan through iterative learning from the service experienced and altering their travel plan. The scenarios in which the flexible public transport offer private and shared services are considered. The system performance is analysed for varying fleet size of flexible public transport and ratio of cost of flexible to fixed public transport.

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Keywords: modal split, demand responsive transport, public transport, , agent-based simulation

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1. Introduction

Conventional public transport systems are characterized by services that are line based and schedule based. They operate along routes and schedules which are mostly fixed during the day offering high frequency services during peak-hours and relatively low frequency services during off peak hours. This requires rigid planning and operations and does not consider the real time variations in demand. Furthermore, it is often not accessible to users from areas with low demand density. This in turn leads to longer waiting times for transit users and the demand from regions of low demand density not being satisfied.

Recent technological advancements, namely real-time fleet management and travel booking platforms, have enabled the emergence of innovative mobility solutions which offer on demand services. These types of flexible public transport services can relieve the disadvantages inherent to fixed public transport systems. The demand is typically specified as a travel request which the operator/driver of the service receives through an online platform. The fleet of vehicles operated by the system may offer door-to-door service picking up passengers from their origin and dropping them off at their destination, or stop-to-stop service in which passengers are picked up and dropped off from pre-defined pickup and drop-off locations. The service offered might be a sequentially shared type in which a vehicle is shared in sequence by many passengers such that at each given time there will be only a single passenger in the vehicle or a simultaneously shared service in which more than one passenger share the vehicle on a given trip. Note that the service discussed here is different from the car (or bike) sharing systems in which travelers pick up vehicles from dedicated stations near their origin and drop off the vehicles at dedicated stations near their destination.

The modelling of fixed and flexible public transport systems have been studied by researchers over the years. Designing fixed public transport systems requires satisfying conflicting objectives. Some of the pioneering works in the area include Res and Baaj (1995), Ceder and Wilson (1986), and Mandl (1980). The problem deals with determining a set of routes over a network comprising of a set of nodes and corresponding links so as to minimize objectives related to passenger travel time, operator's operating cost, or their combination. The modelling of flexible public transport systems has been studied by researchers as a Dial-a-Ride Problem (DARP) which is a generalization of the Vehicle Routing Problem (VRP), which in turn is a generalization of the Travelling Salesman Problem (TSP). The major objective of the DARP is to determine a set of minimum cost paths and schedules to satisfy a set of travel requests subject to a set of constraints on time windows or deviation from the least cost path. Depending on whether the travel requests are known upfront or not, the problem can be considered static or dynamic respectively. An excellent review of the models and algorithms used for DARP is given in Cordeau and Laporte (2007). Due to the complexity of both the problems (NP Hard), generating an exact analytical/mathematical solution becomes nearly impossible for large instances of the problem. Hence heuristic/metaheuristic or evolutionary optimization methods have been used to obtain optimal solutions or improve a set of initial feasible solutions in search for an optimal solution such as in Uchimura et al. (2002), Nanry and Wesley Barnes (2000), Neumann (2014), Kuan et al. (2006), Arbex and da Cunha (2015).

Due to the growing availability of technologies that facilitate the large-scale deployment of flexible public transport services, its interaction with fixed services has recently been a subject of research. An IDARP (Integrated Dial-a-Ride Problem), a generalization of the Dial-a-Ride Problem, was formulated as scheduling travel requests where some portion of the trips is covered by fixed services. In most of those studies, the flexible system is modelled as a complement to fixed public transport services or as a means of access to an extensive public transport network (Posada and Anderson (2016), Uchimura et al. (2002)). In the literature which dealt with competing fixed and flexible systems, the flexible system was in some cases envisaged to consist of a fleet of fully-automated vehicles. The major focus of those works was on the simulation of such services in which fixed service was included as an alternative mode choice (Speranza (2016), Sebastian (2017), Lima Azevedo et al. (2016)). However these studies have not analyzed the effects of factors such as fleet size, operational strategy, and cost ratio on the performance of the system in the context of competing services. It is necessary to understand the extent to which these factors affect the dynamic demand-supply interactions. In this paper, an attempt is made to study the effect of different operational strategies, level of service, and service costs on the overall performance of the system when considering the perspectives of users as well as the operators of both services. The term 'fixed public transport'

refers to a conventional public transport system with pre-determined lines and schedules and a 'flexible public transport' refers to demand responsive transport systems comprising of a fleet of services serving real time requests.

The remainder of this paper is organized as follows. Section 2 describes the Methodology developed for this study, followed by Section 3 which presents the simulation setup and the various scenarios that are investigated. This is followed by Section 4 which presents the simulation results and analysis. The final Section 5, concludes the work with remarks and reflection of the authors.

2. Methodology

This section presents the developed methodology. An agent based simulation model is used for the study. The model is designed to represent the within day and the day-to-day dynamics of the system. An overview of the methodology is given in Fig. 1. The major components of the model are:

- Input
- Modal split
- Assignment
- Evaluation
- Re-planning

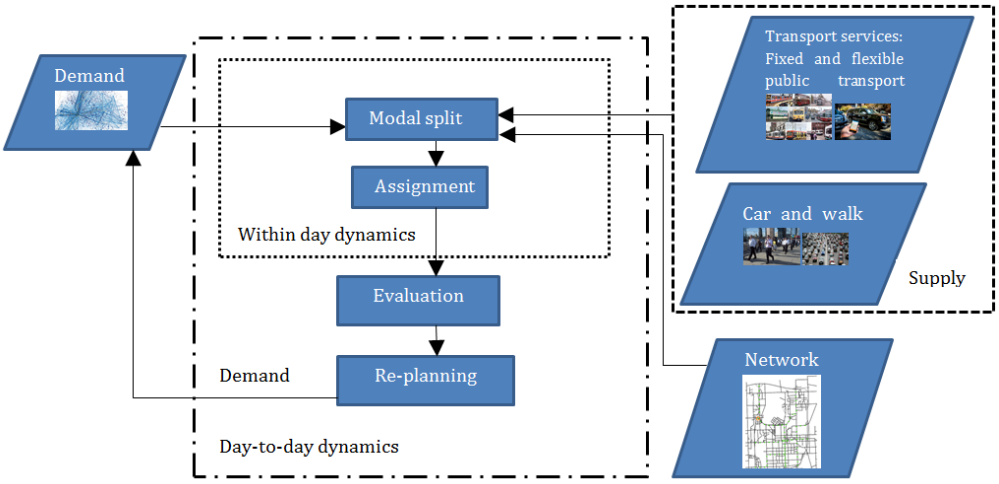

Fig. 1: Overview of the methodology

The Input module comprise of a network (with nodes and connecting links), supply, and demand. The supply consists of transport services provided by service providers and a default set of modes available to each user. The transport services comprise of fixed public transport (with a description of a route and a schedule per line and a fleet of vehicles) and flexible public transport (fleet of vehicles with on-demand services serving real time requests). The default modes available to each user are car and walk. The input data is used in the Modal split module in which users choose from the modes available: car, walk, fixed public transport (fixed PT), and flexible public transport (flexible PT). In the Assignment module, the users assigned to individual vehicles. If a user has chosen fixed PT then they walk from their origin to the nearest stop and wait for a vehicle to pick them up. The Modal split and Assignment form the daily dynamics of the system. The users then evaluate the service based on their experience in the Evaluation module. Based on the evaluation, the users re-plan their travel strategy for the following day in the Re-planning module. The users may change their existing travel strategy in the following ways: change to a different mode, use a different route with the same mode, and change the departure time from their origin.

The flexible PT system comprises of a fleet of vehicles that are controlled by a central dispatching unit which

assigns incoming requests to vehicles in the network. A vehicle that has been assigned with a request, drives to the pick-up location, picks up the passenger and drops off the passenger at their drop off location. The vehicle then stays at the drop-off location until further notice from the system dispatcher. The destination of the passenger is not known to the dispatcher while assigning the request. The dynamic vehicle routing algorithm used in this paper is adopted from Sebastian (2017) in which the framework developed by Maciejewski (2015) was extended.

The open-source multi-agent traffic simulation framework MATSim Horni et al. (2015) was used in model implementation. Each user of the transport system is represented as an agent with a set of travel plans. Once the plans have been performed, each agent evaluates the executed travel plan based on the service experienced. The altered set of travel plans forms the demand for the subsequent simulation cycle. This sequence of network and agent choice simulation, scoring and re-planning forms an iteration which corresponds to a day. This process is continued till some set of convergence criteria is achieved. In MATSim, plans are scored according to utility functions. The scoring of a plan has two parts, namely, utility for performing the activity and a travel disutility for performing the trip. The travel disutility is scored using a mode specific constant, the direct disutility of travelling, disutility for waiting and transfer if any, and the disutility associated with monetary travel cost. The typical scoring of an activity 'q' and a travel leg with mode 'm' is shown in the following set of equations (1).

$$S_{act,q} = \beta_{dur,q} \cdot t_{dur,q}$$
$$S_{leg,m} = C_m + \beta_{trav,m} \cdot t_{trav,m} + \beta_{money} \cdot \gamma_m \cdot d_{trav,m} + \beta_{wait,m} \cdot t_{wait,m} \quad (1)$$

3. Simulation Setup and Scenarios

The test network used in this study is based on the road network of the city of Sioux Falls in the United States. The population and detailed road network for simulation have been adopted from Chakirov and Fourie (2014) and Hörl (2016) respectively. The travel population consists of 84,110 persons with either home-work-home or home-secondary-home activities based on the employment status of each person. The scenarios considered are given in Table 1. Three scenarios in terms of service availability are considered. Under Scenario I, the users may choose between modes of car, fixed PT, and walk. In Scenario II, a fleet of vehicles is introduced which offer flexible PT serving real time requests. The type of service offered is a private (taxi-like) ride with no sharing among passengers. In Scenario III, in addition to the default modes of car, fixed PT, and walk, a fleet of vehicles serving real-time requests operates on a sharing basis, including possible detours for picking-up and dropping-off fellow passengers.

Table 1. Tabulation of the scenarios

Scenario	User mode choice
I	Car, Fixed PT, Walk
II	Car, Fixed PT, Flexible PT (private), Walk
III	Car, Fixed PT, Flexible PT (shared), Walk

In addition to the three scenarios described above, system performance is analyzed for varying flee size of vehicles serving as flexible PT and varying ratio of cost of flexible to fixed PT services. The simulation model is run for fleet size of 1000, 2000, 3000, 4000, and 5000and cost ratios of 2,3,5, and 10. The base case fleet size is 1000 and the base case cost ratio is 2. The utility function coefficient values have been adopted from Sebastian (2017) and are converted to the MATSim implementation framework Horni et al. (2016) and are detailed in in Table 2.

Table 2. Utility values used for simulation

Utility	**Values**
Marginal utility of money (β_m)	1
Utility for performing an activity (β_{dur})	23.29
Car	
Mode specific constant (C_{car})	-4.21

Marginal utility of travel ($\beta_{trav,car}$)	0
Monetary distance rate (γ_{car})	-0.176
Walk	
Marginal utility of travel ($\beta_{trav,walk}$)	-9.91
Fixed pt	
Marginal utility of travel ($\beta_{trav,fixedpt}$)	8.86
Marginal utility of waiting time (β_{wait})	-0.84
Utility of transfer ($\beta_{transfer}$)	-1.67
Monetary distance rate ($\gamma_{fixed\ pt}$)	-0.265
Flexible pt	
Marginal utility of travel ($\beta_{trav,flexpt}$)	8.86
Monetary distance rate (private) ($\gamma_{flex\ private}$)	-0.48
Monetary distance rate (shared) ($\gamma_{flex\ shared}$)	-0.28

4. Results and Analysis

This section presents the simulation results and analysis. Section 4.1 presents the simulation results for fleet size variation for Scenarios II and Scenario III where Scenario I is considered as the Base Case and Section 4.2 presents he results for cost ratio variation for Scenario II and Scenario III where a cost ratio of 2 is considered as the Base Case.

4.1 Effects of the fleet size of flexible public transport

Table 3 presents the mode share variation for Scenario II and Scenario III with varying fleet size of flexible PT. From Table 3, it can be seen that in comparison to the Base Case, a large percentage of users shift from car and fixed PT and a relatively small percent from walking. This indicates that the introduction of flexible PT service can considerably reduce the number of personal car trips as well as cause a mode shift from fixed PT. It can also be seen that with increase in fleet size of flexible PT, there is a steady increase in its modal share. This can be explained from Fig. 2 where the average waiting times per passenger using flexible PT are plotted as a function of its fleet size. It can be seen that the increase in fleet size causes a decrease in the average waiting time in both the scenarios hence making the service more attractive. There is a slight increase in average waiting time for Scenario II from 2000 to 3000 where the pace of increasing demand surpasses the increase in fleet availability. Another trend that becomes evident from Fig. 2 is that the extent to which average waiting times vary for different fleet sizes is lower for Scenario III than for Scenario II. This indicates that the effect of increased fleet size on the average waiting times of passengers is especially important when vehicles are not shared.

The effect of fleet size on waiting time for different time of the day was further investigated and is shown in Fig. 3 and Fig. 4 which plot the hourly variation of average waiting time for Scenario II and III, respectively. It can be seen that the increase in fleet size causes an overall decrease in waiting times throughout the day. It can also be seen that the effect of increase in fleet size on waiting time is more pronounced during peak hours than off-peak hours, indicating high demand for flexible services during peak hours. The average waiting time of zero in these figures indicate zero demand during those hours.

Table 3. Mode share and travel statistic results for varying fleet size

		Mode Share (%)			
	Fleet size of Flexible PT	**Car**	**Fixed PT**	**Walk**	**Flexible PT**
Scenario I (Base Case)	NA	63.6	28.44	7.96	NA
Scenario II	1000	52.17	17.88	5.43	24.52
	2000	48.47	17.13	5.24	29.16
	3000	46.77	16.88	5.25	31.10
	4000	46.07	16.79	5.22	31.92
	5000	45.76	16.82	5.23	32.19
Scenario III	1000	54.05	18.62	5.6	21.73

2000	51.01	17.97	5.47	25.55
3000	50.34	17.84	5.43	26.39
4000	50.03	17.77	5.44	26.76
5000	49.60	17.76	5.45	27.19

Table 4. Mode share and travel statistic results for varying cost ratio

		Mode Share (%)			
	Cost ratio	**Car**	**PT**	**Walk**	**Taxi**
Scenario II	2 (Base Case)	52.30	17.96	5.42	24.32
	3	53.76	18.31	5.41	22.52
	5	56.95	19.28	5.43	18.34
	10	61.07	22.69	5.63	10.61
Scenario III	2 (Base Case)	55.46	19.21	5.72	19.61
	3	56.75	19.91	5.78	17.56
	5	59.17	21.05	5.90	13.88
	10	61.60	24.20	6.19	8.01

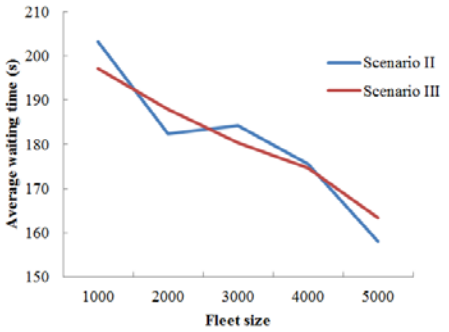

Fig. 2. Variation of average waiting time for flexible pt with fleet size

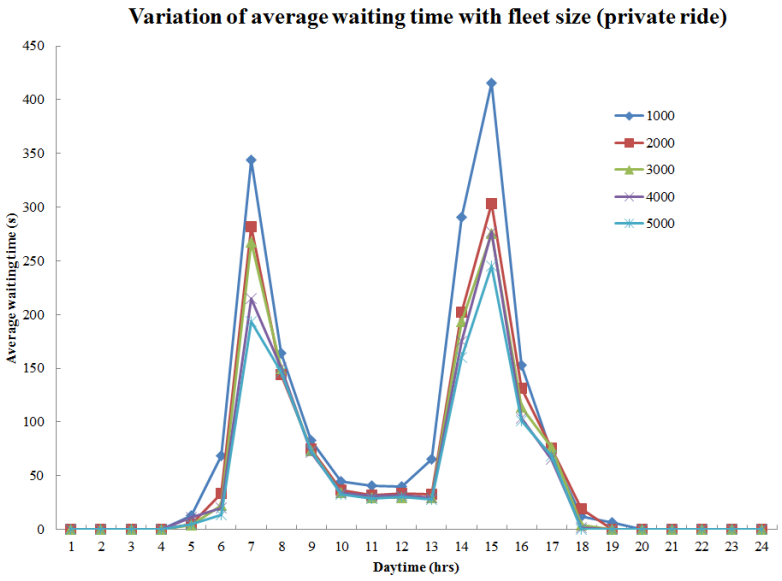

Fig. 3. Hourly variation of average waiting time with fleet size for Scenario II

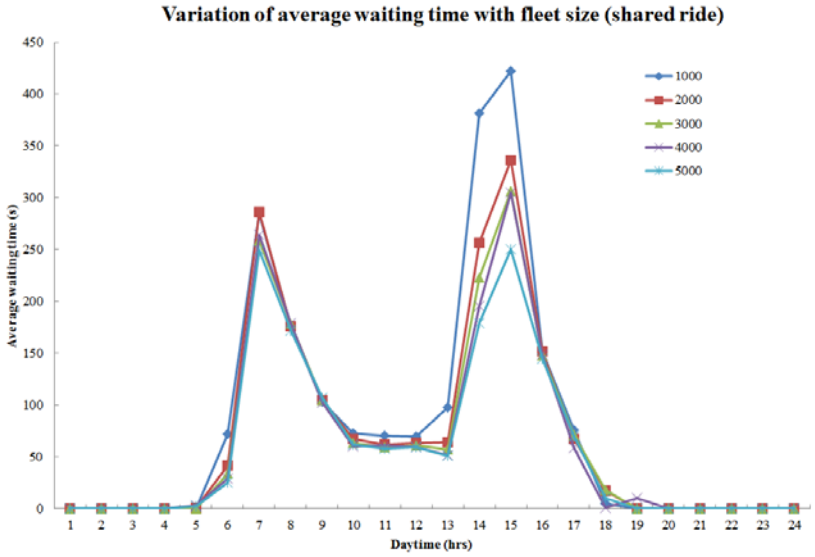

Fig. 4. Hourly variation of average waiting time with fleet size for Scenario III

4.2 Effects of cost ratio between fixed and flexible public transport services

Table 4 shows the mode share results obtained by varying the ratio of cost of flexible PT to fixed PT. The ratios considered are 2,3,5, and 10. Fig. 5 plots the mode share variation for fixed and flexible PT with the cost ratio. The scenarios in which the cost ratio is 2 is chosen as the Base Case. As can be seen from Table 4, there is a steady decrease of mode share for both individual and shared flexible PT services with increasing relative cost ratios. There is also a corresponding increase in the mode share of car and fixed PT when compared to the Base Case. Another interesting trend that emerge can be seen from Fig. 5, is the rate of decrease of mode share of flexible PT for Scenario II and III. It can be seen that the rate of decrease of mode share of flexible PT without shared service is more than that of flexible PT with shared service at higher cost ratios. This is due to the lower average waiting time of shared services which makes it relatively attractive compared to individual flexible PT at higher relative cost ratios.

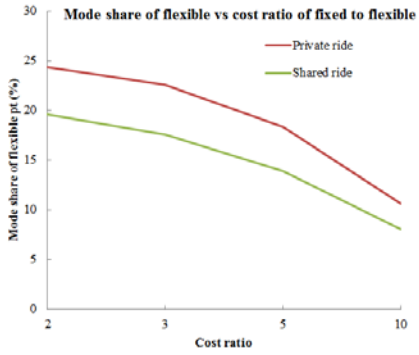

Fig. 5. Variation of mode share with varying relative cost ratio

5. Conclusion

This study analyzed the performance of a system when fixed and flexible public transport systems co-exist while offering competing services. The multi agent simulation framework MATSim was chosen to implement the model. The system performance was analyzed for varying fleet size of flexible PT and varying cost ratio of flexible to fixed service. The analysis showed that the increase in fleet size caused an overall increase in mode share for flexible PT which was caused due to an overall decrease in waiting time of passengers using flexible PT. It was found that the effect on waiting times of passengers by increasing fleet size is more pronounced when an individual taxi-like door-to-door service is offered. The variation of relative cost ratios showed a steady decline of mode share for flexible PT with increasing cost. The results also showed that at higher relative cost ratios, the flexible PT that operate without sharing becomes less attractive than the one with sharing. In addition to addressing the gaps in the scientific literature, the relations investigated in this study is relevant from a practical and policy perspective in the sense that it enables practitioners and policy makers to evaluate the implications of introducing competing flexible PT services with fixed PT services based on the response of users. Another aspect from a modelling perspective is that, the mode share of users obtained from the model depends on the scoring of each plan of user which in turn depends on the values of utility parameters. An effective methodology to model the user behavioral preferences based on real world population is essential in representing passenger preference for future studies in the area. Moreover, the effect of operational aspects such as vehicle relocation strategy and destination knowledge to the dispatcher at the time of making a request on the system performance and the implications of using a flexible PT system for first/last mile travel of fixed PT was not investigated in the study and should form direction for future research.

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