Two-Sided Market Evaluation of Last-Mile Transit Operations with En-Route Transfers

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Extended Abstract for hEART Symposium 2018

Motivation

Recent advances in sensor, automation and vehicle technology have allowed for the development of modular, interlocking autonomous vehicles such as the NEXT Future Transportation NX1 pod. These types of autonomous vehicles are capable of physically connecting to one another while in motion, permitting passengers and freight to move freely between two or more vehicles. Such a service could be a solution to what is often referred to as the “first/last mile” transit problem, especially because previous high-profile attempts to solve the last mile problem with flexible transit service such as Kutsuplus in Helsinki and Bridj in the United States have not been successful. Vehicles capable of transferring passengers could potentially improve outcomes for both the passengers and operators of last mile transit services.

Literature Review

Mobility services designed to solve the last mile problem have been studied extensively (Chang and Schonfeld, 1991a,b; Cortes et al., 2005; Mulley and Nelson, 2009; Chong et al., 2013; Wang and Ordoni, 2014; Guo et al., 2017). Yap et al. (2014) conclude that autonomous vehicles have potential to solve this problem as passengers become more comfortable with the technology. However, existing research has rarely considered passenger transfers when designing or evaluating mobility services. Emerging studies of routing problems consider the possibility of transferring passengers or freight at a specific location. Studies by Cortes et al. (2010), Rais et al. (2013) and Masson et al. (2013) involve the transfer of goods at pre-defined transshipment points. Deleplanque and Quilliot (2013) present an algorithm for solving the static Dial-a-Ride Problem with transfers at any location. In their research, the load or passenger to be transferred is dropped off at the transfer node and picked up at some later time. Bouros et al. (2011) provides a solution to a similar dynamic problem.

In the proposed research, we conduct a first demand evaluation of last-mile mobility service that allows for *dynamic en-route transfers* of passengers between vehicles. This involves integrating an en-route transfer policy into an agent-based day-to-day simulation of a two-sided market (Djavadian and Chow, 2017) to evaluate the equilibration of the demand with this operating policy. A two-sided market framework is used to capture the endogenous decision-making dynamics between the operator and the travelers.

Methodology

In conventional last mile transit operations, either flexible on-demand service or feeder bus routes are used to connect passengers to a train station (see Guo et al., 2017, Djavadian and Chow, 2017). We propose to extend the two-sided market simulation framework from Djavadian and Chow (2017) to include en-route transfer policies, and to apply that to specific last mile scenarios. The advantage of using a two-sided market framework is that operator policies can be equilibrated endogenously to meet the demand of the travelers through the day-to-day adjustment process. This requires parameterizing the transfer policy such that it can be adjusted from one day to the next based on observed performance and demand on previous days. Two-sided market measures can then be used to evaluate the user optimality of a design: e.g. Ramsey pricing criterion for maximizing social welfare (Rochet and Tirole, 2003).

The en-route transfer capability is simulated using an online algorithm shown in Fig. 1, which is benchmarked against an algorithm in which no en-route transfer is allowed. When a new request is made, it is assigned to a vehicle such that the vehicle assignment and positioning of the request within the vehicle's route minimizes the sum of vehicle miles traveled, user travel time and user wait time for the entire system. A comparison between different idle vehicle repositioning strategies like in Ma et al. (2018) is made.

Within the two-sided market context, we propose to use the day-to-day adjustment for the operator to learn the user cost weight to achieve either social optimality or profit maximization. For example, if the operator's cost function C_d is defined in Eq. (1) on a day-to-day basis as a weighted sum of the operator's cost $C_{d,o}$ and the $C_{d,u}$, then the weight θ_d is updated each day d based on a radial basis function response surface (per Chow et al., 2010) constructed from the prior days. An example RBF function is a thin plate spline shown in Eq. (2) where $p(\theta)$ is a first-order polynomial kernel regression.

$$C_d(p_v) = C_{d,o} + \theta_d C_{d,u} \tag{1}$$

$$\theta_d = argmin_\theta \left\{ \sum_{i=1}^{d-1} \lambda_i (r_i^2 \ln r_i) + p(\theta) \right\}, \qquad r_i = \|\theta - \theta_i\|, \theta > 0 \tag{2}$$

Mathematical Formulation

N	The full set of nodes in the simulation network
$R(t)$	The full set of requests in the simulation at time t, with $r \in R(t)$
O_r, D_r	The origin and destination location of request r where $\{O_r, D_r\} \in N$
t_r^r	Time at which request r is made
V	The fixed full set (or fleet) of vehicles in the simulation, with $v \in V$
$x_v(t), y_v(t)$	The coordinates defining the position of vehicle v at time t
$p_v(t)$	The route for vehicle v consisting of a set of origin, destination and transfer nodes $n \in N$
$X(t)$	The full set of passenger transfers at time t, with $x \in X(t)$
s_x, f_x	The start and finish nodes of passenger transfer x where $s_x, f_x \in N$
G_x	The subset of nodes which are considered for s_x, f_x, which are located between the current positions of vehicles participating in transfer x and the destinations of the passengers being considered for transfer where $G_x \subseteq N$
V_x	The subset of vehicles participating in transfer x where $V_x \subseteq V$
$C(p_v)$	Cost function: the sum of operator and traveller costs for a given route or set of routes

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The ***expected contribution*** of this research is a methodology using surrogate response surface models to learn the optimal user costs for operator decision-making each day within a 2-sided market day-to-day adjustment process, and its application to evaluating en-route transfers for last mile shared autonomous vehicle transit feeder services.

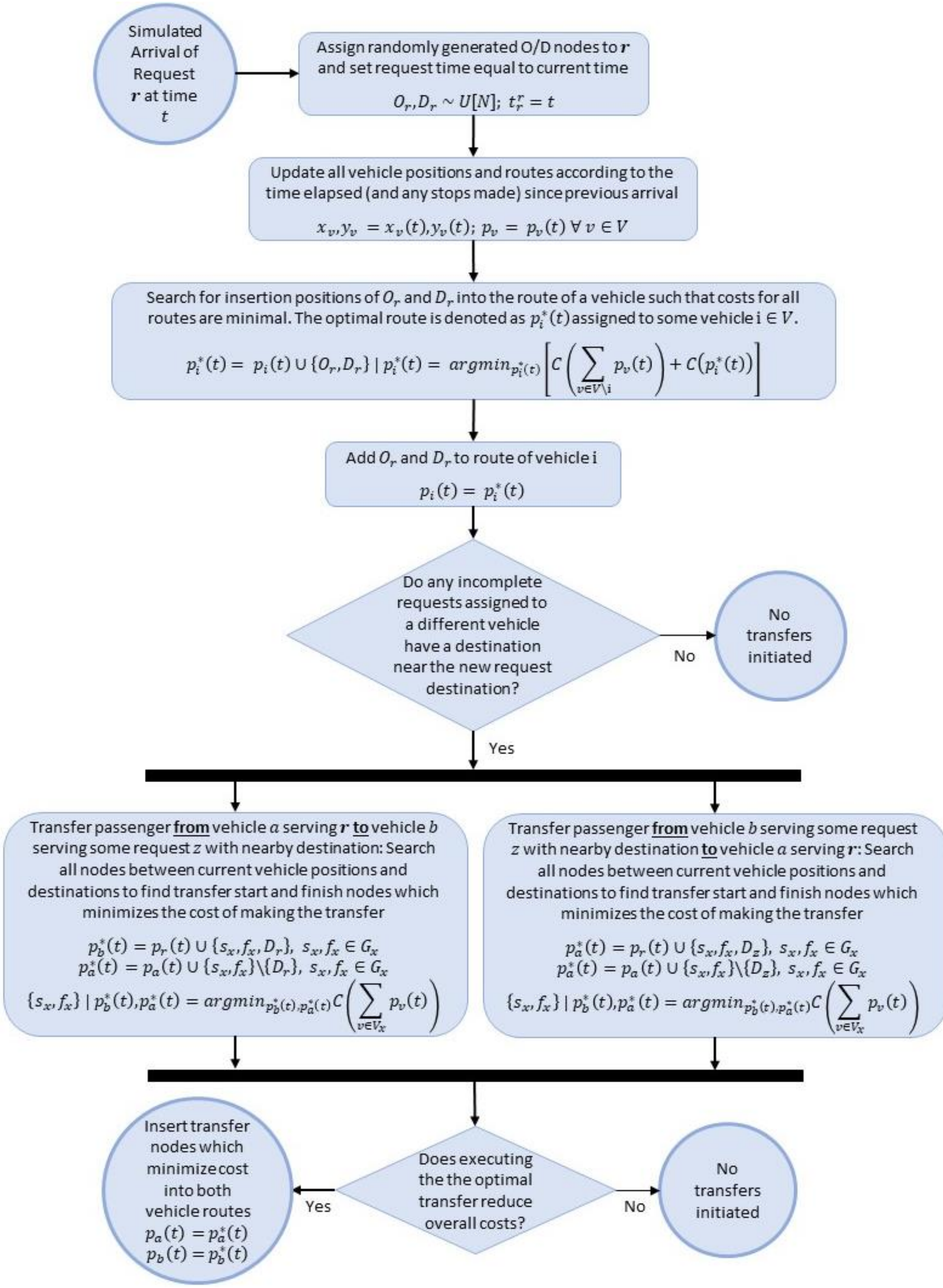

Figure 1: En-route transfer algorithm

Preliminary Results

Early results reveal that in-motion transfer of passengers between vehicles has a limited effect on service performance because transfers are rarely initiated. For a transfer to improve performance, two vehicles must have nearby destinations and similar paths, otherwise one must wait for the other to initiate the transfer, thus increasing passenger travel times. Another interesting result is that including transfers can occasionally lead to suboptimal performance when compared to a system without transfers. Once a transfer is inserted into the routes of two vehicles, both are committed to arriving at the transfer initiation point at the same time and cannot be rerouted prior to the transfer to serve a newly arrived request. This is explored further.

Table 1 presents the average vehicle distance travelled, average pickup waiting time and average passenger travel time for both a service that considers in-motion transfers and one that does not. The results are averaged over 100 runs of the simulation for Scenarios 1 and 2. The performance is very similar between services, which is unsurprising because the transfers occur in less than 1% of all requests. In Scenario 1, the vehicles with transfer capability travelled slightly less distance but passengers saw a slight increase in wait and travel time, likely due to suboptimal routing once transfers have been initiated. Scenario 2 saw similar results, although performance was worse in all metrics when transfers were used.

Table 1: Evaluation of Mobility Services With and Without In-Motion Transfers

	Scenario 1		**Scenario 2**	
	No Transfers Permitted	Transfers Permitted	No Transfers Permitted	Transfers Permitted
Average Vehicle-Miles Per Passenger Served	26.8786	26.8069	25.4982	25.5082
Average Wait Time Per Passenger (min)	10.2853	10.3080	13.8095	13.8206
Average Travel Time Per Passenger (min)	22.5382	22.5926	17.5271	17.5415

Case Study: Dubai to Sharjah last mile feeder system

For the Dubai – Sharjah case study, much of the Dubai workforce commutes from nearby Sharjah which has relatively low housing costs, causing extreme congestion along the highways that connect the two cities as shown in Fig. 2. Three different scenarios are evaluated under "no-enroute", "en-route", and under profit-maximizing and social-optimizing behavior, and different RBF experimental designs:

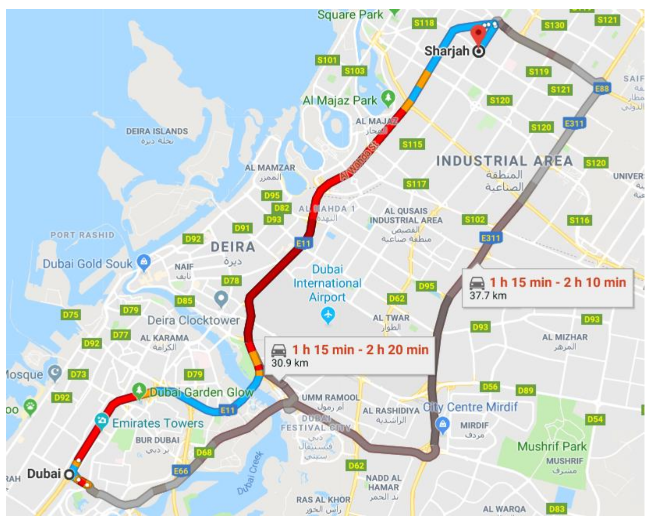

Figure 2: Map of the Dubai-Sharjah Region with Peak Hour Intercity Travel Times

1) The general case with randomly distributed destinations
2) The last mile service case with a common destination for all requests
3) A case study of the congested Dubai – Sharjah corridor in the United Arab Emirates, where the Roads & Transport Authority (RTA) is interested in providing last mile service

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