Evaluation of Cooperation Strategies for Public Transport and Ride-hailing services

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SHORT SUMMARY

Ride-hailing services are continuously gaining popularity in urban cities due to their flexibility and responsiveness. Public transport agencies spot the chance to cooperate with Transportation Network Companies (TNCs) to improve service quality and operational efficiency. While a series of cooperation strategies are proposed and piloted in some cities, little is known regarding how transportation systems respond to these strategies. We proposed three cooperation strategies: no ride-hailing subsidy; providing ride-hailing subsidy and canceling bus; providing ride-hailing subsidy and adjusting bus service frequency. A travelers' choice model for transportation corridors incorporating ride-hailing, public transport, and car is established to analyze the system performance under different strategies. The numerical experiments show that ride-hailing subsidies can reduce the average travel cost and improve public transport ridership in low-demand areas. However, the subsidy strategy can lead to a negative effect on transportation systems in high-demand areas due to limited investment and ride-hailing service supply.

Keywords: Ride-hailing, public transport, subsidy, cooperation strategy, mode choice

1. INTRODUCTION

Ride-hailing services provided by transportation network companies (TNCs) such as Didi and Uber have become a new transport alternative to traditional public transport and privately owned modes. Some studies suggested that, as a new travel option, a significant share of the demand for ride-hailing is absorbed from the demand of traditional public transport systems by virtue of high service flexibility and quality (Clewlow and Mishra, 2017; Narayan et al., 2019).

At the same time, ride-hailing services can also complement public transport systems in some areas (Hall, Palsson, and Price, 2018; Jiang et al., 2018; Kong, Zhang, and Zhao, 2020). First, ride-hailing services can fill in the gap of the public transport system in low-demand areas and off-peak periods. In areas that generate low ridership, public transport agencies usually operate bus routes in low frequency to reduce the operational costs, and the bus stops are typically sparsely distributed in these areas. Ride-hailing services may provide a more flexible and convenient travel mode in areas that are not covered by high-quality public transport services. Second, ride-hailing services may provide convenient first/last-mile connections between the points of origin/destination and public transport networks, which increases the reach and flexibility of fixed public transport routes.

Several transit agencies have started to partner with TNCs in an attempt to design a win-win model (Curtis et al., 2019). In low-demand areas, public transport agencies provide subsidies for specific ride-hailing trips (e.g., trips connecting to public transport stations) and cancel the low-ridership bus routes replaced by the ride-hailing services. Under certain spatial and demand distribution patterns, this can potentially result with a win-win situation where passengers benefit from an improved level-of-service and service providers reduce their operational costs.

While the cooperation between public transport agencies and TNCs is conceptually appealing, public transport agencies need to anticipate how these cooperation strategies will affect the system performance and under what conditions the partnership will be beneficial. Zhang and Khani (2021) proposed a stochastic equilibrium model to evaluate the effect of the TNC fare subsidy strategy on the existing public transport system. The results showed that TNC fare subsidy by public transport agencies improves social welfare and public transport net revenue. However, little is known regarding the impact of the joint design of public transport service and TNCs subsidies on passenger flow distribution.

To fill this research gap, we develop a travelers' choice model for transport corridors incorporating car, line- and schedule-based public transport services, and private door-to-door ride-hailing services. We propose three different strategies in this study: (i) no ride-hailing subsidy (Benchmark); (ii) providing ride-hailing subsidy and canceling the public transport service (strategy 1); (iii) providing ride-hailing subsidy and adjusting the public transport service (strategy 2). The public transport frequency and subsidy level per TNC trip are optimally designed to minimize the average generalized travel cost. A set of numerical cases are conducted to analyze the system performance under different strategies.

The remainder of this short paper is structured as follows. Section 2 explains the travelers' choice model employed in this research. Section 3 introduces the cooperation strategies. In section 4, we conduct a set of numerical experiments to analyze the impacts of the proposed strategies on transportation corridors. Section 5 concludes, including some possible directions for future research are offered.

2. TRAVELERS' FLOW DISTRIBUTION ON TRANSPORTATION CORRIDORS

We consider a linear travel corridor connecting the suburb residential area and Central Business District (CBD), as shown in Fig.1. The transportation corridor consists of highway and subway infrastructure. A subway station is located in the residential area, and the subway line directly connects the area with the CBD. Three modes are available to travel from the residential area to the CBD:

- Drive to CBD directly by car
- First taking a bus service as access mode, then taking the subway towards the CBD

- First taking a ride-hailing service as access mode, then taking the subway towards the CBD

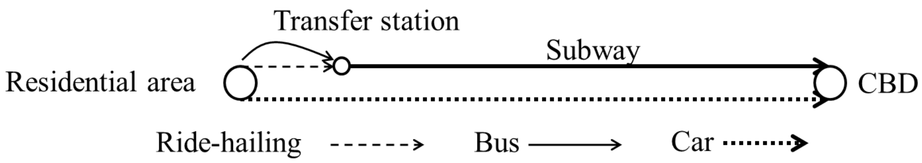

Figure 1 A transport corridor connecting a residential area to the CBD.

The total travel demand along the transportation corridor is known a priori. Travel mode decision generally depends on the evaluation of the alternative modes by each individual traveler. We analyze the system performance under equilibrium states. Car road congestion and bus crowding effects are explicitly considered in this study. As mentioned above, three cooperation strategies are discussed in this study.

Generalized travel cost analysis

For car travelers, the generalized travel cost consists of travel time and monetary cost. The travel time $t_a(q_a)$ depends on the level of traffic congestion, and the monetary cost τ_a is assumed to be constant. The generalized travel cost for car travelers can be expressed as:

$$c_a = \gamma_t t_a(q_a) + \tau_a \tag{1}$$

where γ_t is the value-of-time weight assigned to travel time. $t_a(q_a)$ refers to the total travel time for care travelers, which is an increasing function of traffic volume q_a. The classic US Bureau of Public Roads (BPR) function is adopted in this study to reflect the congestion effect:

$$t_a\left(v_a\right) = t_0\left(1+\alpha\left(\frac{q_a}{c-c_g}\right)^{\beta}\right) \tag{2}$$

where t_0 refers to free-flow travel time. c and c_g represent the capacity and background flow of the highway, respectively. α, β are parameters related to the congestion effect.

The generalized travel cost for public transport travelers includes travel time, waiting time, transfer time, bus crowding, and monetary cost. The travel time of public transport travelers is assumed to be constant. The accessing time for travelers taking the bus service and ride-hailing service to subway station are denoted by t_b and t_r, respectively, and the subway travel time is t_s.

Travelers' waiting time refers to bus waiting time, ride-hailing waiting time and subway waiting time. Bus waiting time w_b and subway waiting time w_s depend on public transport frequency f, which, assuming a perfectly regular service, can be expressed as:

$$w(f) = \frac{1}{2f} \tag{3}$$

In a queuing system, the relationship between utilization rate and waiting time is highly nonlinear. Following Pinto et al. (2020), we define the vehicle utilization rate in ride-hailing system as the ratio of passenger volume q_r to available ride-hailing fleet size m. The range of utilization rate is divided into three stages. In the first stage, the waiting time remains flat, as there are always empty ride-hailing vehicles to serve new requests. In the second and third stages, the waiting time increase with the utilization rate of ride-hailing vehicles with different growth rates. Thus, the ride-hailing waiting time is defined as a piecewise linear function:

$$w_r\left(q_r,m\right)=\begin{cases} w_0 & \frac{q_r}{m}<u_1 \\ w_0+b_1\left(\frac{q_r}{m}-u_1\right) & u_1\le\frac{q_r}{m}<u_2 \\ w_0+b_1\left(u_2-u_1\right)+b_2\left(\frac{q_r}{m}-u_2\right) & \frac{q_r}{m}\ge u_3 \end{cases} \tag{4}$$

where, u_1, u_2, u_3, b_1, b_2 are the parameters in the piecewise linear function.

The vehicle crowding cost for bus travelers is defined as a function of bus frequency f_b and passenger volume q_b:

$$\varphi(q_b,f_b)=w_1+w_2t_b(\frac{q_b}{f_b})^2 \tag{5}$$

where w_1 and w_2 are the parameters in crowding cost function, which can be calibrated by real-world operation data (Manski, 1977).

The transfer penalty, including the transfer time, is a constant denoted by t_t, and the fixed fare for bus and ride-hailing service passenger are τ_b and τ_r, respectively. The subsidy for ride-hailing services and the subway fare are s and τ_s, respectively. Thus, the total generalized travel cost for travelers taking bus service c_b and ride-hailing service c_r and can be expressed as:

$$c_r=\gamma_w(w_r\left(q_r,m\right)+w(f_s)+t_t)+\gamma_t(t_r+t_s)+\tau_r+\tau_s-s \tag{6}$$

$$c_b=\gamma_w(w(f_b)+w(f_s)+t_t)+\gamma_t(t_b+t_s)+\varphi(q_b,f_b)+\tau_b+\tau_s \tag{7}$$

where γ_w is the value of time for waiting time.

Travelers' choice model

The Nested Logit Model is applied to estimate the modal split. The top-level model splits the public transport volume q_t and car volume q_a:

$$q_a=Q\frac{\exp(-\theta_1c_a)}{\exp(-\theta_1c_t)+\exp(-\theta_1c_a)} \tag{8}$$

$$q_t=Q-q_a \tag{9}$$

where θ_1 refers to the standard deviation of perceived error when choosing between car and public transport and Q is total travel demand. c_t is the excepted travel cost of public transport travel modes:

$$c_t=-\frac{1}{\theta_2}\ln(\exp(-\theta_2c_b)+\exp(-\theta_2c_r)) \tag{10}$$

Bus volume and ride-hailing volume are determined by the subsequent level model:

$$q_b=q_t\frac{\exp(-\theta_2c_b)}{\exp(-\theta_2c_b)+\exp(-\theta_2c_r)} \tag{11}$$

$$q_r=q_t-q_b \tag{12}$$

Finally, the travelers' choice can be rewritten as a mathematical programming model as follows:

$$\min(q_a-Q\frac{\exp(-\theta_1c_a)}{\exp(-\theta_1c_t)+\exp(-\theta_1c_a)})^2+(q_b-q_t\frac{\exp(-\theta_2c_b)}{\exp(-\theta_2c_b)+\exp(-\theta_2c_r)})^2 \tag{13}$$

$$s.t.(1)-(7),(9)-(10),(12).$$

The Method of Successive Averages (MSA) is adopted in this study to solve the travelers' choice model.

3. COOPERATION STRATEGIES

Three cooperation strategies are examined in this study: (i) no ride-hailing subsidy (Benchmark); (ii) providing ride-hailing subsidy and canceling bus (strategy 1); (iii) providing ride-hailing subsidy and adjusting bus service frequency (strategy 2).

For each strategy, we optimally design the bus frequency f_b and/or the ride-hailing subsidy amount s for each trip under the constraint of maximal investment amount Φ. The objective is to minimize the average generalized travel cost (ATC) defined as:

$$ATC = \frac{q_a c_a + q_b c_b + q_r c_r}{Q} \tag{14}$$

For benchmark, there is no ride-hailing service subsidy, and all the budget available is assigned to the bus service. The bus operational cost is assumed to convexly increase with respect to service frequency (F. Zhang, Lindsey, and Yang, 2016):

$$b_c(f_b) = k_0 + k_1 f_b + k_2 f_b^2 \tag{15}$$

where k_0, k_1, k_2 are the parameters of the operational cost function, which can be estimated using actual operation data. Therefore, the optimal bus frequency can be determined by solving the following optimization model:

$$\begin{aligned} & \min_{f_b} ATC \\ & s.t. \\ & b_c(f_b) \le \Phi \\ & f_b^{\min} \le f_b \le f_b^{\max} \\ & (1)-(12),(15) \end{aligned} \tag{16}$$

where f_b^{min} and f_b^{max} refer to the minimal and maximal bus frequency, respectively.

For strategy 1, bus service is eliminated, and all the investment is assigned instead to the ride-hailing service. The total cost of ride-hailing service subsidy is:

$$r_c(s) = s \cdot q_r \tag{17}$$

Thus, the subsidy for each ride-hailing trip can be optimized by solving:

$$\begin{aligned} & \min_{s} ATC \\ & s.t. \\ & r_c(s) \le \Phi \\ & 0 \le s \le \tau_r \\ & (1)-(12),(17) \end{aligned} \tag{18}$$

For strategy 2, the investment is optimally distributed over the bus and ride-hailing services by adjusting the bus frequency and ride-hailing subsidy amount per trip, which can be determined by solving the following optimization problem:

$$\begin{aligned}
&\min_{f_b, s} ATC \\
&s.t. \\
&b_c(f_b) + r_c(s) \le \Phi \\
&0 \le s \le \tau_r \\
&f_b^{\min} \le f_b \le f_b^{\max} \\
&(1)-(12),(15),(17)
\end{aligned} \tag{19}$$

The optimal bus frequency and subsidy amount can be easily obtained through an exhaustive search.

4. NUMERICAL STUDY

Case set-up

To assess the performance of the three proposed strategies, we conduct a series of numerical experiments for a transport corridor using the parameters listed in Table 1.

Table 1 Parameter settings

Notation	Description	Value
Q	Total demand in the residential area	1000pax/h
Φ	Total investment	4082\$/h
γ_w, γ_t	Value of time for travel and waiting	10\$/h, 16.5\$/h
τ_a, τ_b, τ_s, τ_r	Monetary cost of car, bus, subway and ride-hailing	12\$, 0.5\$,1.5\$, 3.75\$
t_b, t_s, t_r,	Travel time of bus, subway and ride-hailing service	20min, 30min, 5min
f_s	Subway frequency	20run/h
t_t	Transfer time	5min
α, β	Parameters in car travel time function	0.15, 2
t_0, c, c_b,	Free flow travel time, capacity and background flow on the highway	20min, 1800pcu/h, 1500pcu/h
w_1, w_2	Parameters in bus crowding cost function	7.23, 0.15
u_1, u_2, u_3, b_1, b_2	Parameters in ride-hailing waiting time function	3, 20, 50, 0.5, 0.8
m	Available ride-hailing vehicle number	500veh/h
f_b^{min}, f_b^{max}	Minimal and maximal frequency	2run/h, 12run/h
k_0, k_1, k_2	Parameters in bus operation cost function	3750, 80, 0.75
θ_1, θ_2	Standard deviations of perceived error	3, 4

Results

The system performance and ridership levels for the three travel modes under different strategies are presented in Table 2 and Fig. 2, respectively. The average generalized travel cost (ATC) value of strategy 1 is the lowest among the three strategies. The subsidized ride-hailing fare is only 0.13$/trip, which is cheaper than the bus fare (0.5$) in this scenario. As a result of subsidy, about one in four car travelers shift their travel mode to ride-hailing, which causes a decrease in automobile ridership (from 81% to 61%). This suggests that ride-hailing subsidies can reduce the congestion effect on the highway.

Strategy 2 can also reduce the ATC compared to the benchmark scenario. However, due to the constraint of maximal bus headway (i.e. minimal service frequency), some of the investment is assigned to the bus service and thereby the investment for the ride-hailing service is limited. Strategy 2 only provides a lesser subsidy for each ride-hailing traveler (0.98$/trip, i.e. ride-hailing fare of 2.77$/trip compared to 0.5$/trip for bus) but cuts down the bus service quality considerably, which almost absorbs all the bus passengers to ride-hailing .

Table 2 The system performance under three proposed strategies.

Optimal solution	**Benchmark**	**Strategy 1**	**Strategy 2**
Bus headway (min)	10.00	-	30.00
Ride-hailing subsidy ($/trip)	-	3.68	0.98
ATC ($)	17.36	16.62(-4.23%)	17.08(-1.62%)

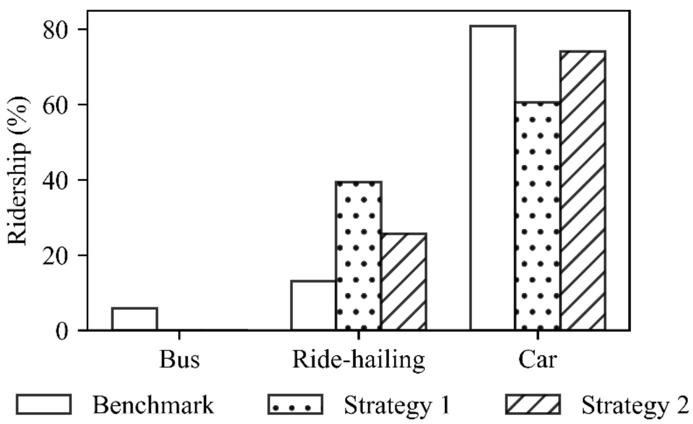

Figure 2 Travel mode ridership under different cooperation strategies.

A set of experiments are conducted to evaluate the cooperation strategies performance under different demand levels. The ATCs under different strategies and demand levels are shown in Fig. 3a. Strategy 1 and strategy 2 both reduce the system ATC when total demand is low. Once the demand exceeds 1600 pax/h, the ATC of strategy 1 increases sharply. This can be explained by the increase of ride-hailing travel cost because of its limited capacity. Due to the cancelation of the bus service in this scenario, the ride-hailing service has to serve more passengers with a limited available fleet size, resulting in a considerable increase in the waiting time of ride-hailing users. Furthermore, due to the constraint of total investment, the ride-hailing subsidy amount per trip decreases with the increase in travel demand.

The increase of ride-hailing travel cost also affects the share of car trips. The number of car trips under each of the strategies is presented in Fig. 3b. Strategy 1 and 2 lead some car travelers to shift their travel mode away from car when the total demand is lower than 1600pax/h. However, with an increase in demand, the car modal share under strategy 1 is higher than the benchmark due to the increase in ride-hailing travel costs and the unavailability of the bus alternative. Under strategy 2, all the investment is assigned to the bus service to minimize the ATC and thereby the ride-hailing subsidy is set to zero when the total demand reaches 1600pax/h. Consequently, the ATC and car modal share of strategy 2 are equal to the benchmark.

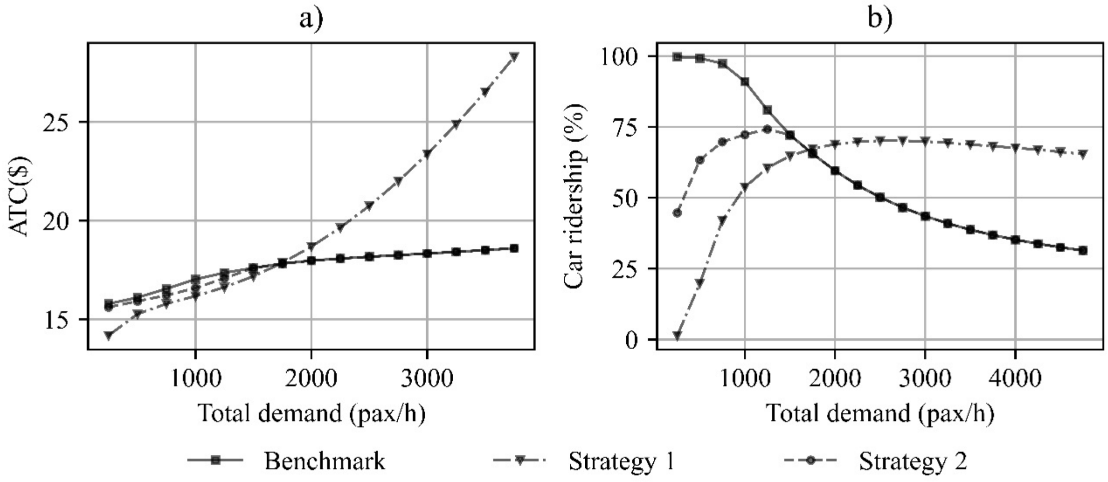

Figure 3 a) ATC and b) car ridership with varying total demand.

5. CONCLUSION AND OUTLOOK

This study evaluated the impact of cooperation strategies between public transport agencies and TNCs feeding to transport corridors. To analyze the system performance under different strategies, we design a flow distribution choice model amongst car, ride-hailing and public transport that accounts for congestion effects.

From the experimental results, we gain some insights and provide some managerial suggestions. First, the ride-hailing subsidy can reduce the average generalized travel cost in low-demand areas. However, the effect of the ride-hailing subsidy is limited when part of the investment is assigned to maintaining the competing parallel bus operation. The subsidy enhances the competitive impact of ride-hailing service, which leads to an extremely low bus ridership. Agencies should therefore choose whether to invest in ride-hailing or bus services for feeding connections. Second, due to the limited ride-hailing fleet size, the ride-hailing subsidy may lead to an increase in travel cost and a shift back to car at high demand level. Therefore, we suggest analyzing whether the ride-hailing service capacity can deal with the increasing demand before applying the strategy so that the fleet can be scaled accordingly.

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