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Economic Analysis of Competition in Complementary Transport Services: Integrating Bike Sharing Service with Transit System

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Outline

Introduction

Research background

Model formulation

Problem description
Interior equilibrium
System performance

Numerical study

Experimental Settings
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Discussion

Limitation and
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/01 Introduction

- Research background

Introduction

Bike-sharing system

Globally deployed: more than 2000 bicycle sharing programs worldwide, 18 million bikes in service

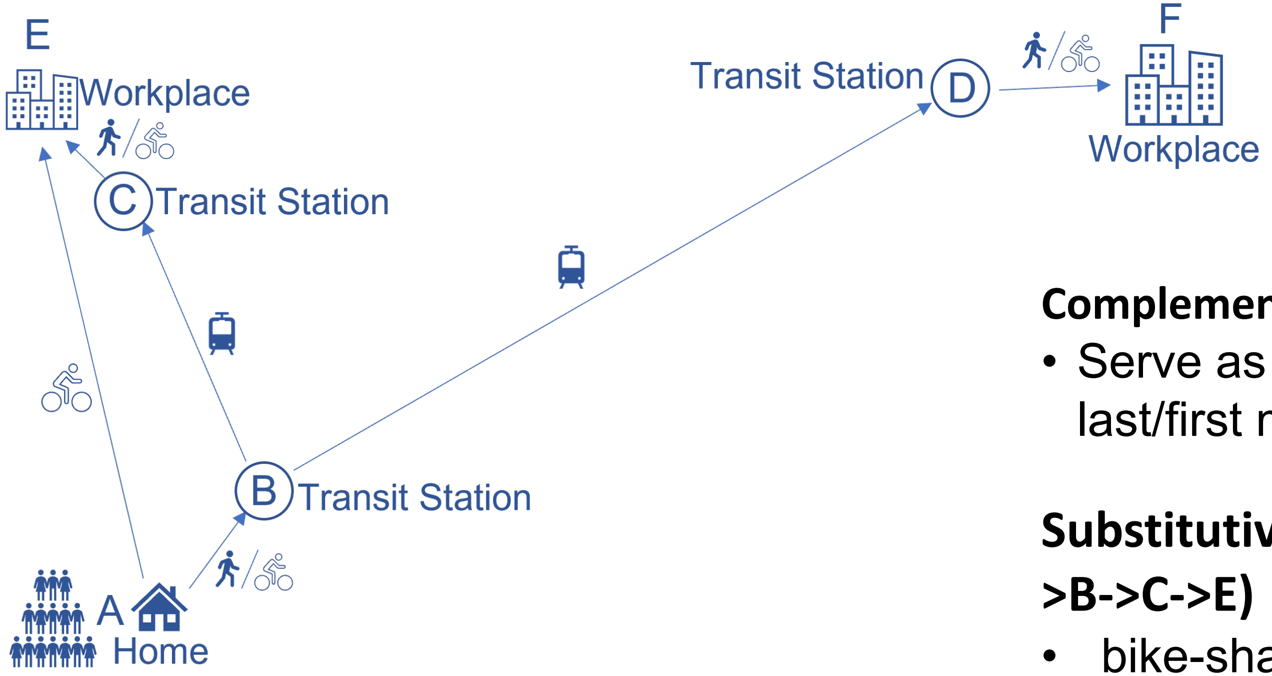
Emerging of relevant research

- Bike-way planning, operation, management
- Interaction with surrounding environment

An excellent review by Shui and Szeto (2020)

Introduction

No attention has been paid to two opposite impacts of bike sharing system when integrated with transit service: **complementary and substitutive**



Complementary with transit service (A->B->D->F)

- Serve as a feeder mode and address the last/first mile problem

Substitutive and Complementary (A->E vs A->B->C->E)

- bike-sharing systems can also divert some travellers from the transit service for short-distance trips

/02 Model formulation

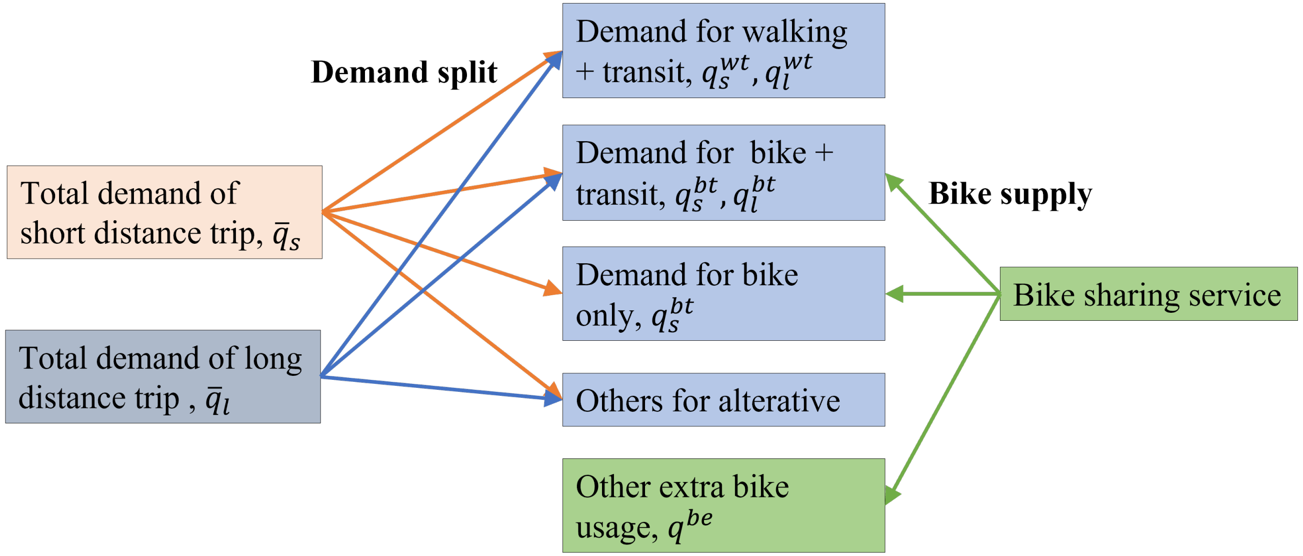
- Problem description
- Interior equilibrium
- System performance

Problem description

A common scenario that travellers in an urban area in the morning go to work from home (termed as commuters henceforth).

- Short-distance trips, given demand $\bar{q}_s$
- Long-distance trips, given demand $\bar{q}_l$

Shared bike service is introduced,



$$q^b = q_s^{bt} + q_s^b + q_l^{bt} + q^{be}$$

Clearly, without bike-sharing service,
$q_s^{bt} = q_s^b = q_l^{bt} = 0$, and thus $q_i^t = q_i^{wt}$, $i \in \{s, l\}$

Cost of different travel modes

Walking: $c^w(n)$ n-th traveller, $\frac{d}{dn}c^w(n)>0$

Transit: $c_i^t = \boldsymbol{\alpha}\frac{\mathbf{1}}{\mathbf{2}\boldsymbol{f_i^t}}$ (waiting cost) + $\boldsymbol{\beta T_i^t}$ (in-vehicle time) + $\boldsymbol{p_i^t}$ (ticket fare), $i \in \{s, l\}$

Bike: 1. access cost $c^{b,1}(n) = M\left(q^b, s^b, n\right)$, $\frac{d}{dn}c^{b,1}(n) = \frac{\partial M}{\partial n}$, $\frac{\partial M}{\partial q^b} > 0$, $\frac{\partial M}{\partial s^b} < 0$

2. riding effort (non-monetary cost for riding a bike)
- for feeder mode users : $c^{b,2}(n)$
- for commuters by bike only : $c^{b,3}(n)$

$$\frac{d}{dn}c^{b,2}(n) > \frac{d}{dn}c^{b,3}(n) > 0$$

Commuters who ride a bike for feeder mode are generally reluctant to ride too long distance

3. usage price: p^{bt} for feeder mode users, p^{be} for commuters who ride a bike only and other users. Assume $p^{be} = p^{bt} + \delta p$ for simplification.

Total Cost and Interior equilibrium

Short-distance trips

- Walking + transit (wt): $C_s^{wt}(n) = c^w + c_s^t$
- Bike + transit (bt): $C_s^{bt}(n) = c^{b,1} + c^{b,2} + p^{bt} + c_s^t$
- Bike only (b): $C_s^b(n) = c^{b,1} + c^{b,3} + p^{be}$
- Alternative mode (a): C_s^a

Long-distance trips

- Walking + transit: $C_l^{wt}(n) = c^w + c_l^t$
- Bike + transit: $C_l^{bt}(n) = c^{b,1} + c^{b,2} + p^{bt} + c_l^t$
- Alternative mode: C_l^a

Extra bike demand: $C^{be} = c^{b,1} + p^{be}$

Interior equilibrium

- Without bike service, only walking + transit and alternative mode

  $C_i^{wt}\left(q_i^{wt}\right) = C_i^a$, $i \in \{s, l\}$, q_i^{wt}-th traveller is indifferent between wt and a

- With bike service,

  Short: $C_s^{wt}(q_s^{wt}) = C_s^{bt}(q_s^{wt})$; $C_s^{bt}\left(q_s^{wt} + q_s^{bt}\right) = C_s^b\left(q_s^{wt} + q_s^{bt}\right)$; $C_s^b\left(q_s^{wt} + q_s^{bt} + q_s^b\right) = C_s^a$;

  Long: $C_l^{wt}(q_l^{wt}) = C_l^{bt}(q_l^{wt})$; $C_l^{bt}\left(q_l^{wt} + q_l^{bt}\right) = C_l^a$;

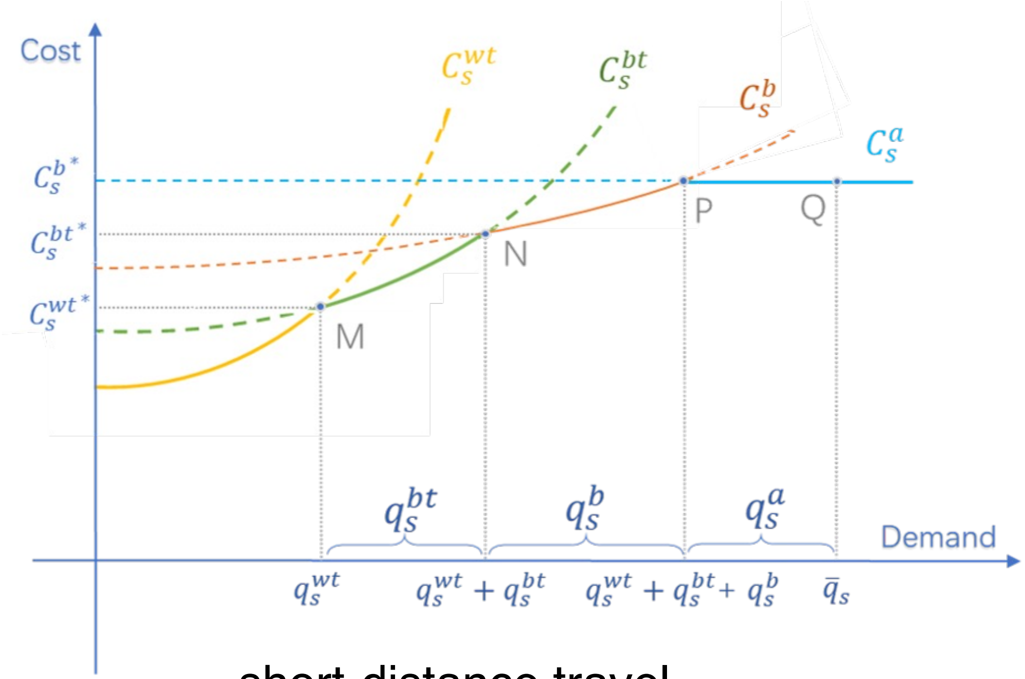
  Extra bike demand: $C^{be} = D^{-1}\left(q^{be}\right)$; where $q^{be} = D\left(C^{be}\right)$ is the demand function, $D^{-1}\left(q^{be}\right)$ is the inverse function.

Interior equilibrium

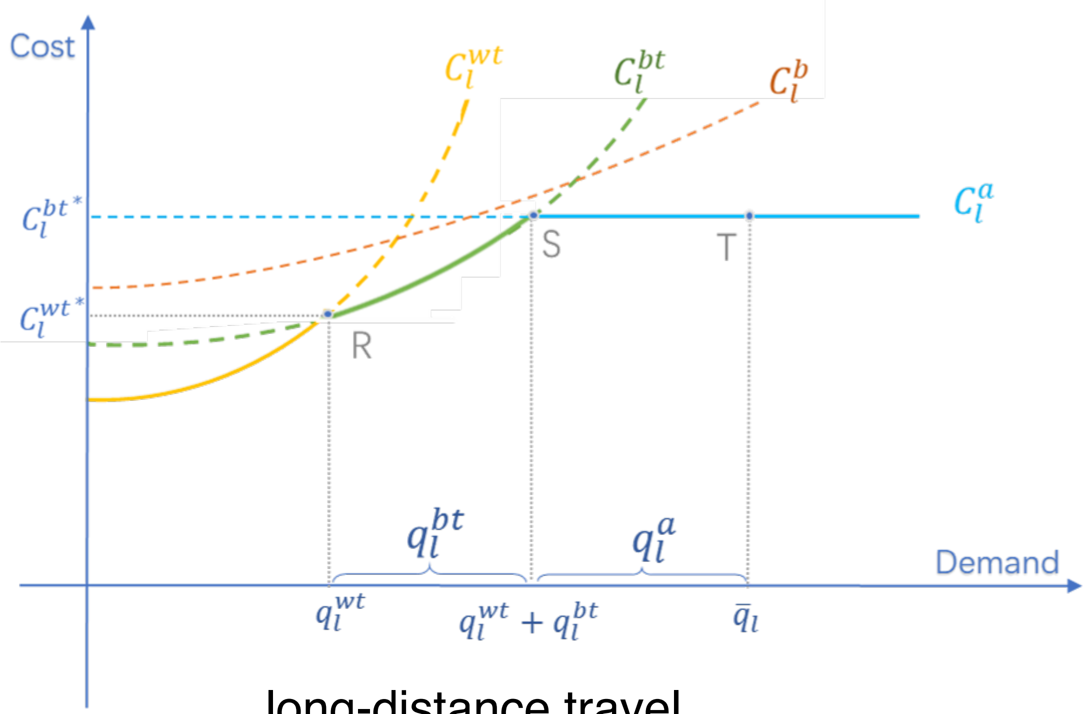
- With bike service,

Short: $C_s^{wt}(q_s^{wt}) = C_s^{bt}(q_s^{wt})$; $C_s^{bt}(q_s^{wt}+q_s^{bt}) = C_s^{b}(q_s^{wt}+q_s^{bt})$; $C_s^{b}(q_s^{wt}+q_s^{bt}+q_s^{b}) = C_s^{a}$;

Long: $C_l^{wt}(q_l^{wt}) = C_l^{bt}(q_l^{wt})$; $C_l^{bt}(q_l^{wt}+q_l^{bt}) = C_l^{a}$;



short-distance travel



long-distance travel

Performance measure

Total social welfare: $\boldsymbol{\Psi = \Omega^t + \Omega^b + \Gamma_s + \Gamma_l + \Gamma^{be}}$

Profit of transit operator: $\Omega^t = p_s^t q_s^t + p_l^t q_l^t - k(q_s^t, q_l^t, f_s^t, f_l^t)$

Profit of bike operator: $\Omega^b = p^{be}(q_s^b + q^{be}) + p^{bt}(q_s^{bt} + q_l^{bt}) - k(q^b, s^b)$

Travellers' surplus: $\Gamma = \Gamma_s + \Gamma_l + \Gamma^{be}$

Short-distance $\Gamma_s = u_s \bar{q}_s - \int_0^{q_s^{wt}} C_s^{wt}(x)dx - \int_{q_s^{wt}}^{q_s^{wt}+q_s^{bt}} C_s^{bt}(x)dx - \int_{q_s^{wt}+q_s^{bt}}^{q_s^{wt}+q_s^{bt}+q_s^b} C_s^b(x)dx - C_s^a q_s^a$

Benefit of a trip completion

Long-distance $\Gamma_l = u_l \bar{q}_l - \int_0^{q_l^{wt}} C_l^{wt}(x)dx - \int_{q_l^{wt}}^{q_l^{wt}+q_l^{bt}} C_l^{bt}(x)dx - C_l^a q_l^a$

Extra bike $\Gamma^{be} = \int_0^{q^{be}} (D^{-1}(x) - C^{be}(x))dx$

Performance measure

Total social cost when bike sharing service is available:

$$\Phi = \sum_{i\in\{s,l\}} \left(\int_0^{q_i^{wt}} c_i^{wt}(x)dx + \left(\alpha \frac{1}{2f_i^t} + \beta T_i^t\right)(q_i^{wt} + q_i^{bt}) + C_i^a q_i^a \right)$$
$$+ \int_0^{q^b} c^{b,1}(x)dx + \int_0^{q_s^{bt}+q_l^{bt}} c^{b,2}(x)dx + \int_{q_s^{wt}+q_s^{bt}}^{q_s^{wt}+q_s^{bt}+q_s^b} c^{b,3}(x)dx$$
$$+ k^t(q_s^t, q_l^t, f_s^t, f_l^t) + k^b(q^b, s^b)$$

Different operating regimes

Non-cooperative (NC) game: bike sharing system vs transit system

$$\max_{(p^{bt}, s^b)} \Omega^b \qquad \max_{(p_s^t,\ p_l^t,\ f_s^t,\ f_l^t)} \Psi$$

Nash Bargaining (NB) game: joint benefit against a performance benchmark or status quo

$$\max_{(p^{bt}, s^b, p_s^t,\ p_l^t,\ f_s^t,\ f_l^t)} \Theta = \left(\Omega^b - \Omega^{b,0}\right)(\Psi - \Psi^0)$$

/03 Numerical study

Conclusions

Parameters and settings

Parameters or Functions	Specification
Value of time	$\alpha = 90$ HKD/hr, $\beta = 50$ HKD/hr
In-vehicle time	$T_s^t = 20$ min, $T_l^t = 45$ min
Benefits of a transit trip completion	$u_s = 100$ HKD, $u_l = 120$ HKD
Demand	$\bar{q}_s = 55000$ trips/hr, $\bar{q}_l = 45000$ trips/hr
Cost of alternative travel mode	$C_s^a = 100$ HKD, $C_l^a = 155$ HKD
Transit operating cost	$k^t = 35000 + 1.5(q_s^t + q_l^t)$ $+40(f_s^t + f_l^t) + 45((f_s^t)^2 + (f_l^t)^2)$ HKD/hr
Bike operating cost	$k^b = 1000 + 0.5q_b + 20s^b$ HKD/hr
Price difference for q^{be}, q_s^b and q_s^{bt}, q_l^{bt}	$\delta p = 8$ HKD
Walking cost	$c^w(q) = 30 + 0.003q$ HKD
$c^{b,1}$	Bike access cost, $c^{b,1}(q_b, s_b, q) = 0.0004q + 15 + 0.2(\frac{q_b}{s_b})^{0.5}$
$c^{b,2}$	Bike riding cost for connection sub-trip of q_i^{bt}, $c^{b,2}(q) = 20 + 0.0012q$
$c^{b,3}$	Bike riding cost for bike only mode of q_s^b, $c^{b,3}(q) = 50 + 0.0001q$
q^{be}	Other extra bike demand, $q^{be}(c) = 5000 - 25c$

Numerical results

(f_i^t: run/hr; s_b: bike/km^2 × hr; monetary: HKD; Demand: trips/hr)

Variables	T-SO	T-PM	T-SO-0	B-PM	NC	NB
p_s^t	1.51	26.00	2.81	1.51	0.00	0.00
f_s^t	20.07	15.84	19.89	20.07	22.99	23.03
p_l^t	1.51	43.31	3.65	1.51	36.76	36.79
f_l^t	23.96	18.95	23.76	23.96	22.03	22.05
p^{be}	-	-	-	18.34	15.63	15.52
p^{bt}	-	-	-	10.34	7.63	7.52
s^b	-	-	-	1558	1237	1273
$q_s^{wt}(10^4)$	1.65	0.82	1.61	1.179	0.99	0.98
$q_s^{bt}(10^4)$	-	-	-	0.419	0.776	0.785
$q_s^b(10^4)$	-	-	-	1.50	1.88	1.87
$q_s^a(10^4)$	3.847	4.684	3.892	2.402	1.856	1.873
$q_l^{wt}(10^4)$	2.80	1.39	2.73	1.18	0.99	0.98
$q_l^{bt}(10^4)$	-	-	-	3.05	1.20	1.21
$q_l^a(10^4)$	1.696	3.106	1.768	0.275	2.319	2.314
$q^{be}(10^3)$	-	-	-	3.61	3.78	3.78
$k^t(10^5)$	1.476	0.970	1.450	1.681	1.412	1.418
$k^b(10^4)$	-	-	-	5.879	4.688	4.783
$\Omega_b(10^5)$	-	-	-	6.41	4.56	4.56
$\Omega_t(10^5)$	-0.81	7.19	0.00	-0.80	6.60	6.63
$TSW(10^4)$	-6.64	-46.47	-6.75	-40.10	-3.33	-2.65
$TC(10^7)$	1.09	1.21	1.10	1.11	1.21	1.21

Without bike sharing

- T-SO transit operator at its social optimum.
- T-PM transit operator maximizes its profit.
- T-SO-0 transit operator maximizes the social welfare when subject to break-even

With bike sharing

- B-PM bike sharing operator maximizes its profit as reacting to T-SO
- NC non-cooperative game,
- NB Nash bargaining

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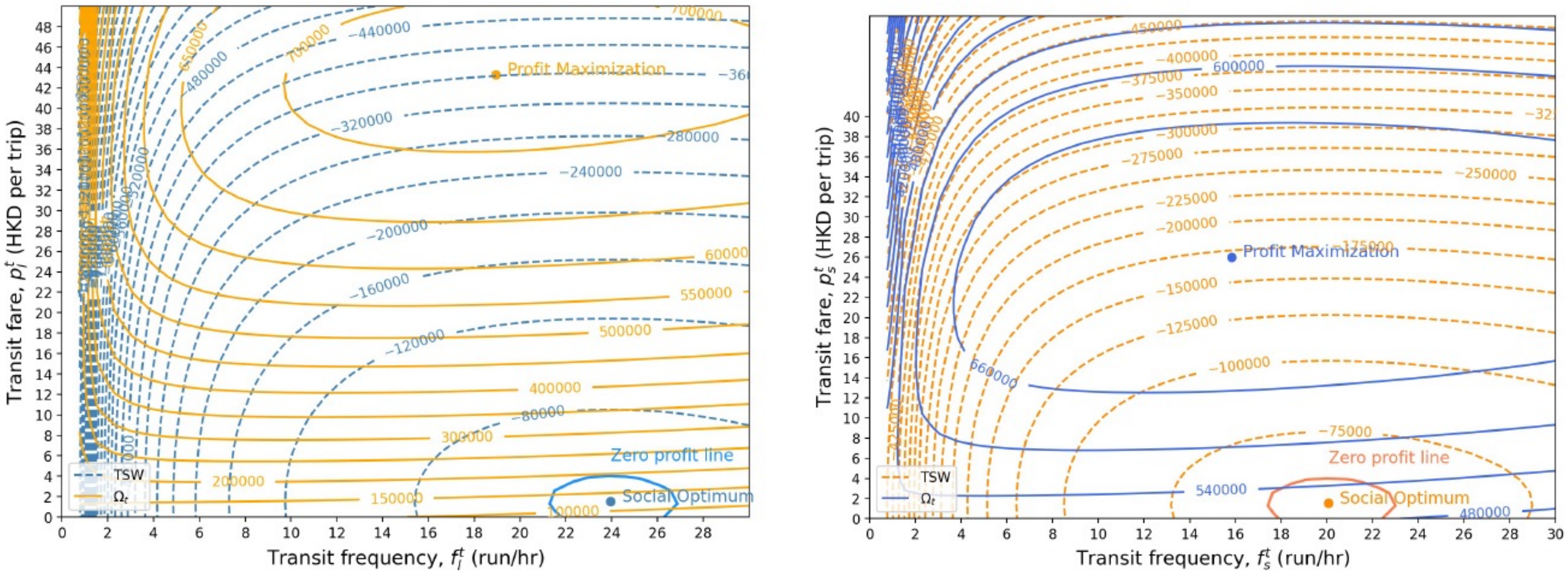
Frequency-fare contours



(a) For long-distance travel

(b) For short-distance travel

Observations

no bike sharing

- Financial deficit at T-SO
- Transit pricing T-SO < T-SO-0 < T-PM
- Transit service frequency, T-SO > T-SO-0 > T-PM

Numerical results

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Observations

when shared bike service becomes available

- Total transit demand increases after introducing bike sharing
- Coexist of complementary and substitutive effects
- optimal transit fare of short distance trips for NC and NB is zero
- f_S^t in NC> B-PM, p^{bt} in NC < B-PM because of non-cooperation game
- NC as our status quo, the optimal solution of NB seems close to NC

/04 Discussion

- Limitation
- Future work

Limitation and future work

We only tackle the static travel demand under equilibrium condition

If time-varying user choices, evolving traffic status, spatiotemporal distributed OD demand and network-wide interactions are taken into consideration, some of our results and observations in our paper may not stand.

In a future study, more efforts can be devoted to a detailed network model, where the model could be extend to temporal and spatial dimensions.

Thanks

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