Design of Tradable Permits System for Mobility Sharing Focused on Temporal-Spatial OD connection

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Background

automobile dependent society

➡ **multimodal transport society**

Needs of new mobility services and transport policy

- easy switch between transport modes
- good connections between modes
- flexible price mechanism and charging scheme

➡ **Mobility Sharing**

Smart Bike @Oslo


Vélib‘ @Paris


LISELEC @La Rochelle

Motivation

- Sharing System has **constrained supply capacity**
- Early Studies
  - Akamatsu (2007): Bottleneck Tradable Permits
  - Yang and Wang (2011): Tradable Mobility Credits
- Technical issues
  - Early studies focus on road network.
  - Mobility sharing doesn't have constrained road capacity, but have **constrained vehicle capacity**.
  - A trip generates the **externality** of vehicle moving.
- Research Objectives
  - Designing tradable permits system for mobility sharing
  - Proposing Solution Algorithm

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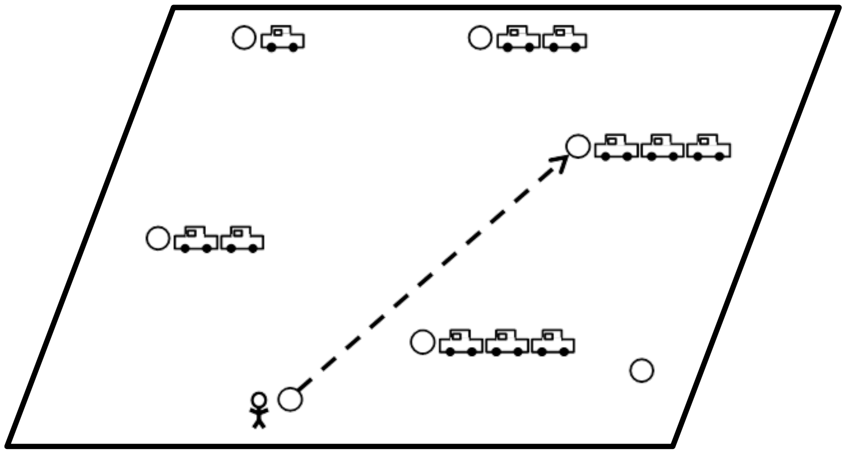
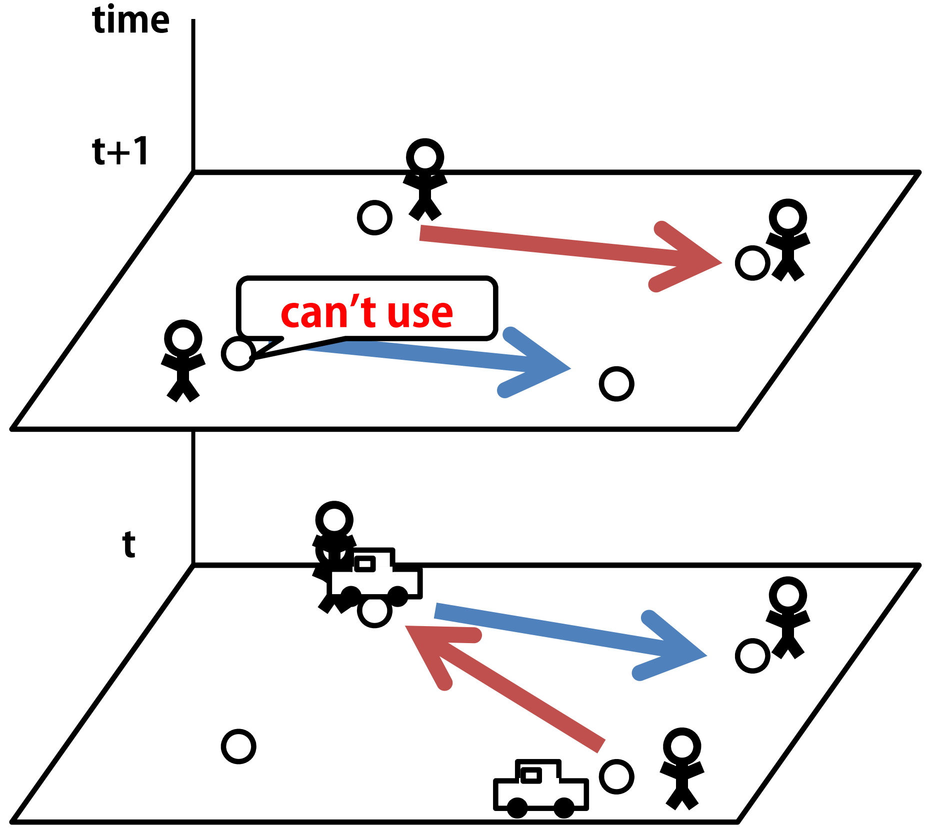
The Externality of Vehicle Moving in Mobility Sharing

1) spatial dispersion of mobility



2)mismatch between previous users and next users



the important point of mobility sharing

"sharing a vehicle by more than one person" is not essential.
"Connecting more than one trip temporally and spatially" is essential.

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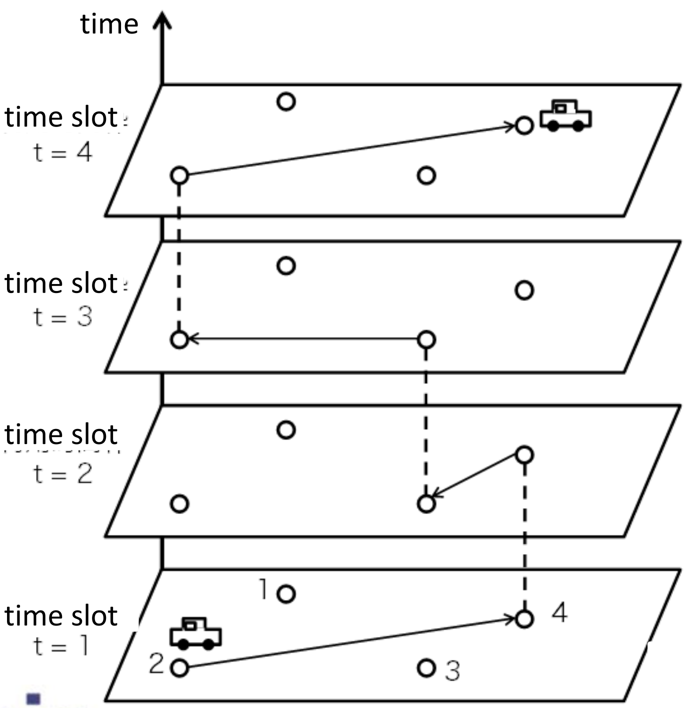
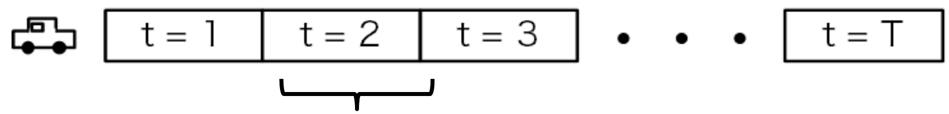
Setting1: the Assumption of Transportation Services

We assume the following statements.
1. Mobility sharing means car sharing in this research.
2. A trip can be done in a time slot.
3. There is no delay.
4. The number of vehicle is μ and each vehicle can move **independently**.

temporal-spatial network



time slot



We don't consider the delay effect.

$i \in I$	: user i	$p, q \in N$	: port node
$t \in T$	: time slot t	$pq \in L$	: OD pair pq

Setting2: Supplier and the Capacity limit

the setting of service supplier

We assume that **service supplier** is the player to **maximize social surplus** by operating vehicle effectively. The supplier tackles an unbalanced demand problem between ports by allocating users to permits satisfying temporal-spatial OD connected condition at all time slot.

capacity limit μ

Capacity limit means **the number of vehicles** service supplier has.
Service supplier can issue permits depending on the capacity limit.

$$\sum_{i \in I} \sum_{pq \in L} x^i_{pq}(t) = \mu \qquad \forall t \in T$$

$x^i_{pq}(t) \in \{0,1\}$ is a discrete variable. If user i is allocated to a permit to use vehicle between OD pq at time slot t, this variable is 1. Otherwise this variable is 0.

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Setting3: Users and Their Values of Permit

the setting of users and users' value of permit

Users have the value of permits and the value of each permit is different by time slot and OD pair. Users determine the value by their OD demand, their desired usage timeslot, their value of time and so on.
We assume that users do a one way trip by vehicle and if users don't get a permit, they can use an alternative whose utility is 0.

$$v^i_{pq}(t) \equiv \underline{w^i_{pq}}(t) - (\underline{h^i(t, \hat{t}^i)} + \gamma^i \underline{t_{pq}})$$

$$v^i_a(t) \equiv 0$$

willingness to pay
schedule cost
travel cost

$$u^i(\boldsymbol{x}^i, p^i) = \boldsymbol{v}^i \cdot \boldsymbol{x}^i - p^i$$

where

$$\boldsymbol{v}^i = (v^i_{pq}(t))_{pq \in L, t \in T}$$

$$\boldsymbol{x}^i = (x^i_{pq}(t))_{pq \in L, t \in T}$$

We assume that users don't change OD-demand but change timeslot to use.

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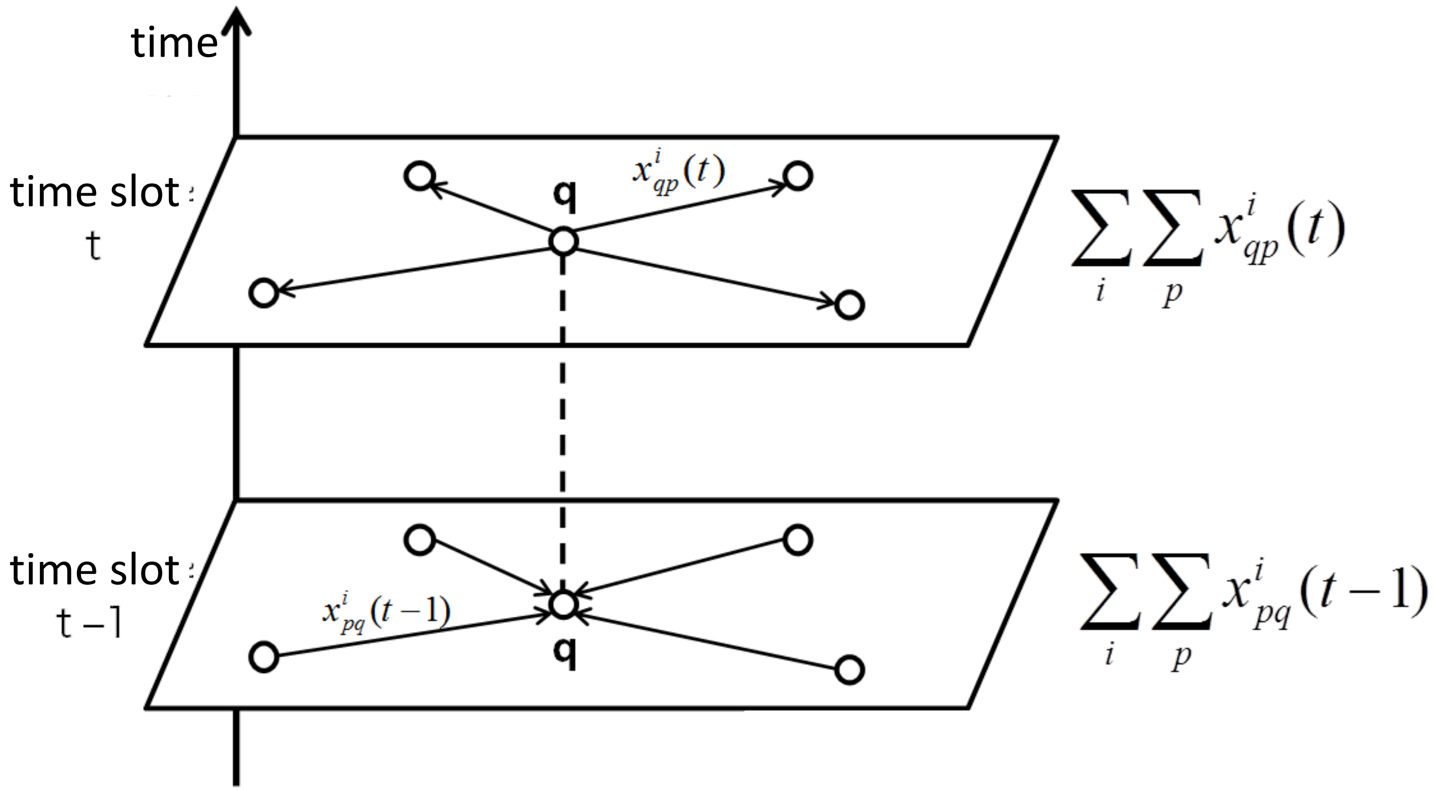
Setting4: Temporal-Spatial OD connected Condition

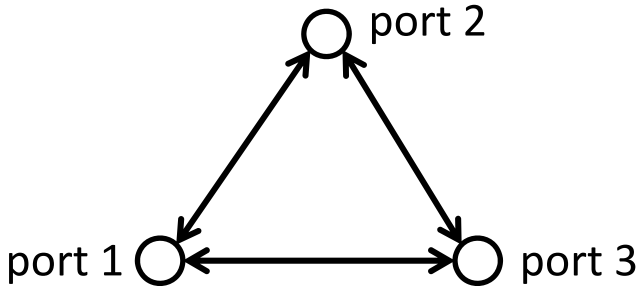
Meeting temporal-spatial OD connected condition is satisfying the following equation for any node q.

$$\sum_{i \in I} \sum_{p \in N} x^i_{pq}(t-1) = \sum_{i \in I} \sum_{p \in N} x^i_{qp}(t) \qquad t = 2, \cdots, T, \forall q \in N$$



Example of the Setting

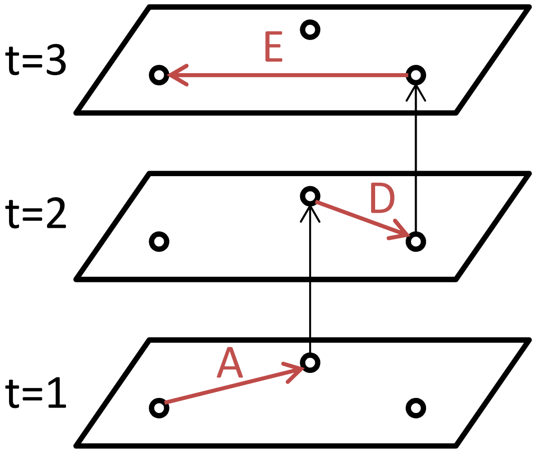
example network



users' demand and value of permit

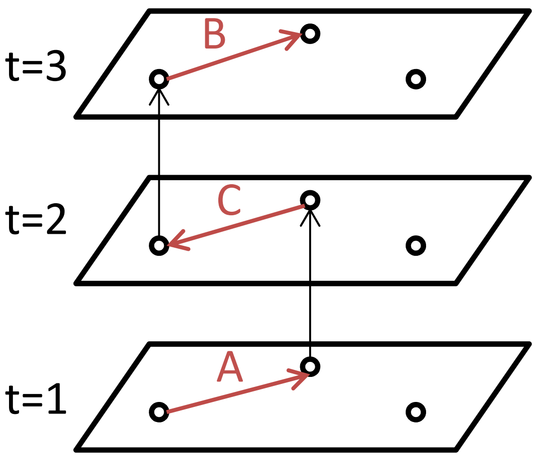
User ID	OD	value (t = 1)	value (t = 2)	value (t = 3)
A	1→2	90	80	70
B	1→2	60	70	80
C	2→1	70	80	70
D	2→3	70	60	50
E	3→1	50	60	70

An allocation {A, D, E}



Sum of values (Social Surplus) is 220.

Another allocation {A, C, B}



Sum of values (Social Surplus) is 240.

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Permits Allocation of Social Optimum

- optimization problem to maximize the sum of users' values[SO]

$$SS \equiv \max_{\{\boldsymbol{x}^i\}} \sum_{i \in I} \sum_{t \in T} \sum_{pq \in L} v^i_{pq}(t) x^i_{pq}(t)$$

subject to

$$\sum_{t \in T} \sum_{pq \in L} x^i_{pq}(t) = 1 \quad \text{single demand condition} \quad \forall i \in I$$

$$\sum_{i \in I} \sum_{pq \in L} x^i_{pq}(t) = \mu \quad \text{capacity limit} \quad \forall t \in T$$

temporal-spatial OD connected

$$\sum_{i \in I} \sum_{p \in N} x^i_{pq}(t-1) = \sum_{i \in I} \sum_{p \in N} x^i_{qp}(t) \quad t = 2, \cdots, T, \forall q \in N$$

$$x^i_{pq}(t) \in \{0, 1\} \quad \text{each user's permits allocation} \quad \forall pq \in L, \forall i \in I, \forall t \in T$$

➡ **If users bid their true values, service supplier only has to solve this optimization problem [SO] and social optimum is achieved. However, if users bid their false values strategically, it is difficult to maximize social welfare. Therefore, we need a mechanism to make users bid true values.**

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VCG Mechanism for Mobility Sharing

Vickrey–Clarke–Groves Mechanism satisfy efficiency and strategy-proofness.
We extend VCG mechanism for mobility sharing permits.

VCG mechanism for mobility sharing permit

1. All users bid the permits which they want to use.
2. Service supplier solve winner determination problem[WDP] under temporal-spatial OD connected condition and capacity limit.
3. Winners have to pay the permit price. The price is Vickrey payments. Vickrey payments means the externality that a user exerts on the other users by his presence in society. It is the difference between the welfare of the others "without him" and the welfare of the others "with him".

Under this mechanism, users have an incentive to bid their true values. Therefore, supplier can solve the optimization problem and the social optimum is achieved.

However, the winner determination problem is included in combinatorial optimization problems. And these problems are NP-hard in general.
In this sense, solution algorithm is important.

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Solution Algorithm of [WDP]

- Approximate Solution Algorithm
  - We assume that users bid for only 1 timeslot permit or users can't bid for more than 2 timeslot permits.
  - Users will bid for the most variable timeslot permit for them.
  - This assumption is single-minded bids in combinatorial auction.
  - Computational effort is small and this algorithm requires polynomial time.

- Exact Solution Algorithm
  - Users can bid for more than 1 timeslot permit.
  - Computational effort is large and this algorithm requires exponential time.

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Approximate Solution Algorithm

By the assumption that users bid for the highest time slot permit, we redefine [WDP] as [WDP-Greedy].

$$SS \equiv \max_{\{\boldsymbol{x}_1^i\}} f_1(\boldsymbol{x}_1^i) + \max_{\{\boldsymbol{x}_2^i\}} f_2(\boldsymbol{x}_2^i) + \cdots + \max_{\{\boldsymbol{x}_\mu^i\}} f_\mu(\boldsymbol{x}_\mu^i)$$

where

$$f_l(\boldsymbol{x}_l^i) = \sum_{i \in I_{l-1}} \sum_{t \in T} \sum_{pq \in L} v_{pq}^i(t) x_{pq}^i(t) \qquad \textbf{[WDP-Greedy-Sub]} \qquad l = 1, 2, \ldots, \mu$$

subject to

$$\sum_{t \in T} \sum_{pq \in L} x_{pq}^i(t) = 1 \qquad \textbf{single demand condition} \qquad \forall i \in I_{l-1},\ \forall l$$

$$\sum_{i \in I_{l-1}} \sum_{pq \in L} x_{pq}^i(t) = 1 \qquad \textbf{capacity limit} \qquad \forall t,\ \forall l$$

temporal-spatial OD connected

$$\sum_{i \in I_{l-1}} \sum_{p \in N} x_{pq}^i(t-1) = \sum_{i \in I_{l-1}} \sum_{p \in N} x_{qp}^i(t) \qquad t = 2, \cdots, T,\ \forall p \in N,\ \forall l$$

$$x_{pq}^i(t) \in \{0, 1\} \qquad \textbf{each user's permits allocation} \qquad \forall pq \in L,\ \forall i \in I_{l-1},\ \forall t,\ \forall l$$

➡ **This algorithm can solve [WDP-Greedy-Sub] in sequence and the computational effort is small.**

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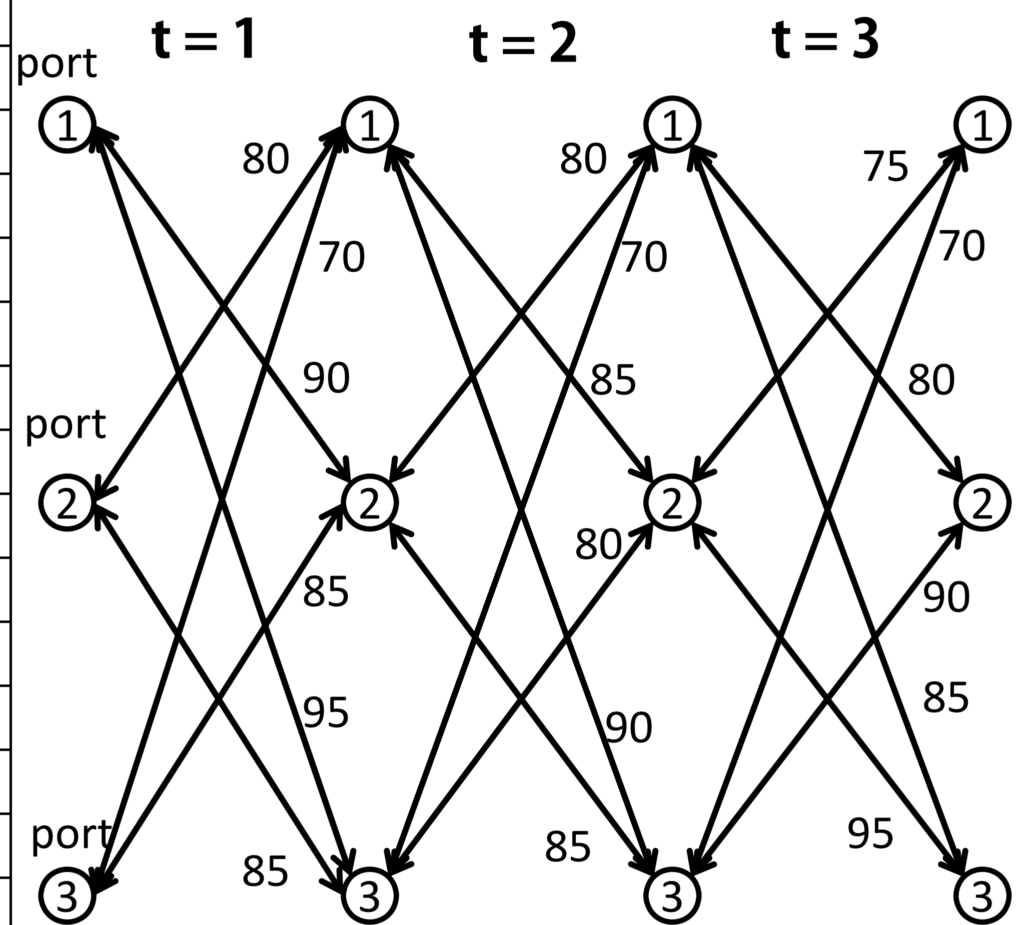
Example

User ID	OD	value (t = 1)	value (t = 2)	value (t = 3)
A	1→2	90	~~80~~	~~70~~
B	1→2	~~75~~	85	~~65~~
C	1→2	~~60~~	~~70~~	80
D	1→3	95	~~85~~	~~75~~
E	1→3	~~70~~	90	~~70~~
F	1→3	~~65~~	~~75~~	85
G	2→1	80	~~70~~	~~60~~
H	2→1	~~60~~	80	~~50~~
I	2→1	~~35~~	~~55~~	75
J	2→3	85	~~65~~	~~45~~
K	2→3	~~75~~	85	~~65~~
L	2→3	~~75~~	~~85~~	95
M	3→1	70	~~60~~	~~50~~
N	3→1	~~50~~	70	~~50~~
O	3→1	~~55~~	~~65~~	70
P	3→2	85	~~75~~	~~65~~
Q	3→2	~~60~~	80	~~60~~
R	3→2	~~70~~	~~80~~	90

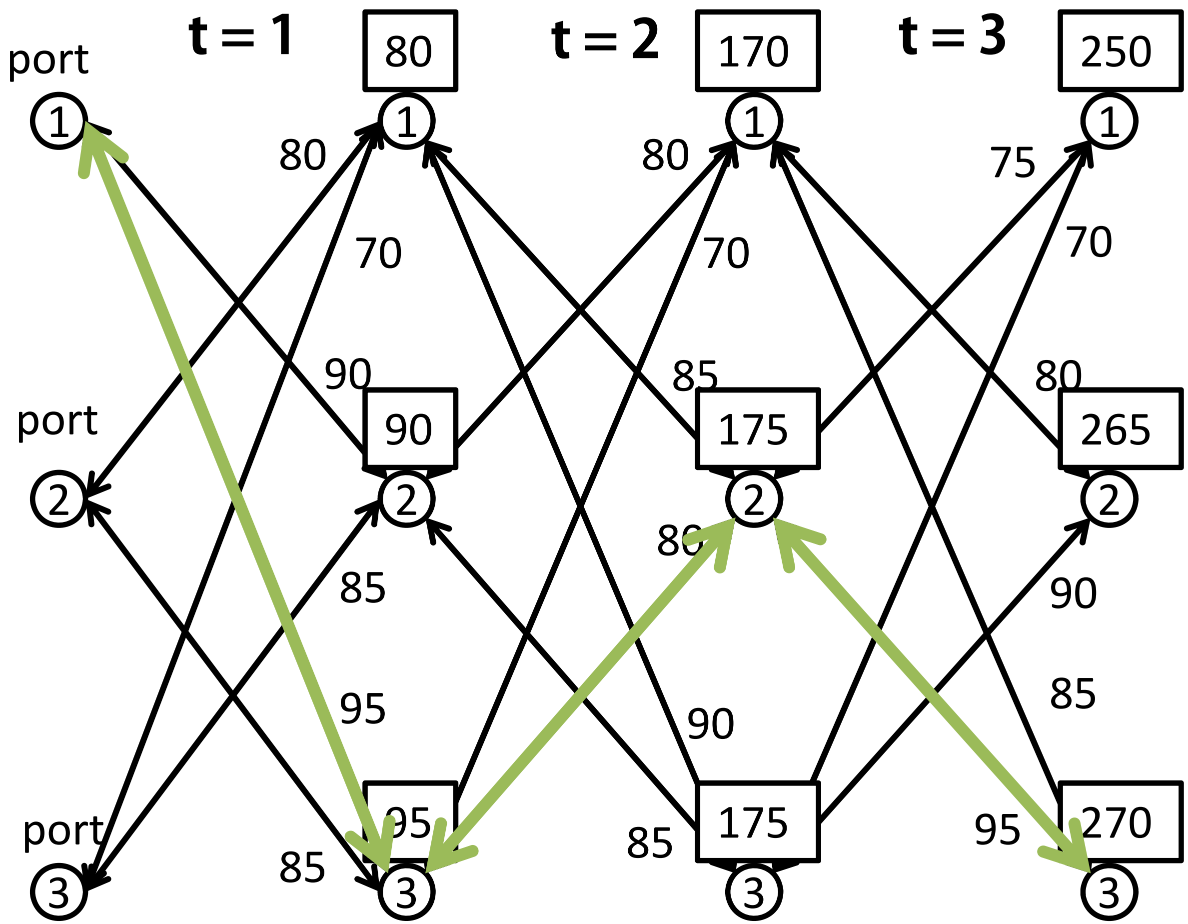
network representation



link weight: 1st price

Example: first vehicle path

Solving longest path problem



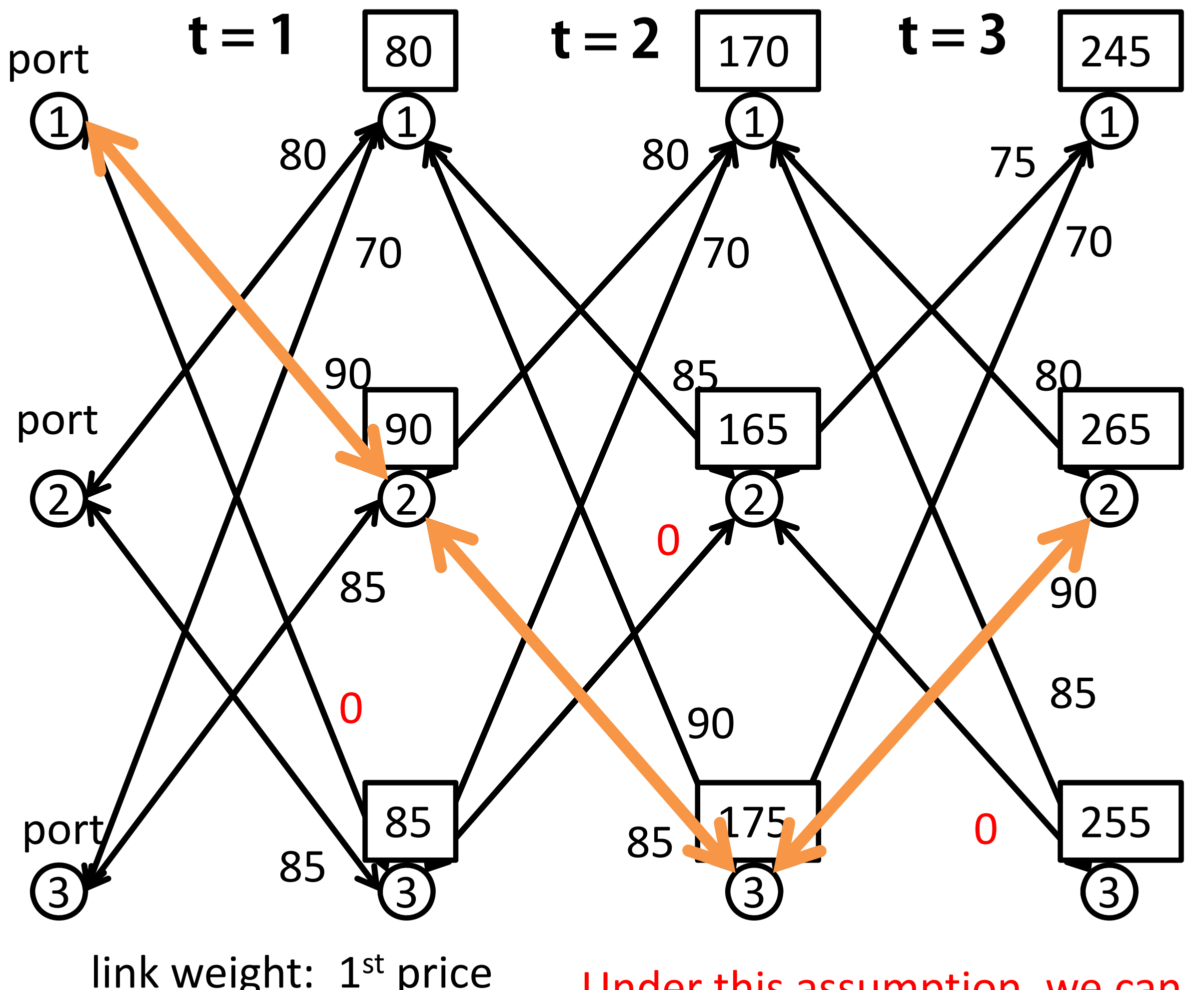
link weight: 1st price

First Vehicle

Winners set is {D, Q, L}.
Sum of value is 270.

Example: second vehicle path

Eliminating the winners of first vehicle from users set, update link weight.



First Vehicle

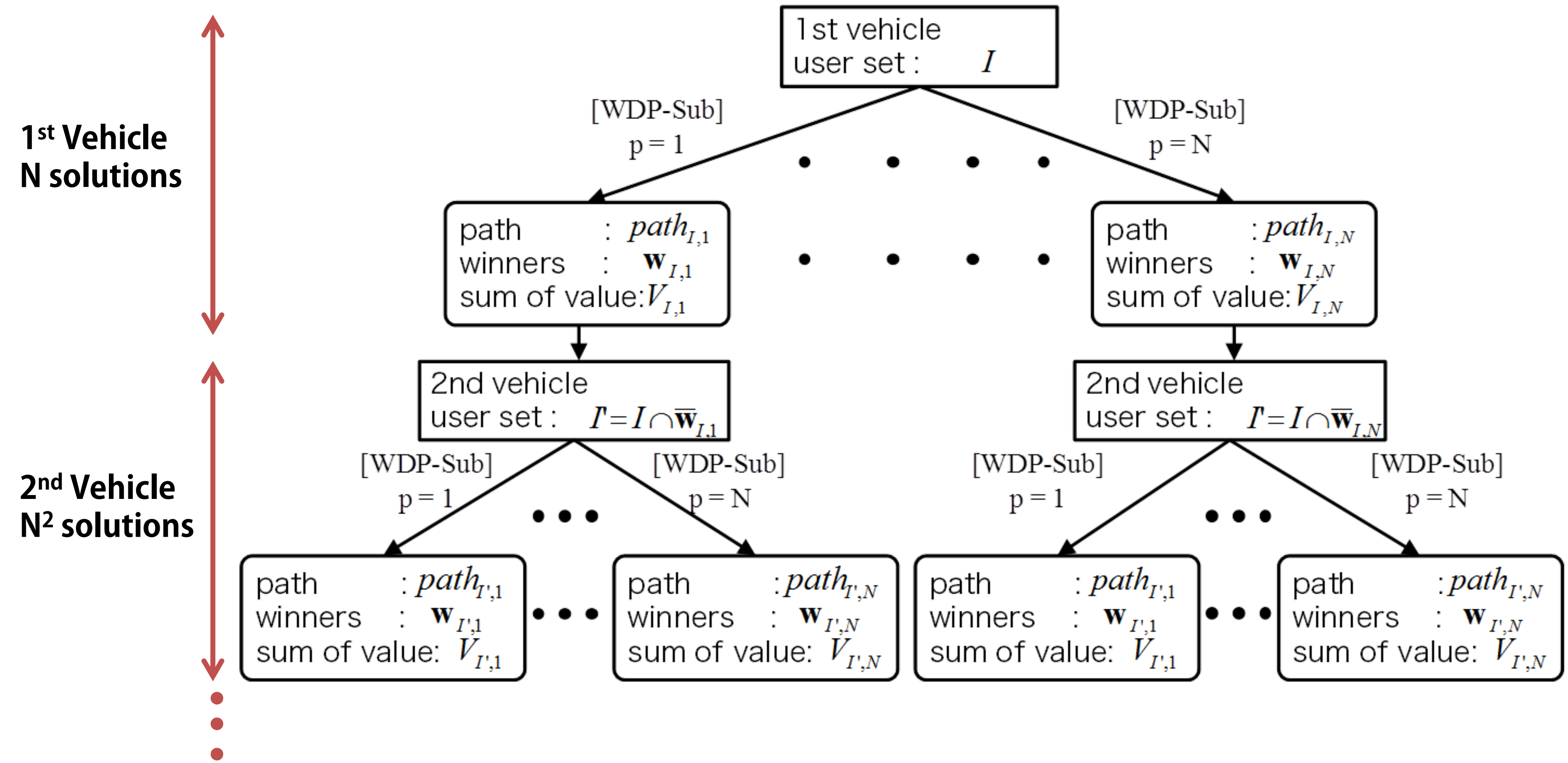
Winners set is {D, Q, L}.
Sum of value is 270.

Second Vehicle

Winners set is {A, K, R}.
Sum of value is 255.

Under this assumption, we can solve WDP in sequence.

Exact Solution Algorithm

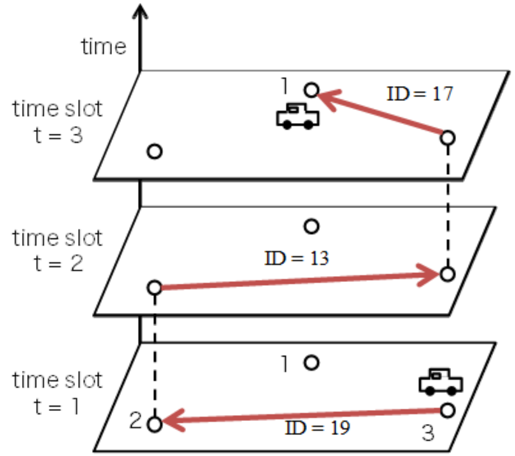


μ^{th} Vehicle
N^{μ} solutions

Solving [WDP-Sub] with respect to each final destination, the algorithm search optimal solution by breadth first search of these solutions.

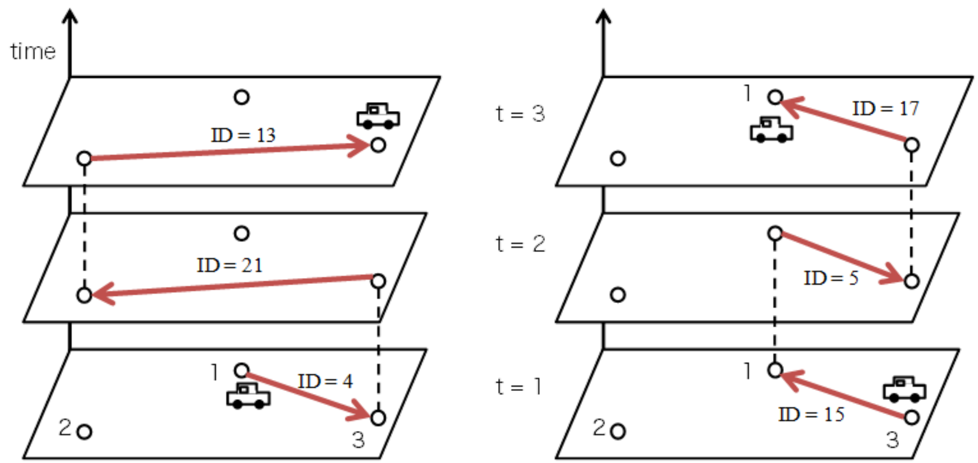
example calculation

capacity is 1.
winners :
{19, 13, 17}

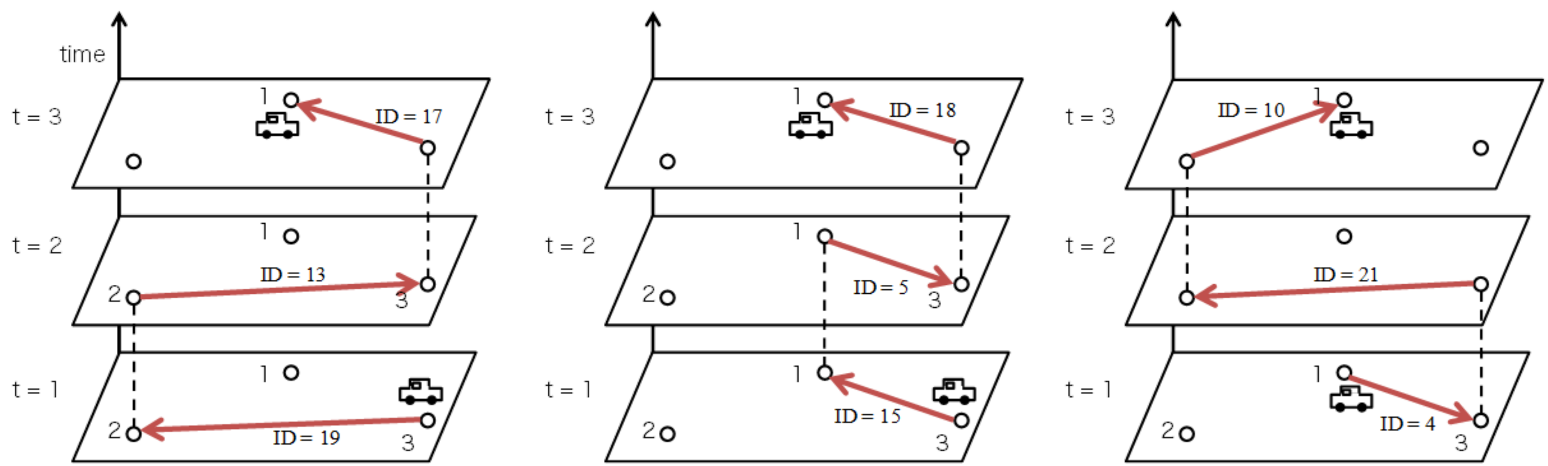


The winners in the case that the number of vehicle is one are not necessarily included in the winners in the case that the number of vehicle is two. Therefore, searching optimal solution requires more time than the situation of approximate algorithm.

capacity is 2.
winners :
{4, 21, 13,
15, 5, 17}

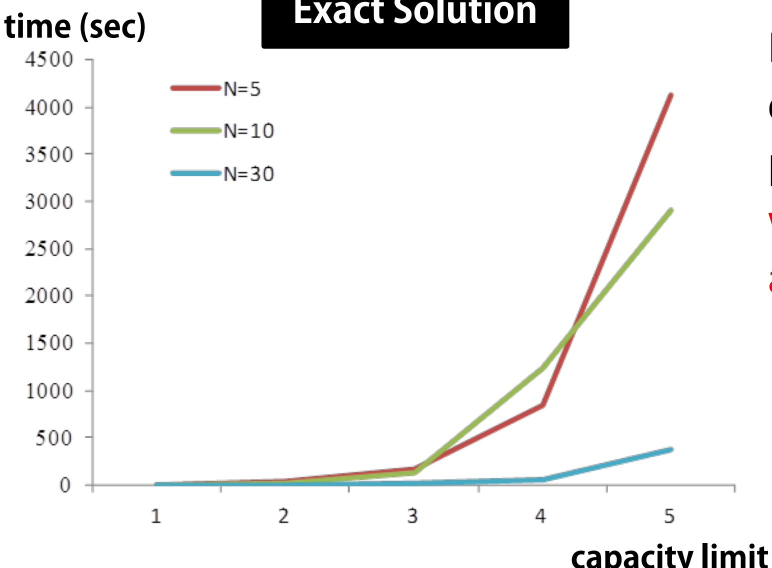


capacity is 3.
winners :
{19, 13, 17,
15, 5, 18,
4. 21. 10}

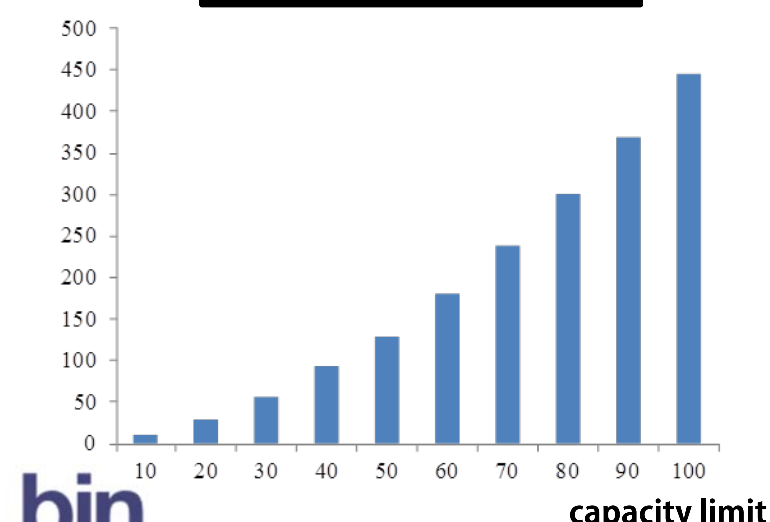


the comparison of computational time

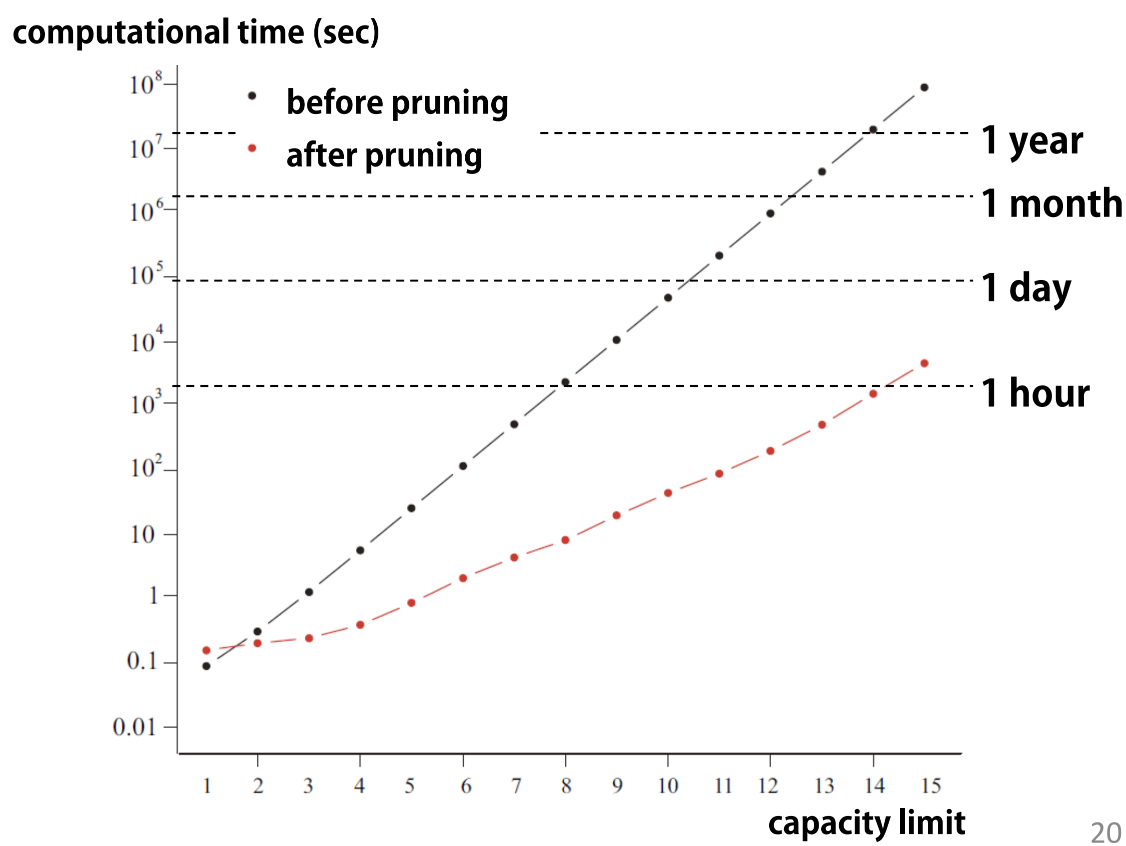
Exact Solution



Approximate Solution



Exact solution algorithm requires exponential time, on the other hand approximate algorithm requires polynomial time. Therefore exact algorithm is not working at all. However, pruning by the solution of approximate algorithm makes exact algorithm speed up.



Summary and Discussion

- We designed tradable permit system for mobility sharing and the mechanism achieved social optimum satisfying temporal-spatial OD connected condition.
- Exact Solution Algorithm requires exponential time but pruning using the solution of approximate algorithm has a large increase in speed of exact solution algorithm.
- In this study, we show the theoretical and computational possible application of tradable permits system for mobility sharing.

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