A hybrid implementation mechanism of tradable network permits system:

An auction mechanism with day-to-day capacity control

Kentaro Wada & Takashi Akamatsu

Graduate School of Information Sciences, Tohoku University

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Introduction

- Congestion pricing (price-based regulation)
  - working effectively when a road manager can calculate an optimal toll level
  - needing **accurate** and **detailed demand information**

    e.g., OD demands, VOT, desired arrival/departure time

- **Asymmetric information**

    between the manager and road users
  - very difficult to obtain such private information
  - distorting toll levels
  - resulting in economic losses

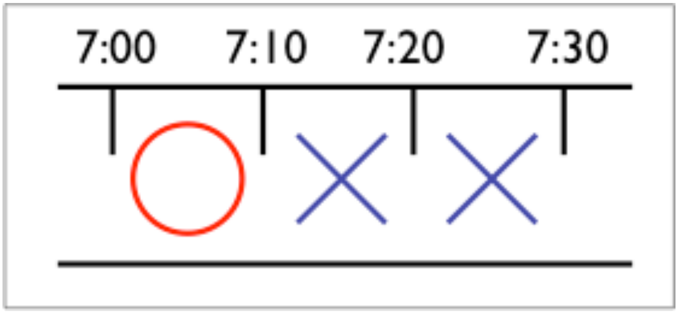
What is tradable network permits scheme?

❖ **Tradable Network Permits (TNP)** [*Akamatsu et al. (06, 07)*]

- a right that allows a permit holder to pass through **specific bottleneck** during **pre-specified time period**

– quantity-based regulation

  e.g., highway booking



❖ **Trading market** for network permits

- time-dependent
- freedom of permit choice

– **Allocation** and **prices** are determined through the markets.

Why is the TNP scheme needed?

❖ **No queuing congestion**

- # of permits of each link ≤ bottleneck capacity

❖ **No detailed information on user demand**

- manager only needs to know bottleneck capacity.

  cf. congestion pricing (or price-based regulation)

❖ **Efficiency in general networks** [*Akamatsu, (07)*]

- equilibrium resource allocation pattern

  = **Dynamic System Optimal (DSO) assignment**

- assumption: **trading markets are perfectly competitive**,
  i.e., trading processes were treated as a **black box**.

How to implement the TNP scheme?

- *Markets do what they are supposed to do, however, **only if they are well structured**.* [*McMillan (02)*]
  - preventing **manipulating** prices
  - achieving an efficient allocation

- Auction mechanism for a bottleneck [*Wada & Akamatsu (10)*]
  - Vickrey-Clarke-Groves (VCG) mechanism
  - **strategy-proof** (i.e., truthful bidding is a dominant strategy)
  - **Permits allocation pattern is efficient**.
- General networks
  - A naïve formulation of the problem leads to **NP-hardness** owing to the complex relationship between link and path.

Purpose of the study

- **A novel auction mechanism to implement TNP scheme for general networks**
  - enabling each user to purchase the preferred bundle of permits (path)
  - achieving a DSO allocation of network permits in a computationally efficient manner

- Approach
  - evolutionary (day-to-day) approach
  - **a path-based auction with day-to-day capacity control**
  - obviating path enumeration by introducing a column generation procedure

Tradable permits for managing traffic congestion

❖ Quantity-based regulation + market institution

- possibilities of using tradable permits for managing congestion [*Verhoef et al., (97)*]

✓ none describes **time-dependent tradable permits** for eliminating **bottleneck congestion.**

❖ Tradable travel credit scheme [*Yang and Wang (11)*]

- is superficially similar to but **fundamentally different** from tradable network permits scheme
- is not a quantity-based regulation for **directly** reducing congestion but rather a **redistribution scheme of income**

Setting

- A discrete time DTA on general networks with multiple Origin-Destination (OD) pairs
  - point (or physical) queue model
  - μ_a - bottleneck capacity = # of permits of link *a*
    - **no queuing congestion**

- Behavior assumption for **atomic** road user
  - *at most* single trip per day between an OD
  - **utility max**.: choice rule of *path* and *destination arrival time*
  - must purchase a bundle of permits corresponding to a path

User valuation and utility

- User *i*'s valuation for path *r* and destination arrival time *t*
  - **private information**
  - including **constant** travel time

$$v_{i,r}(t) = [\boldsymbol{v}_i]_{r,t} \geq 0$$

- Quasi-linear utility = valuation − permit purchase cost

$$u_{i,r}(t) = v_{i,r}(t) - p_r(t)$$

- Allocation of bundles of permits (**paths**)

$$f_{i,r}(t) = [\boldsymbol{f}_i]_{r,t} \in \{0,1\}$$

$$\sum_{r,t} f_{i,r} \leq 1$$

DSO allocation of network permits

❖ **Dynamic system optimal problem [DSO] (atomic user)**

$$\max_{\{\boldsymbol{f}_i\}} \sum_i \boldsymbol{v}_i \cdot \boldsymbol{f}_i$$ *… social surplus*

- subject to

$$\mathbf{1} \cdot \boldsymbol{f}_i \leq 1 \qquad \forall i$$ *… at most single trip per day*

$$\sum_i \boldsymbol{x}_i \leq \boldsymbol{\mu}$$ *… link capacity constraint*

$$\boldsymbol{x}_i = \Delta_i \boldsymbol{f}_i \qquad \forall i$$ *… relationship path and link allocation*

- allocation of permits (**Links**): $\mathrm{x}_{i,a}(t) = [\boldsymbol{x}_i]_{a,t} \in \{0, 1\}$
- path-link incidence matrix: Δ_i

Difficulties of solving the problem [DSO]

- ❖ **Incomplete information** on the objective function
  - **Users' private valuations** are unknown

✓ Vickrey-Clarke-Groves (VCG) combinatorial auction

- gives users an incentive to report their valuations truthfully
- must solve [DSO] **exactly** in many times to calculate allocation and **individual payment (i.e., marginal cost)**

- ❖ [DSO] is integer multi-commodity flow problem
  - complex relationship between **link and path variables on individual allocations**
  - **NP-hard**: no polynomial time algorithm exists

Basic ideas of day-to-day auction mechanism

- Decomposition of [DSO] based on Benders' method
  - **master-P** – adjusting # of bundles of permits (**path capacity**) on day-to-day basis
  - **sub-P** – assigning bundles (path capacity) to users

- Solve the **sub-P** by an **auction mechanism**
  - gives users an incentive to report their valuation truthfully
  - can obtain the efficient permit allocation **with incomplete information**

  - **Assumption**: users try to maximize their **current utilities,** i.e., (myopic) best response dynamics

Reformulation of the problem [DSO]

- Introducing ***non-individual*** integer variables
  - $\boldsymbol{F}$ - **aggregated** path variables (**path-capacities**)
  - $\boldsymbol{X}$ - **aggregated** link variables
- Equivalent optimization problem to the problem [DSO]

$$\max_{\{\boldsymbol{F}_w\},\{\boldsymbol{f}_i\}} \sum_i \boldsymbol{v}_i \cdot \boldsymbol{f}_i$$ *... social surplus*

- subject to

$$\mathbf{1} \cdot \boldsymbol{f}_i \leq 1 \qquad \forall i$$ *... at most single trip per day*

$$\sum_i \boldsymbol{f}_i \leq \boldsymbol{F}_w \qquad \forall w$$ *... Path capacity constraint for OD pair w*

$$\boldsymbol{X} \leq \boldsymbol{\mu}$$ *... link capacity constraint*

$$\boldsymbol{X} = \sum_w \Delta_w \boldsymbol{F}_w$$ *... relationship path and link allocation*

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- subject to

$$\boldsymbol{1} \cdot \boldsymbol{f}_i \leq 1 \qquad \forall i$$

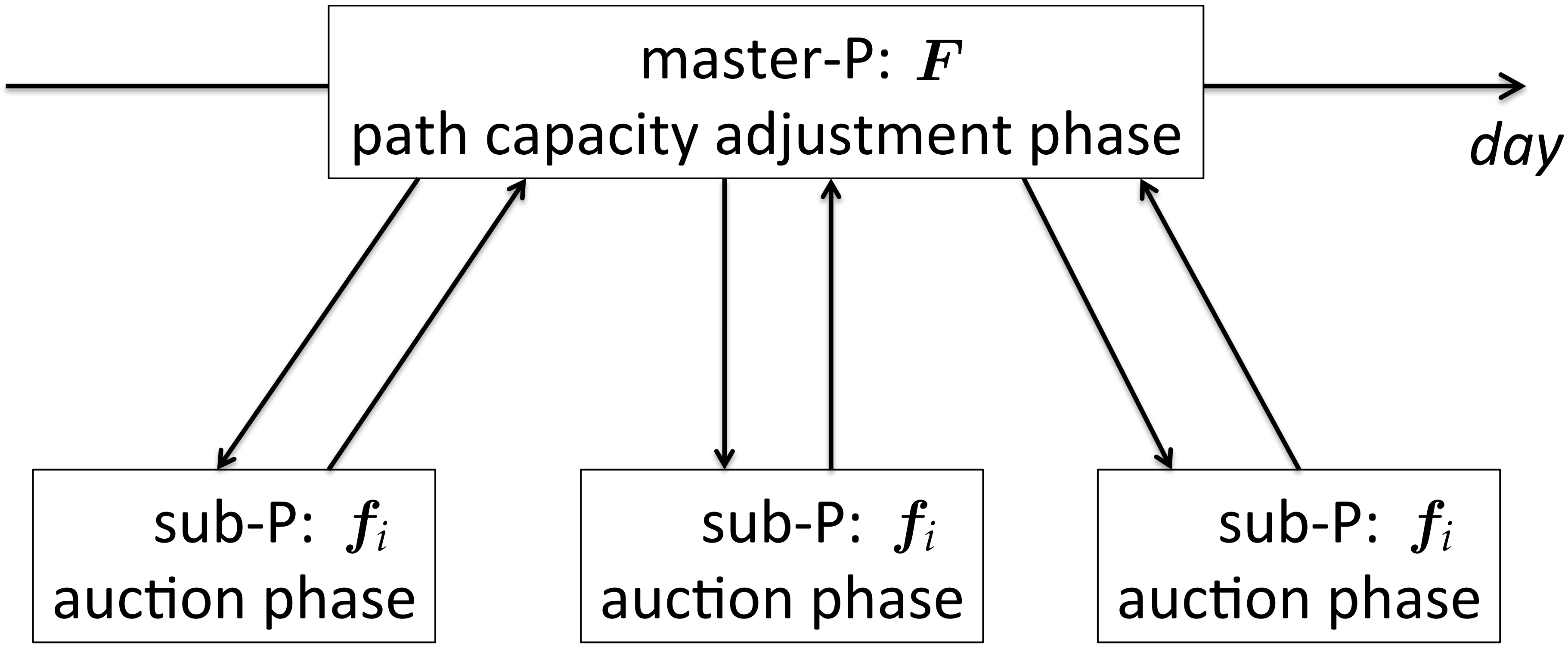
$$\sum_i \boldsymbol{f}_i \leq \boldsymbol{F}_w \qquad \forall w$$

all constrains for individual variables are represented by path variables.

$$\boldsymbol{X} \leq \boldsymbol{\mu}$$

$$\boldsymbol{X} = \sum_w \Delta_w \boldsymbol{F}_w$$

Framework of the day-to-day auction mechanism



Decomposition of the problem [DSO]

❖ **Sub-problem (assignment problem): auction phase**

- assigning bundles to users for **fixed path capacities**
- satisfying **totally unimodularity**, i.e., **LP = IP**

$$\max_{\{\boldsymbol{F}_w\}} \sum_w S_w(\boldsymbol{F}_w) \quad = \max_{\{\boldsymbol{f}_i\}} \sum_i \boldsymbol{v}_i \cdot \boldsymbol{f}_i$$

- subject to

$$\boldsymbol{X} \leq \boldsymbol{\mu}$$

$$\boldsymbol{X} = \sum_w \Delta_w \boldsymbol{F}_w$$

subject to

$$\mathbf{1} \cdot \boldsymbol{f}_i \leq 1 \qquad \forall i$$

$$\sum_i \boldsymbol{f}_i \leq \boldsymbol{F}_w$$

unknown variables:
individual path variables

Decomposition of the problem [DSO]

- **Dual sub-problem: auction phase**
  - providing information on prices/payoffs
  - π_i : user *i*'s payoff, $\boldsymbol{p}$: bundles prices

$$\max_{\{\boldsymbol{F}_w\}} \sum_w S_w(\boldsymbol{F}_w)$$

- subject to

$$\boldsymbol{X} \leq \boldsymbol{\mu}$$

$$\boldsymbol{X} = \sum_w \Delta_w \boldsymbol{F}_w$$

$$= \min_{\{\boldsymbol{p}_w\},\{\pi_i\}} \sum_i \pi_i + \boldsymbol{p}_w \cdot \boldsymbol{F}_w$$

subject to

$$\pi_i \mathbf{1} \geq \boldsymbol{v}_i - \boldsymbol{p}_w \qquad \forall i$$

unknown variables:
payoff / price variables

Decomposition of the problem [DSO]

❖ **Master problem: path capacity adjusting phase**

- adjusting path capacities based on **demand information** (payoffs and prices) of each day auction phase

$$\max_{\{\boldsymbol{F}_w\}} \sum_w S_w(\boldsymbol{F}_w) \qquad = \min_o [\sum_i \pi_i^o + \boldsymbol{p}_w^o \cdot \boldsymbol{F}_w]$$

- subject to

o: set of all extreme points of dual constraints

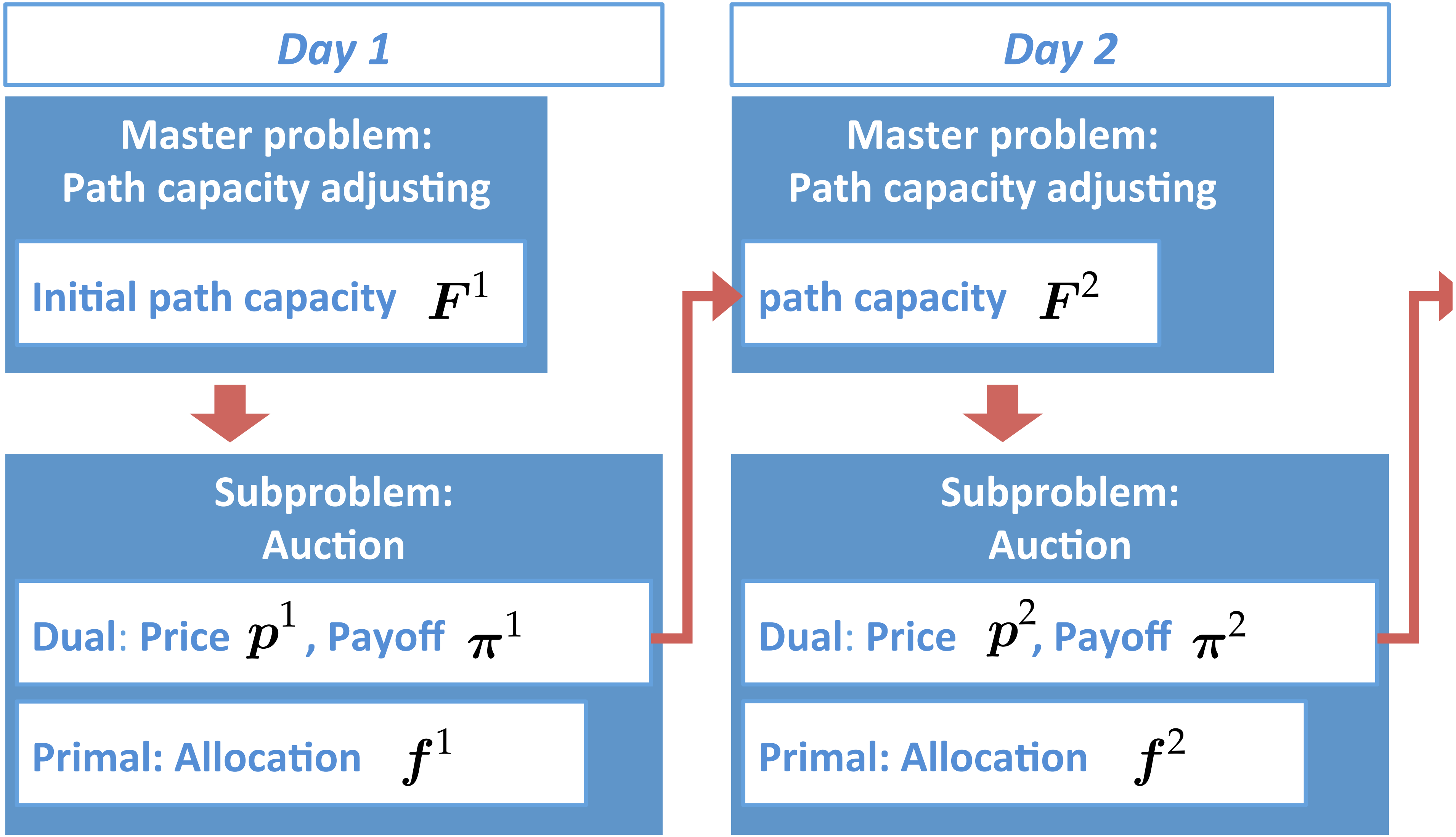
$$\boldsymbol{X} \leq \boldsymbol{\mu}$$

$$\boldsymbol{X} = \sum_w \Delta_w \boldsymbol{F}_w$$

unknown variables: non-individual variables

- using relaxation: generating extreme points iteratively
- using heuristics: linear relaxation, box-step constraints

Procedure of day-to-day auction mechanism



Obtaining truthful users' valuation

- **Ascending proxy auction** [*Demange et al. (86), Parkes & Ungar (02)*]
  - users report their valuations to proxy agents
  - agents bid most preferred items under the current prices
  - choosing the overdemanded set & raising prices in the set
  - **Individual rationality**: winners' payoffs are non-negative
  - **strategy-proof**: honesty is a best strategy for users
  - **efficiency**: Pareto efficient allocation can be achieved

- Corresponding to the mathematical programming
  - the process of the auction is corresponding to the **primal-dual (Hungarian) algorithm** for solving the sub-problem

Properties of the day-to-day auction mechanism

- **Proposition 1 (Convergence property)**

  The day-to-day auction mechanism converges ***in a finite number of iterations****.*

- **Proposition 2 (Efficiency property)**

  The permits allocation pattern by the mechanism converges to ***the most efficient allocation*** *when the number of users is large.*

proof:

$$\lim_{N \to \infty} \frac{S_L - S_I}{S_L} = 0$$

S_L : obj. fun. of linear relaxation of MP

S_I : obj. fun. of integer MP

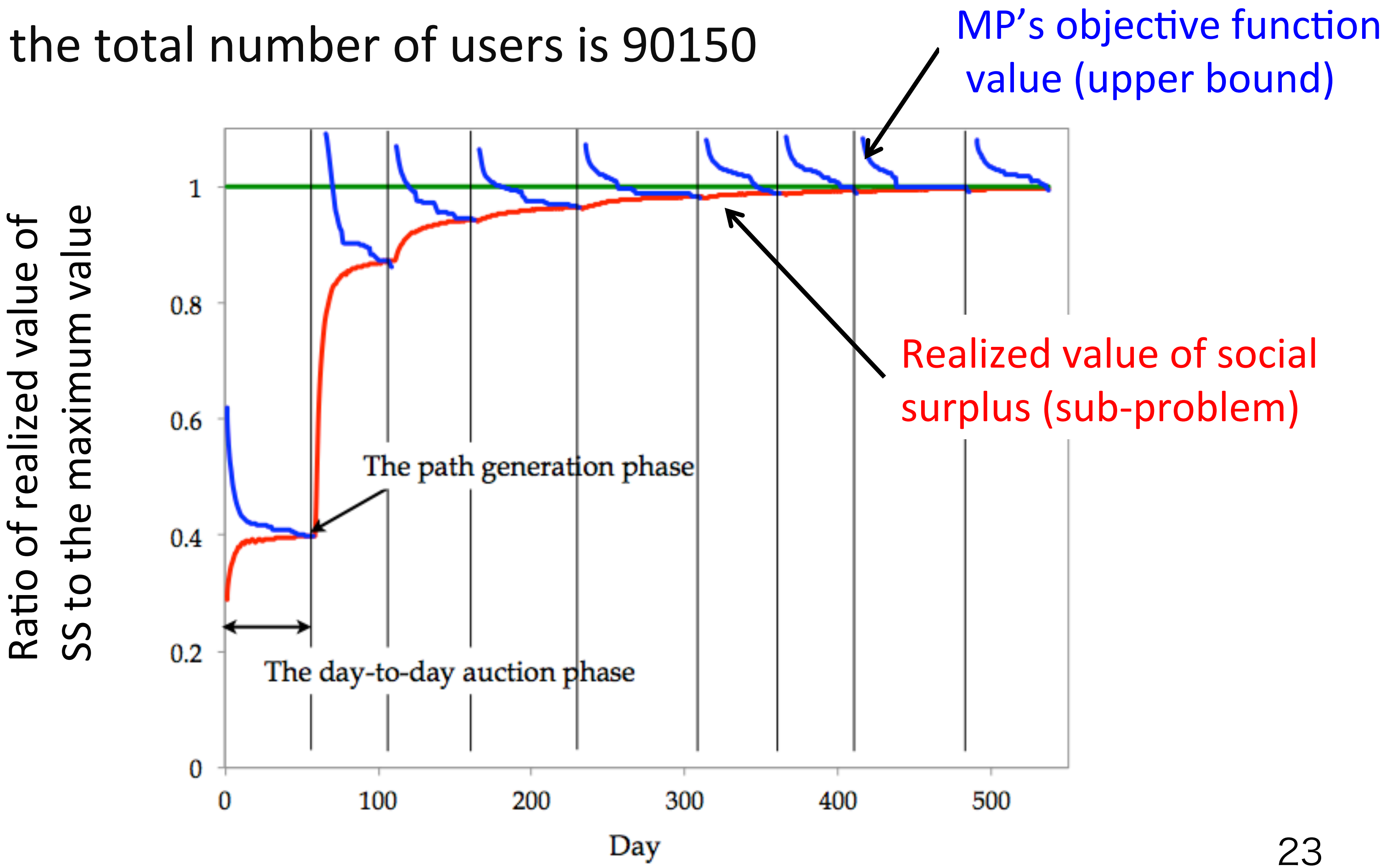
Extension: obviate path enumeration

- Introducing **column generation** procedure
  1. Considering a **subset of paths** of [DSO]. For the fixed path set, executing the day-to-day auction mechanism.
  2. After convergence, **each user generates** preferred path based on the previous day-to-day auction. Go to Step 1.

  - Path generation is efficient because **the numerous # of users generate paths simultaneously**

Numerical example: convergence process

- Sioux Falls network with 528 OD pairs
- the total number of users is 90150



Conclusion

- We proposed the day-to-day auction mechanism for implementing tradable network permits scheme for general networks
- We showed that the mechanism has desirable properties: strategy-proof; finite convergence; Pareto efficiency (DSO).
- We extended the mechanism to obviate path enumeration by introducing a column generation procedure.

Thank you for your attention

My first baby (son) was born yesterday !!

wadaken@plan.civil.tohoku.ac.jp

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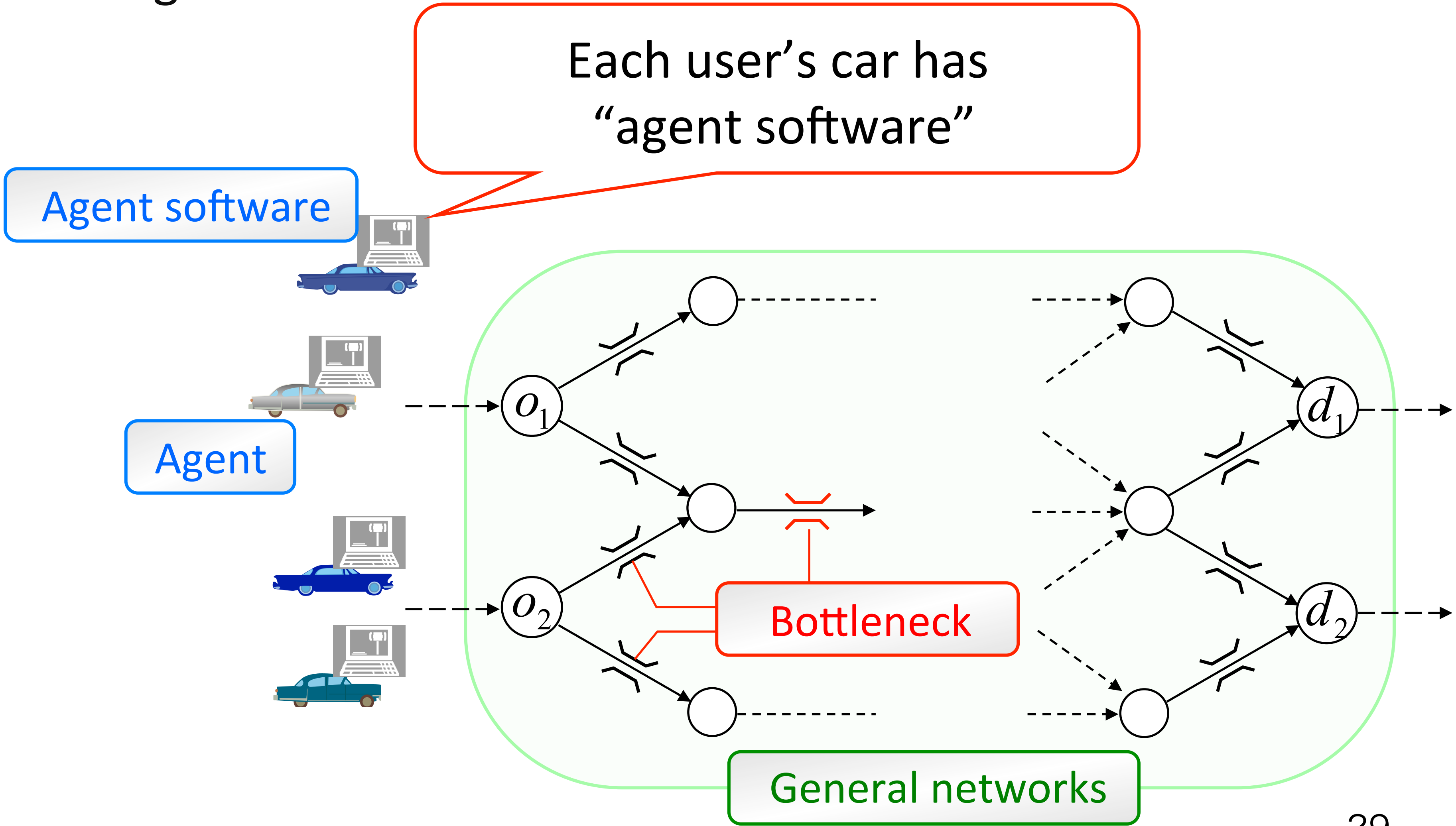
Future works

- Applying the proposed mechanism to the management of other transportation networks
  - railway networks, freight networks, logistics networks etc.
  - Problem: a network manager aims to maximizes not the social surplus but his/her profit

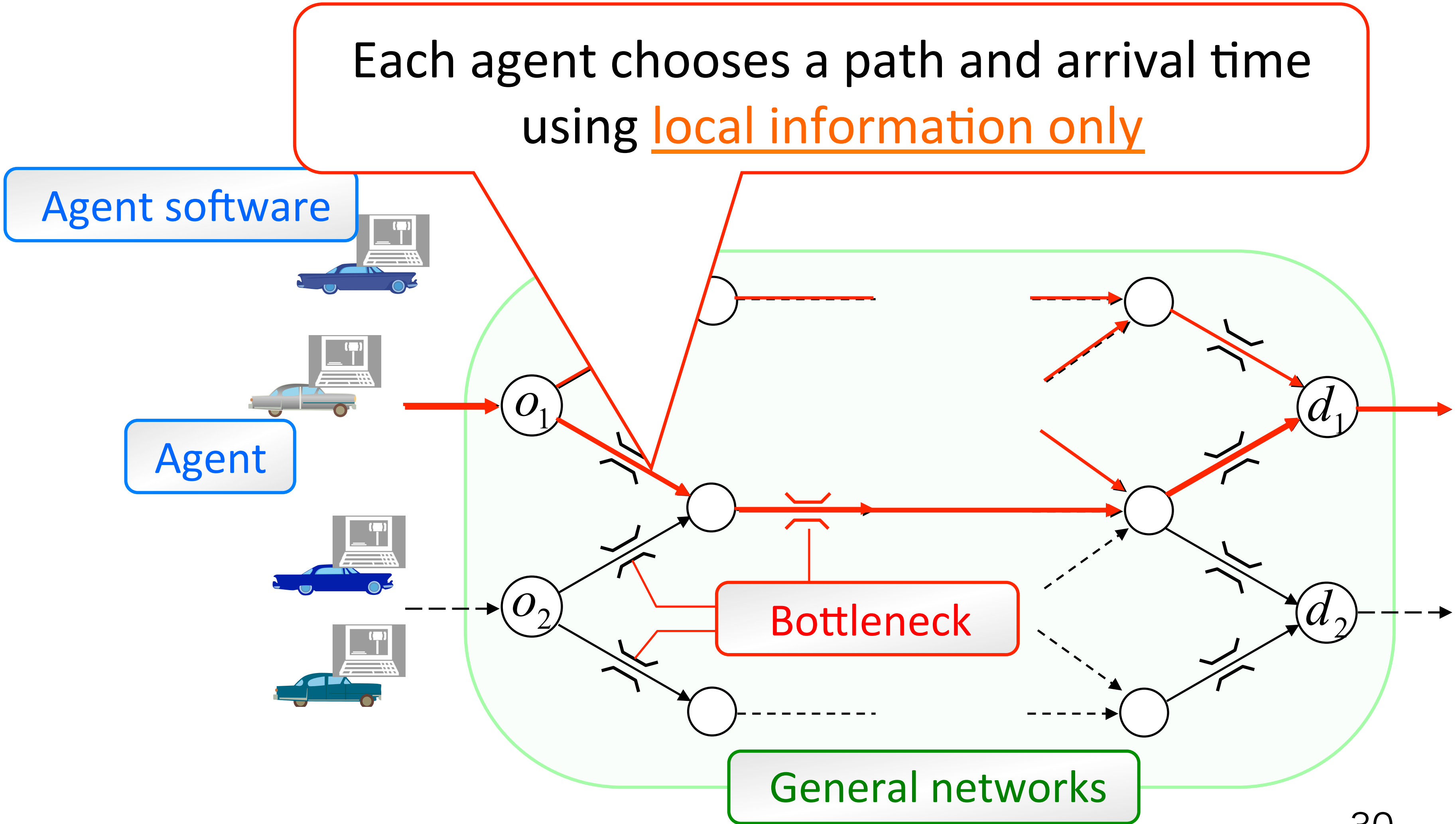
- Tradable network permits under the second-best situation
  - Queuing congestion occurs at a link that is not controlled.
  - needing connect the tradable network permits scheme to a DTA problem.

Unrealistic!?

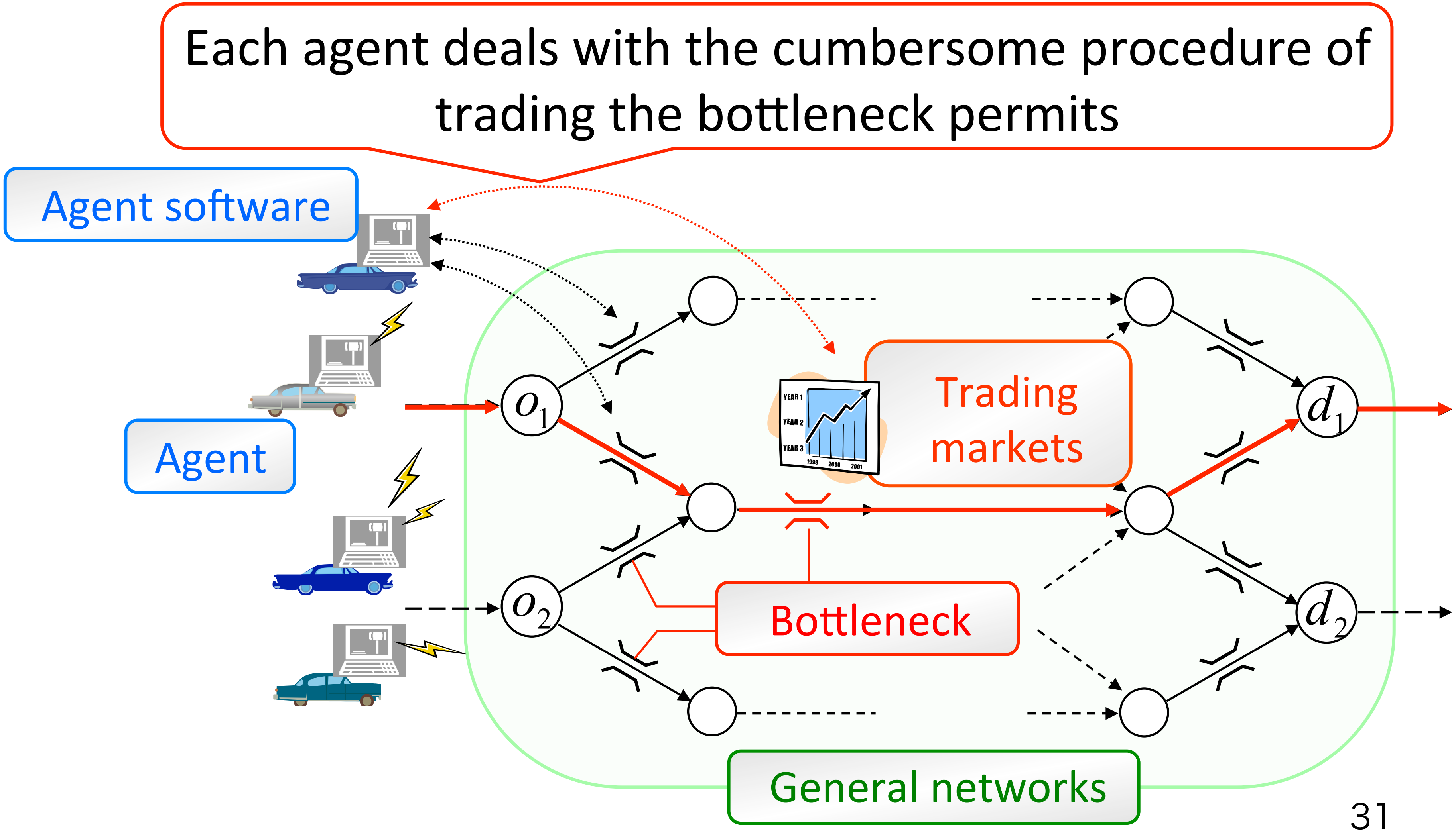
- imagine that …



Multi-agent system



Multi-agent system



Feasibilities for implementation

- Technical point of views
  - Procedures for network permits
    - » Dedicated short range communication (DSRC) system (e.g., Electric toll collection (ETC))
  - Trading markets
    - » Internet auction markets (inexpensive!!)

- Institutional point of views
  - Minimal legal restrictions is needed

Assigning schemes of network permits

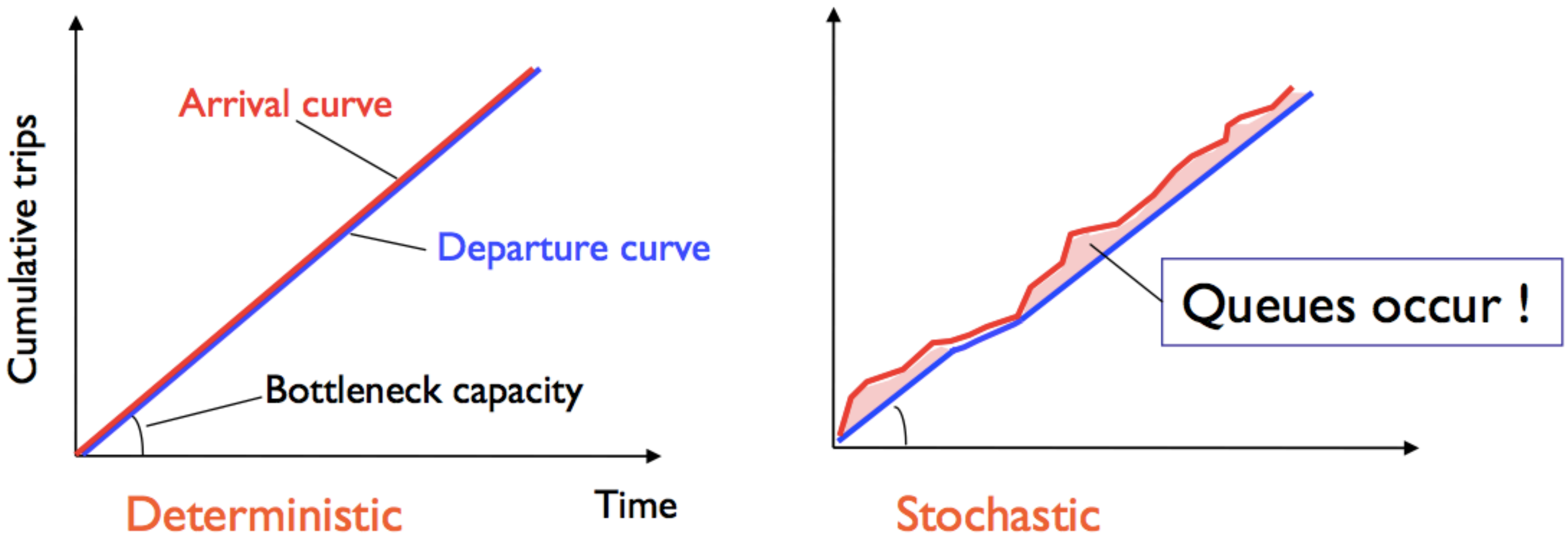
- Market selling scheme (In this study)
  - The road manager **sells** all the bottleneck permits to users in the trading market

- Free distribution scheme
  - The road manager distributes all the permits to users **for free** according to methods that consider the **equity among users**, e.g., rotation system of license plate numbers

- Remark
  - In terms of the efficiency of resource allocation, the two schemes are essentially identical.

Tradable network permits with stochastic arrivals

❖ Some users arrive at a bottleneck late (or fast)



- Stochastic queuing congestion can be decreased when a number of permits for the link is less than the capacity

- **about 80%** [*Kasahara & Akamatsu (06)*]