Tradable Network Permits Scheme and Its Implementation Mechanisms

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References

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Price vs Quantity-based regulations

- Price-based regulation
  - Congestion Pricing [Pigou, 1920; Knight, 1924, Vickrey, 1969]
  - If the **marginal cost** is imposed, an optimal traffic pattern is achieved in a distributed manner (Wardrop equilibrium)
  - need **accurate and detailed demand information**

    e.g., OD demands, VOTs, desired arrival times

- **Asymmetric information**

  between the road manager and users

  - very difficult to obtain such **private information**
  - distort toll levels and result in economic losses

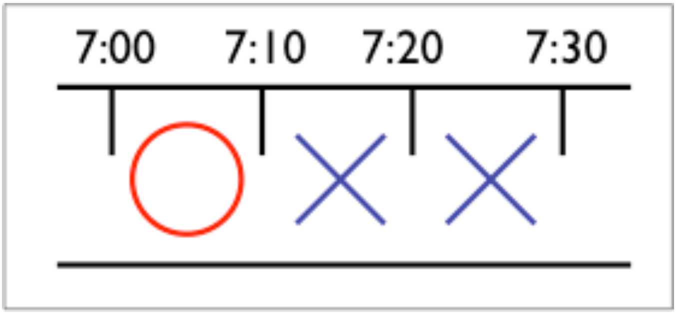
Price vs Quantity-based regulations (cont.)

- Quantity-based regulation
  - License numbers-based rationing, Advance highway booking [e.g., Akahane & Kuwahara, 1996]
  - **restrict the use of road directly** by assigning priority-service permits to road users using particular rules
  - can achieve a quantitative policy target **without requiring detailed demand information**

- Infringement on freedom of choice
  - an unrefined rule (e.g., first-come-first-served) may cause economic losses
  - *could be resolved by an additional* ***choice mechanism***

What is tradable network permits scheme?

- **Tradable Network Permits (TNP)** [Akamatsu et al., 2006, 2007]
  - a right that allows a permit holder to pass through **a specific bottleneck during a pre-specified time period**



- **Trading market** (choice mechanism)
  - for network permits of each link and each time period
  - **Permits allocation and price** are simultaneously determined through the markets

What is tradable network permits scheme?

- **Two assigning schemes** of network permits
  - **Market selling scheme**
    - » The road manager ***sells*** all the permits to users through the trading markets
    - » Income transfer: from users to the road manager
  - **Free distribution scheme**
    - » The road manager ***distributes*** all the permits to users ***for free*** by a method that considers the **equity among users**

      e.g., License plate-based lotations
    - » Income transfer: among users

Why is the TNP scheme desirable?

- **No bottleneck congestion**
  - # of permits of each link for each period

    $\leq$ bottleneck capacity

- **No detailed information on demand**
  - The manager only needs to know bottleneck capacities

- **Efficiency of equilibrium** [Akamatsu et al., 2006]
  - Departure-time choice problem with single bottleneck
  - Equilibrium assignment = System optimal assignment

Contents

- Properties of the TNP scheme for **general networks**
- Theoretical relationships with **congestion pricing**
- **Implementation mechanisms** of the TNP scheme

Remark on tradable "credit" scheme

- Tradable travel credit scheme [Yang and Wang, 2011]
  - The road manager issues some amount of credits (<u>depend on a policy target</u>) and distributes them to users for free
  - Users can trade credits through a credit market
  - Users have to pay some credits for the use of road

  - ***<u>The manager</u>*** imposes an **<u>(optimal) *credit charge*</u>** on each link, like congestion pricing
  - is ***<u>not</u>*** a quantity-based regulation for ***<u>directly</u>*** reducing congestion but rather a **redistribution scheme of income**

Problem setup

- Network
  - General network with many-to-many OD demands

  (for notational simplicity, we here consider O2O OD demands)

- Road manager: **Social** generalized trip cost minimization
  - issue permits: # of permits of link (*i, j*) = capacity μ_{ij}

- Road user: generalized trip cost minimization
  - Trip cost = travel time + schedule delay + permits purchase
  - choose ***path*** and ***departure-time*** simultaneously
  - ***must purchase a bundle of permits*** corresponding to a path

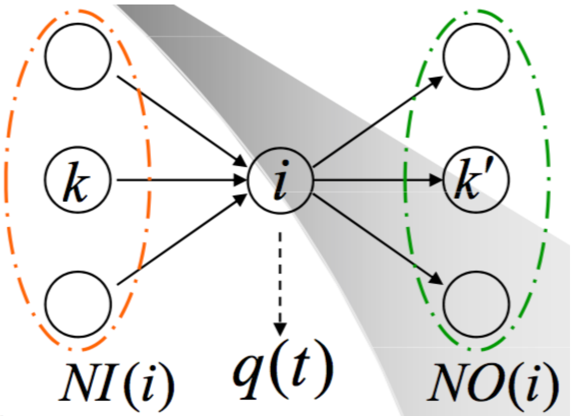
Equilibrium conditions under TNP (1)

- Flow conservations
  - OD flows

OD demand w. r. t. (*h, s*) **[given]**

$$\int_{\mathcal{T}} q^h(t,s)\mathrm{d}t = Q^h(s) \quad \forall h, s$$

OD flow rate at time *t* of *h*th VOT users who have desired arrival time *s*



  - Flow conservation at each node *i*

$$\sum_{k'} y^h_{ik'}(t) - \sum_k y^h_{ki}(t - t_{ki}) = -\sum_s q^h(t,s)\delta_{id} \quad \forall h, t, i$$

Outflow rate from node *i* at time *t*

Inflow rate to node *i* at time *t* = outflow rate from node *k* at time $t - t_{ki}$

t_{ki} : FF travel time of link (*k, i*) **[constant]**

Equilibrium conditions under TNP (2)

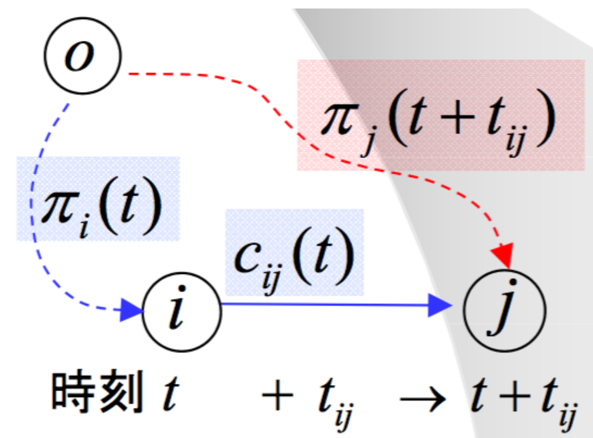
- Users' choice conditions
  - Path choice (link-based formulation)

Minimum trip cost from origin to node *i* at time *t*

$$\begin{cases} \pi_j^h(t + t_{ij}) = c_{ij}^h(t) + \pi_i^h(t) & \text{if} \quad y_{ij}^h(t) > 0 \\ \pi_j^h(t + t_{ij}) \leq c_{ij}^h(t) + \pi_i^h(t) & \text{if} \quad y_{ij}^h(t) = 0 \end{cases} \qquad \forall h, ij, t$$

$$c_{ij}^h(t) \equiv p_{ij}(t) + \alpha^h t_{ij}$$

Permit price VOT of *h*th user group



  - Departure/Arrival-time choice

$$\begin{cases} \rho^h(s) = \pi_d^h(t) + w^h(t,s) & \text{if} \quad q^h(t,s) > 0 \\ \rho^h(s) \leq \pi_d^h(t) + w^h(t,s) & \text{if} \quad q^h(t,s) = 0 \end{cases} \qquad \forall h, s, t$$

Equilibrium conditions under TNP (2)

- Users' choice conditions
  - Path choice (link-based formulation)

Minimum trip cost from origin to node *i* at time *t*

$$\begin{cases} \pi_j^h(t+t_{ij}) = c_{ij}^h(t) + \underline{\pi_i^h(t)} & \text{if} \quad y_{ij}^h(t) > 0 \\ \pi_j^h(t+t_{ij}) \le c_{ij}^h(t) + \pi_i^h(t) & \text{if} \quad y_{ij}^h(t) = 0 \end{cases} \quad \forall h, ij, t$$

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Minimum generalized (equilibrium) trip cost

Schedule delay cost

Equilibrium conditions under TNP (3)

- Market equilibrium (clearance) condition
  - assumption: perfectly competitive market

$$\begin{cases} \sum_h y_{ij}^h(t) = \mu_{ij} & \text{if} \quad p_{ij}(t) > 0 \\ \sum_h y_{ij}^h(t) \leq \mu_{ij} & \text{if} \quad p_{ij}(t) = 0 \end{cases} \qquad \forall ij, t$$

Demand: Total inflow

Supply: Bottleneck capacity

  - If the link is not fully utilized, users can use it **for free**.

Efficiency of equilibrium

❖ ***Social*** trip cost minimization problem (LP problem)

$$\min_{(\mathbf{q},\mathbf{y})\geq\mathbf{0}} . \sum_{h,s} \int_{\mathcal{T}} w^h(t,s) q^h(t,s) \mathrm{d}t + \sum_{h,ij} \int_{\mathcal{T}} \alpha^h t_{ij} y_{ij}^h(t) \mathrm{d}t$$

Total schedule delay cost

Total travel time cost (monetary equivalence)

s.t. $\int_{\mathcal{T}} q^h(t,s)\mathrm{d}t = Q^h(s) \quad \forall h, s$

$$\sum_{k'} y_{ik'}^h(t) - \sum_k y_{ki}^h(t - t_{ki}) = -\sum_s q^h(t,s)\delta_{id} \quad \forall h, t, i$$

$$\sum_h y_{ij}^h(t) \leq \mu_{ij} \quad \forall ij, t$$

Proposition. *Social cost is minimized at equilibrium under TNP scheme.*

Proof. Equilibrium conditions = KKT conditions of LP problem

Efficiency of equilibrium (cont.)

- Dual problem (cost variables can be determined)

$$\max_{\mathbf{p}\geq \mathbf{0},(\rho,\pi)} . \underbrace{\sum_{h,s} \rho^h(s) Q^h(s)}_{\text{Total equilibrium cost}} - \underbrace{\sum_{ij} \int_{\mathcal{T}} p_{ij}(t)\mu_{ij}}_{\text{Total revenue of permits}}$$

s.t.

$$\pi_j^h(t + t_{ij}) \leq c_{ij}^h(t) + \pi_i^h(t) \quad \forall h, ij, t$$

$$\rho^h(s) \leq \pi_d^h(t) + w^h(t,s) \quad \forall h, s, t$$

- The revenue is ***not*** a social cost but just ***income transfer***
- Market selling and free distribution schemes are identical in terms of the efficiency of equilibrium

Congestion pricing vs TNP

- Perfect information case: identical
  - The road manager can determine a time-dependent optimal toll pattern by solving the equivalent (primal or dual) LP

[e.g., Yang and Meng, 1998]

- Imperfect information case
  - In the congestion pricing, the road manager needs to know

$$\min_{(\mathbf{q},\mathbf{y})\geq\mathbf{0}} \cdot \sum_{h,s} \int_{\mathcal{T}} w^h(t,s) q^h(t,s)\mathrm{d}t + \sum_{h,ij} \int_{\mathcal{T}} \alpha^h t_{ij} y_{ij}^h(t)\mathrm{d}t$$

$$\text{s.t.} \quad \int_{\mathcal{T}} q^h(t,s)\mathrm{d}t = Q^h(s) \quad \forall h,s$$

  - <u>*In the TNP, the manager needs to know* ***capacity only***</u>

Congestion pricing vs TNP (cont.)

- Effect of mispricing
  - Congestion pricing does ***not*** lead to **social cost minimization** but also causes a economic loss due to ***queuing congestion***
  - TNP scheme does ***not*** lead to **social cost minimization**
  - Note: Degree of mispricing: the road manager > the markets

- Effect of inaccurate users' behaviors
  - Users may arrive at a bottleneck earlier or later
  - Queueing congestion may occur under the TNP scheme but this is also the case for the congestion pricing

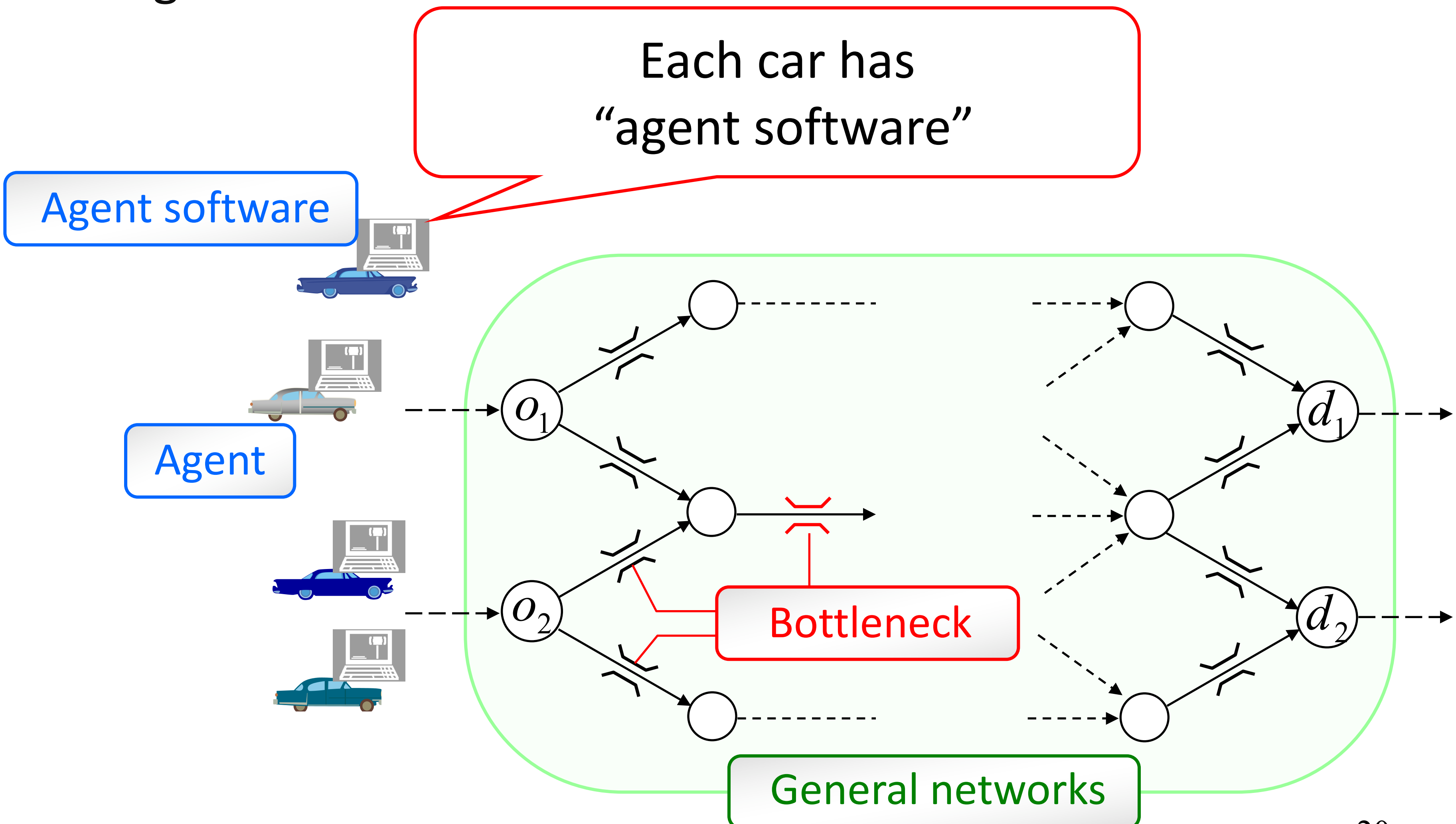
Conclusion. *TNP scheme has definite advantages over CP.*

How to implement the TNP scheme?

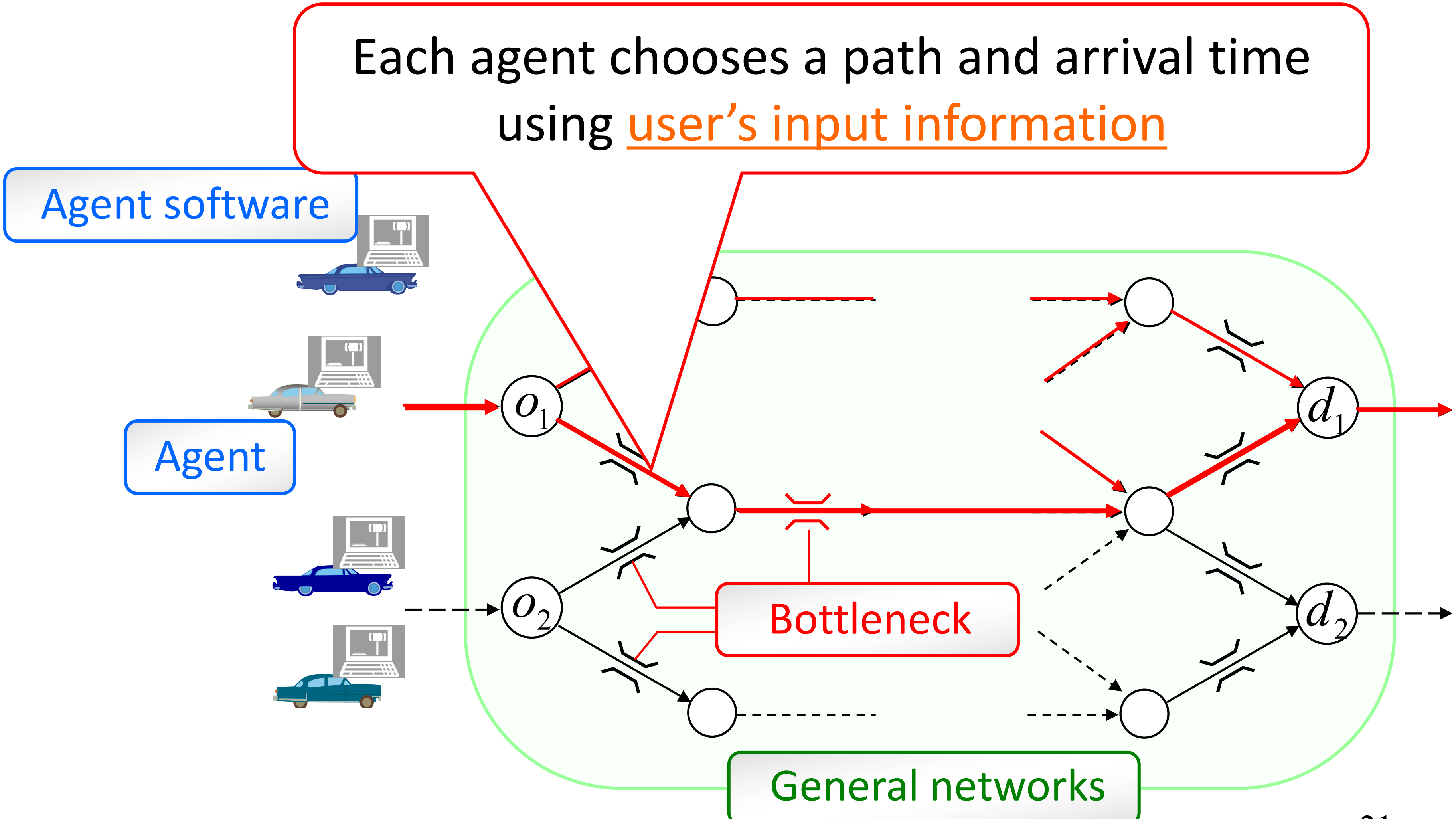
- Technological point of view
  - Permit authentication: Application of DSTC
  - Trading markets: Internet auction
- Situation
  - Dedicated road networks would be the first step
  - General road networks may be very challenging
- Users' point of view
  - **Complicated trading procedures (lead to high transaction cost) must be avoided.**

Multi-agent system for the TNP scheme

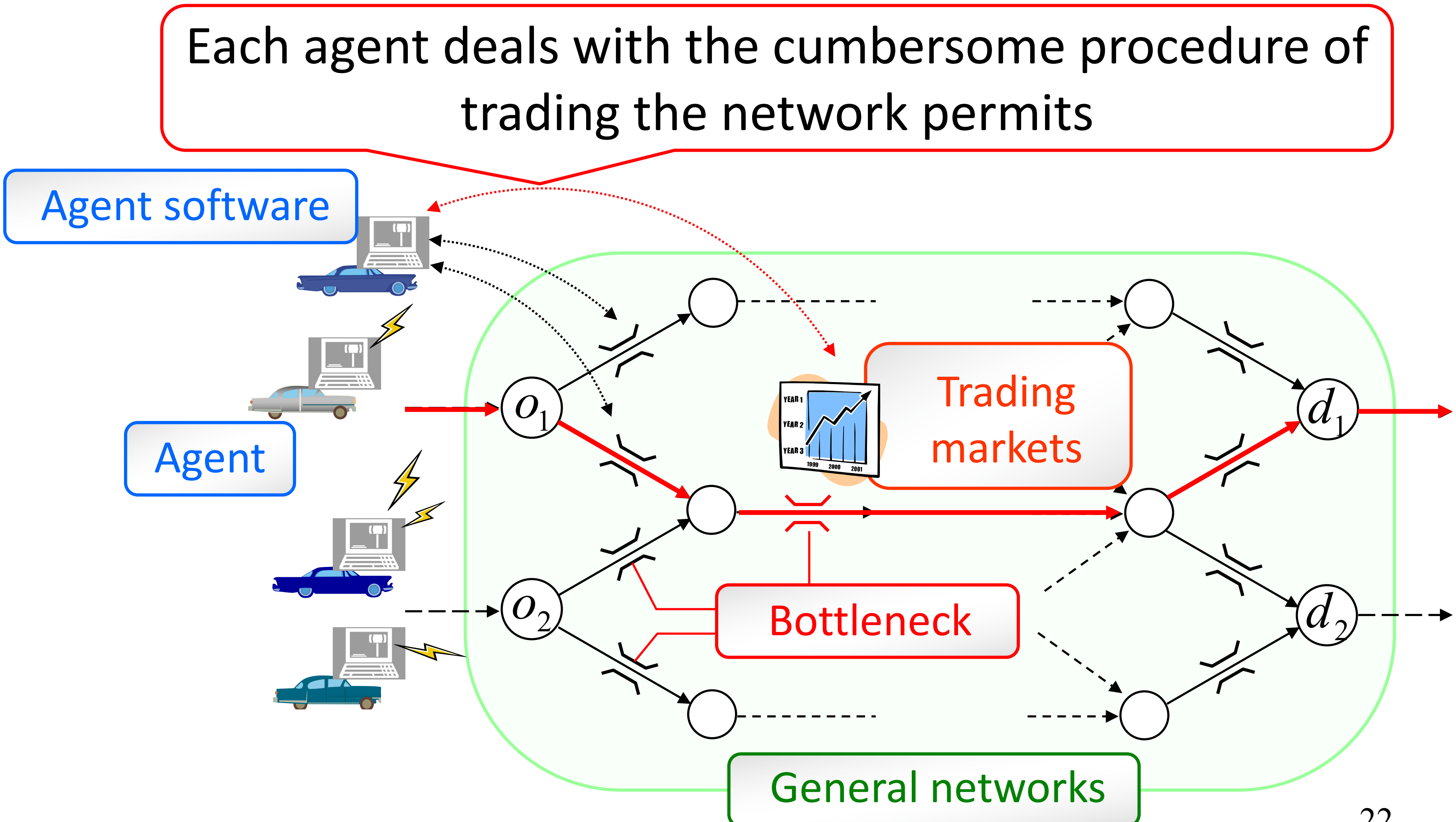
- imagine that …



Multi-agent system for the TNP scheme



Multi-agent system for the TNP scheme

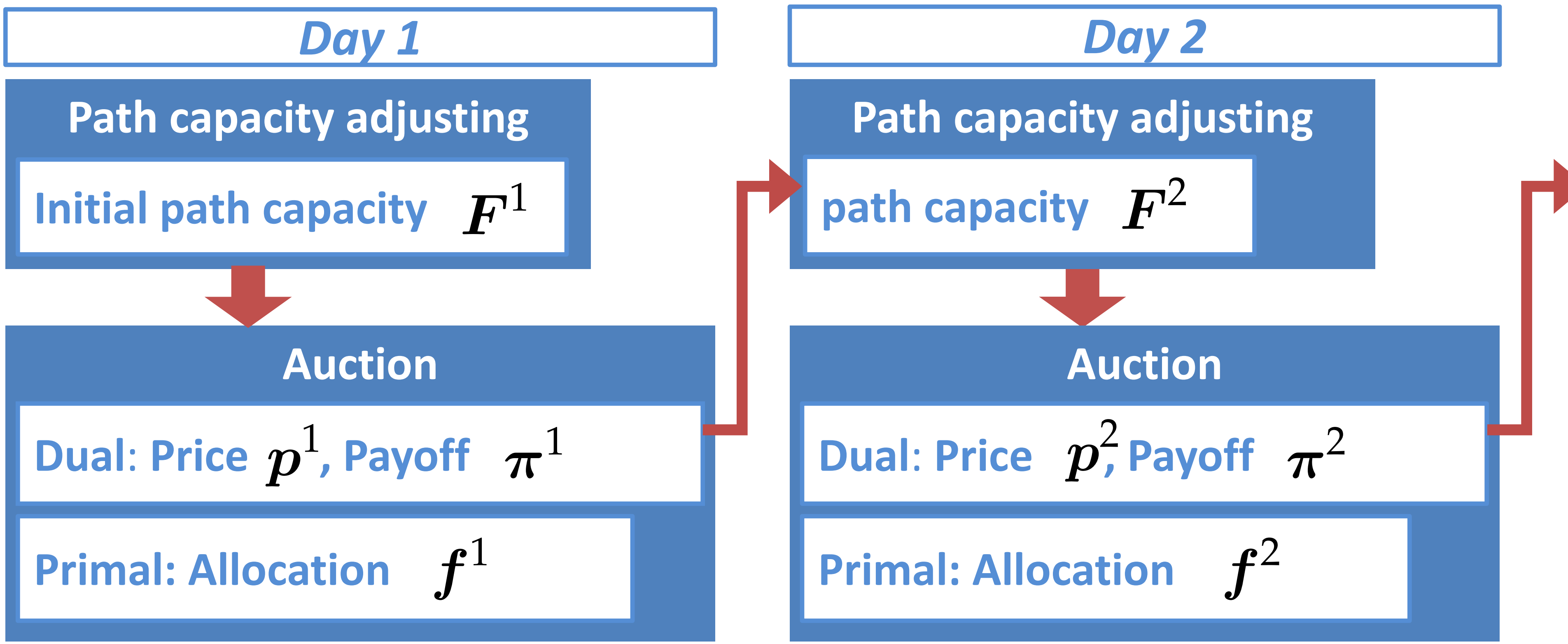


Design of a MA system

- Essential components of determining (theoretical) property of a multi-agent system:
  - Design of agents' path and departure-time behaviors
    - makes the system to reach a user equilibrium
    - Wada et al. (2008): **Evolutionary game theory approach**
  - Design of trading rules of the markets
    - makes the system to reach a market equilibrium
    - Wada and Akamatsu (2010, 2013): **Auction theory approach**

Auction with day-to-day capacity control

- Path-based auction + "Path" capacity (# of bundles) adjustment
  - » Users do not need to bid a set of links of path
  - » Day-to-day dynamics ***converges to a social optimal state*** when the number of users is large (analogous to ***welfare theorem***)



Summary

- ITS has a large potential for dramatically improving efficiency of transportation systems ***if the systems are implemented together with appropriate schemes***

- Tradable network permits scheme
  - lays out the combination of a ***"reservation-based allocation mechanism"*** and ***"market-based pricing mechanism"*** as a single framework
  - *simultaneously resolves the* ***efficient allocation*** *and* ***asymmetric information problems*** *in general networks with bottleneck congestion*

Further issues

- Design of online auction mechanisms
  - enhancing the flexibility of users' decision making
- Examine quantitative impacts of introducing of the TNP scheme by a traffic simulator
  - How much cost can be reduced by the TNP scheme?
- Study the TNP scheme in a second-based situation
  - # of managed bottlenecks are limited

Thank you!

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