 Tradable Network Permits Scheme and Its Implementation Mechanisms

Kentaro Wada
University of Tokyo, UC Irvine (visiting scholar)
(joint work with Takashi Akamatsu, Tohoku University)

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References


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 & Kuwashara, 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 ≤ 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 (depend on a policy target) 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

- The manager imposes an (optimal) credit charge on each link, like congestion pricing
- is not a quantity-based regulation for directly 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 \(\mu_{ij}\)

- **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
    
    \[
    \int_T q^h(t, s) \, dt = Q^h(s) \quad \forall h, s
    \]
    
    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)
    \[
    \begin{aligned}
    \pi^h_j(t + t_{ij}) &= c_{ij}^h(t) + \pi^h_i(t) & \text{if } y^h_{ij}(t) > 0 \\
    \pi^h_j(t + t_{ij}) &\leq c_{ij}^h(t) + \pi^h_i(t) & \text{if } y^h_{ij}(t) = 0
    \end{aligned}
    \]
    
    
    Permit price \quad VOT of hth user group

  - Departure/Arrival-time choice
    \[
    \begin{aligned}
    \rho^h(s) &= \pi^h_d(t) + w^h(t, s) & \text{if } q^h(t, s) > 0 \\
    \rho^h(s) &\leq \pi^h_d(t) + w^h(t, s) & \text{if } q^h(t, s) = 0
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    \]
    \[\forall h, i, j, t\]

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    \end{align*}
    \]
    \[\forall h, s, t\]

- Minimum trip cost from origin to node i at time t
- Minimum generalized (equilibrium) trip cost
- Schedule delay cost
Market equilibrium (clearance) condition

- assumption: perfectly competitive market

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

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)

\[
\min_{(q,y)\geq 0} \sum_{h,s} \int_{\mathcal{T}} w^h(t,s)q^h(t,s)dt + \sum_{h,ij} \int_{\mathcal{T}} \alpha^h t_{ij} y_{ij}^h(t)dt
\]

s.t.
\[
\int_{\mathcal{T}} q^h(t,s)dt = Q^h(s) \quad \forall h, s
\]

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

\[
\sum_h y_{ij}^h(t) \leq \mu_{ij} \quad \forall i, j, t
\]

**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)

\[
\max_{p \geq 0, (\rho, \pi)} \sum_{h, s} \rho^h(s) Q^h(s) - \sum_{ij} \int_{\mathcal{T}} p_{ij}(t) \mu_{ij}
\]

\[
\text{Total equilibrium cost} \quad \text{Total revenue of permits}
\]

s.t.

\[
\pi^h_j(t + t_{ij}) \leq c^h_{ij}(t) + \pi^h_i(t) \quad \forall h, ij, t
\]

\[
\rho^h(s) \leq \pi^h_d(t) + w^h(t, s) \quad \forall h, s, t
\]

- 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
  - In the TNP, the manager needs to know capacity only

\[
\begin{align*}
\min_{(q,y) \geq 0} \sum_{h,s} \int_{\mathcal{T}} \omega^h(t,s)q^h(t,s)dt &+ \sum_{h,ij} \int_{\mathcal{T}} \alpha^h t_{ij} y_{ij}^h(t)dt \\
\text{s.t. } \int_{\mathcal{T}} q^h(t,s)dt &= Q^h(s) \quad \forall h, s
\end{align*}
\]
**Congestion pricing vs TNP (cont.)**

- **Effect of mispricing**
  - Congestion pricing does **not** lead to **social cost minimization** but also causes an 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 ...

Each car has “agent software”

![Diagram](image-url)
Multi-agent system for the TNP scheme

Each agent chooses a path and arrival time using user’s input information
Multi-agent system for the TNP scheme

Each agent deals with the cumbersome procedure of trading the network permits
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*)

**Day 1**

- Path capacity adjusting
- Initial path capacity $F^1$

**Auction**

- Dual: Price $p^1$, Payoff $\pi^1$
- Primal: Allocation $f^1$

**Day 2**

- Path capacity adjusting
- path capacity $F^2$

**Auction**

- Dual: Price $p^2$, Payoff $\pi^2$
- Primal: Allocation $f^2$
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!

wadaken@iis.u-tokyo.ac.jp