Urban Congestion Pricing: Practice and Theory

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Motivation (1/2)

Motivation (2/2)

- **Holistic Solution to Tackle Urban Traffic Congestion**
  - **Better integrated urban planning**

    e.g. highway building, parking area, optimize road network
  - **Promotion of public transport**

    e.g. Bus, railway, subway, bus rapid transit
  - **Promotion of intelligent transport system**

    e.g. traffic signal control system, parking guidance and traveler information systems
  - **Government policies on private vehicles**

    e.g. Vehicle population control, plate-number-based rationing schemes, road pricing, high taxes on private vehicles.

PART I

Congestion Pricing Practice

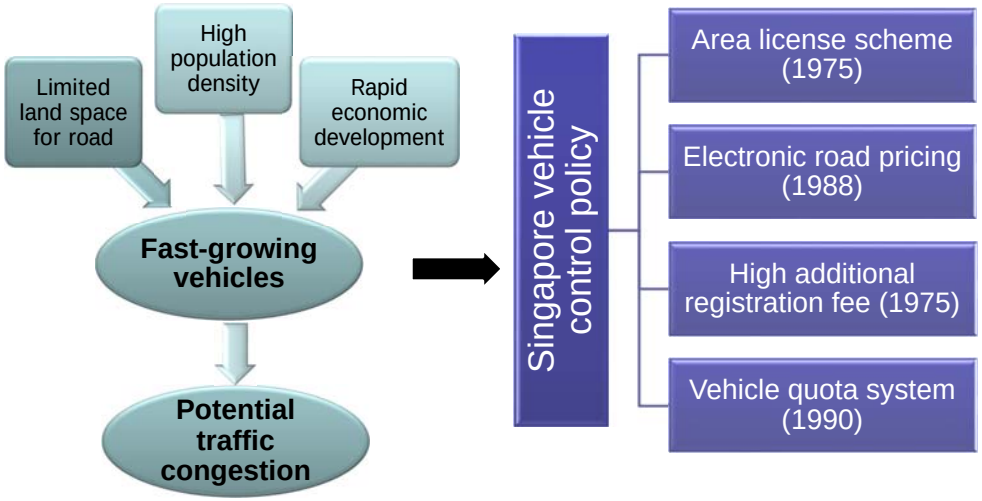
Singapore Traffic Statistics

- **Area: 716.1 sq km** **Population: 5.4 million**
- **Total Road Length: 3,452 km**
  - Expressways: 164 km
  - Arterial roads: 662 km
- **Vehicle Population: 974,170**
  - Cars: 540,063
  - Taxis: 27,695
  - Buses: 17,509
- **Road Traffic Condition**
  - Average daily traffic volume: 28,9000
  - Average speed during peak hours(km/h):

    Expressway - 61.6; **Arterial road - 28.9**.

Source: Singapore Land Transport Authority Website (2013 Singapore transport report): http://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/FactsandFigures/Statistics%20in%20Brief%202014.pdf

Singapore Vehicle Population/Usage Control Policies



SG Vehicle Population Control (1/3)

- **Singapore Vehicle Population Control**

  - **Import Duties and Additional Registration Fees (ARF)–> Annual growth rate 8% (before 1990)**

    The ARF is a high tax imposed on registration of a vehicle from 1975.

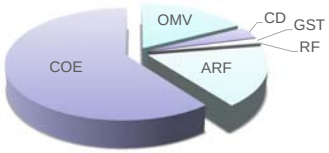
  - **Certificate of Entitlement (COE) in Vehicle Quota System**

    The COE premium is determined by the market force through bidding rounds; The COE biddings starts on the first and third Monday of the month.

SG Vehicle Population Control (2/3)

Example

COE RESULTS 2014
Jul 2014, 2nd Tender



- Goods and Service Tax (GST)：7%×(OMV+CD)
- ARF(Additional Registration Fee): 100% × OMV
- RF(Registration Fee):$140

Mazda 3 Sedan 1.5 Standard (A)

- OMV(Open Mark value: $18,100
- COE(Certificate of Entitle) : $62,890
- CD(Custom Duty)：20% ×OMV

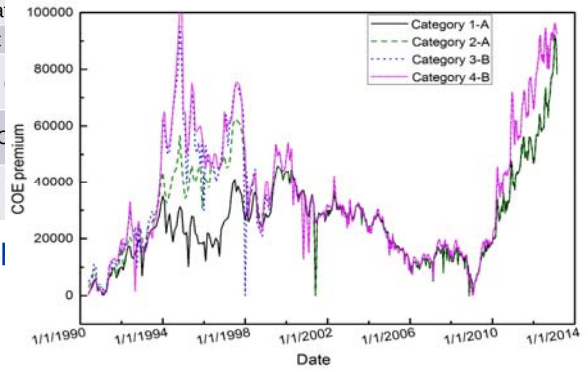
Total =OMV+COE+CD+GST+ARF+RF =$10,4370 (8.8 Million JPY)

SG Vehicle Population Control (3/3)

- Changes in COE premiums for vehicles (1990-2013)

Category From 1999	Previous Category` May 1990 - Apr 1999	Highest		Lowest	
		SGD	Period	SGD	Period
Cat A	Cat 1 (1000 cc & below) / Cat 2 (1001 - 1600 cc) & taxi	92100	Jan 2013	2	Nov 2008
Cat B	Ca / Cat				
Cat C	Cat 5				
Cat D	C				
Cat E					

- Changes in COE p 2013)



Singapore Congestion Pricing

- **Singapore Vehicle Usage Control**
  - Parking fee
  - Fuel tax
  - Less car-oriented infrastructure
  - Congestion pricing (first implementation in the world)

Area Licensing Scheme (ALS): 1975-1998

↓

Electronic Road Pricing (ERP): 1998-now

↓

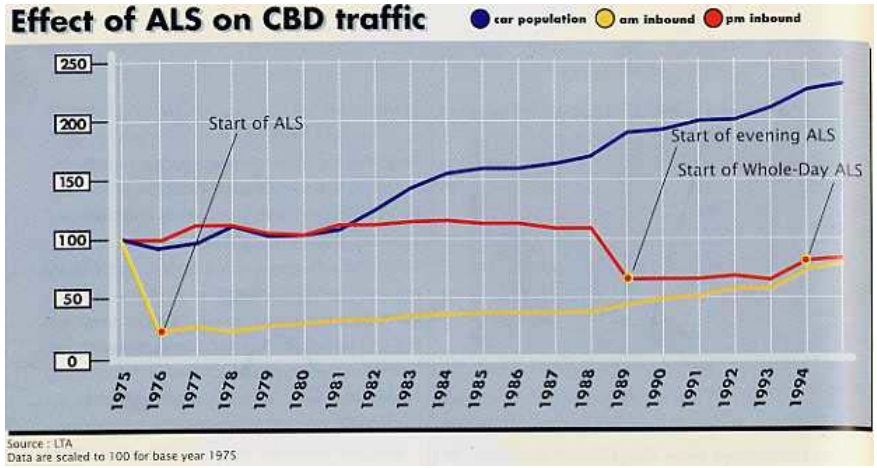
Distance-based Congestion Pricing (future)

Congestion Pricing Schemes - Area Licensing Scheme (1975 -1998) (1/5)

Restricted Zone (RZ)

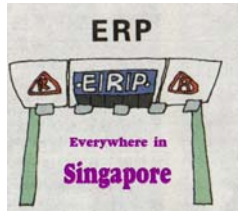
Different types of ALS license

Area Licensing Scheme (1975 -1998) (2/5)



Electronic Road Pricing (ERP) (1998-) (3/5)

- **Shortcomings of ALS**
  - High manpower required
  - Inconvenient for purchase of licenses
  - Inequity issue :daily-based charge
- **Electronic Road Pricing (ERP)**
  - Automated (non-stop) with electronic system
  - Electronic Transactions (about 280,000 per day)
  - More equitable: entry-based charge

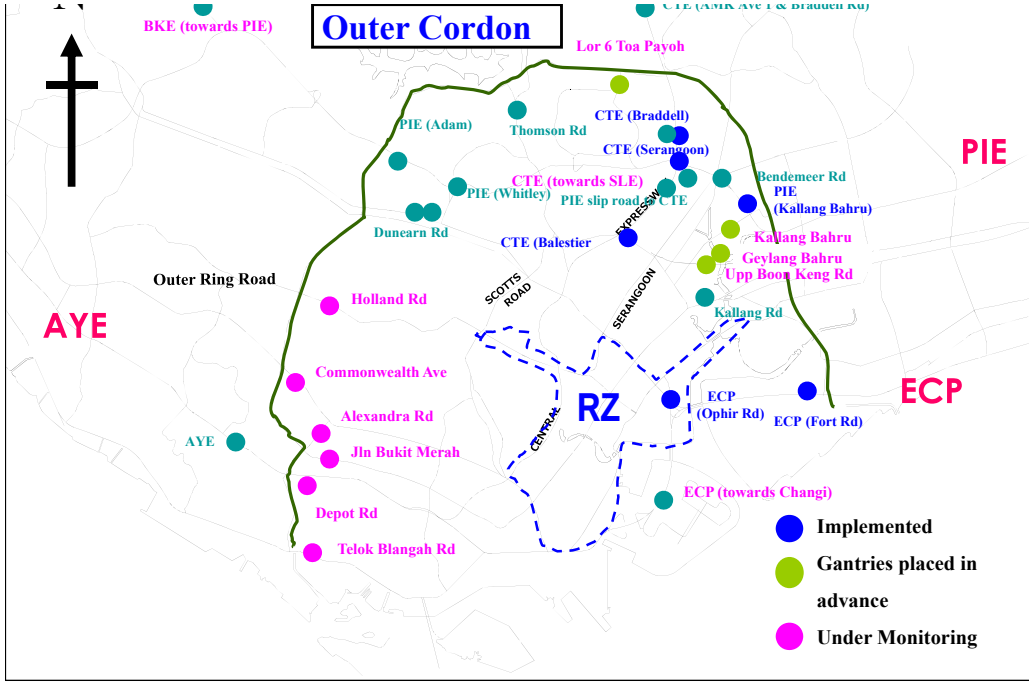


Congestion ERP Facilities (4/5)

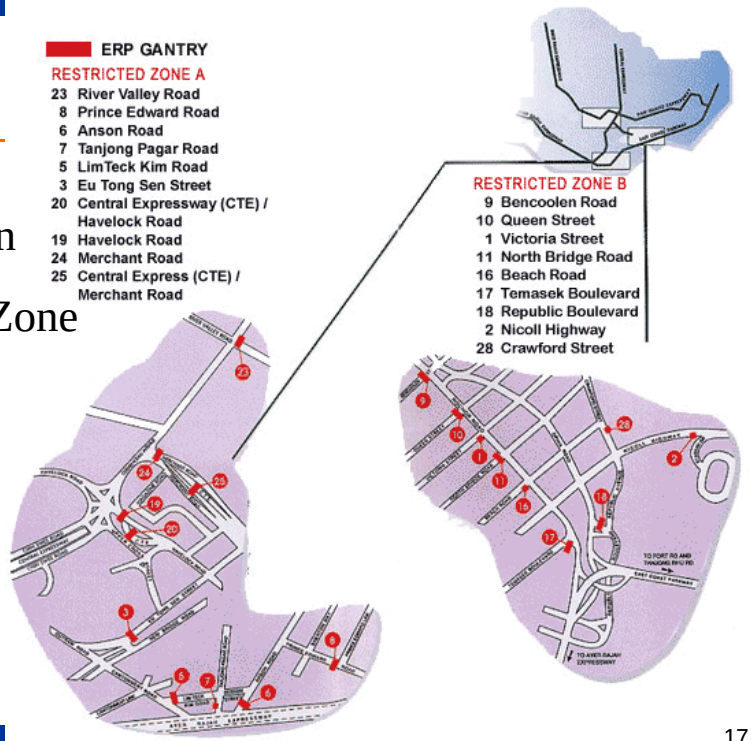
1. Gantry

2. In-vehicle Unit

3. Central Computer System



Gantry Locations in Restricted Zone



Limitations of ERP's Toll Charge Rules (5/5)

- **ERP's Pay-per-entry Basis Charge: Inequitable**
  - Undercharges long journeys and over-restrains short ones
  - LTA of Singapore has proposed distance-based toll charge for the second generation of ERP system
- **Three Alternative Toll Charge Methods for Cordon-based Congestion Pricing Schemes**
  - Distance-based
  - Time-based
  - Congestion-based

Encouraging aggressive driving behavior and may cause more traffic safety issues

Congestion Pricing Practices In Other Cities (1/5)

- **London Congestion Charge**
  - London congestion charge is a fee charged on most motor vehicles operating within the Congestion Charge Zone (CCZ) in central London between 07:00 am and 6:00 pm Monday to Friday.

Sign indicating the entrance of congestion charge area.

Sign indicating the exit of congestion charge area.

Congestion Pricing Practices In Other Cities (2/5)

- **Milan Congestion Charge- Ecopass and Milan Area C**
  - Ecopass pollution charge ended on 2011, and was replaced by the Area C scheme, which was effect on 2012, initially as an 18-month pilot program. Then the scheme was made permanent in March 2013.
  - The charge applies to every vehicle entering the city centre on weekdays (except Saturday) from 7:30 am to 7:30 pm

Ecopass traffic sign delimiting restricted area.

Area C sign

Congestion Pricing Practices In Other Cities(3/5)

❑ Durham City Congestion Charge

Durham introduced charges for “old town” centers in October 2002, reducing vehicle traffic by 85% after a year; prior to this 3,000 daily vehicles had shared the streets with 17,000 pedestrians.

Congestion Pricing Practices In Other Cities (4/5)

❑ Rejected proposals

Urban congestion pricing policy is under various pressure from public and some of them have to be stopped under oppositions.

- **Hong Kong** have conducted a pilot test on an electronic congestion pricing system between 1983 and 1985 with positive result. However, public is against this policy stalled its permanent implementation.
- **New York City** shelved a proposal for a three-year pilot program for implementation in Manhattan, and a new proposition was denied in 2008, with a potential federal grants of USD 354 million being reallocated to other American cities.

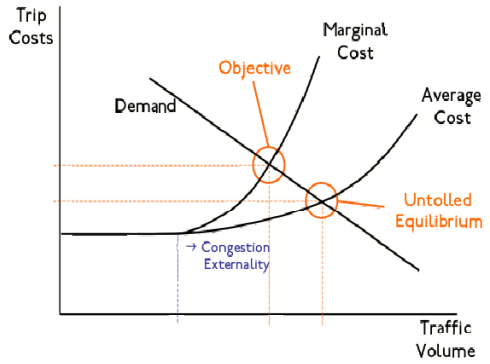
Congestion Pricing Practices In Other Cities (5/5)

❑ Current Proposals

- **United States:** San Francisco transport authority proposed initial congestion pricing scenarios in 2008, and the updated proposal calls for implementing a six-month to one-year trial in 2015.
- **China:** In 2011, local officials announced plans to introduce congestion pricing in Beijing.
- **Brazil:** the federal government of Brazil enacted the Urban Mobility Law that authorizes municipalities to implement congestion pricing to reduce traffic flows.

PART II

Congestion Pricing Theory



Theoretical Developments (2/3)

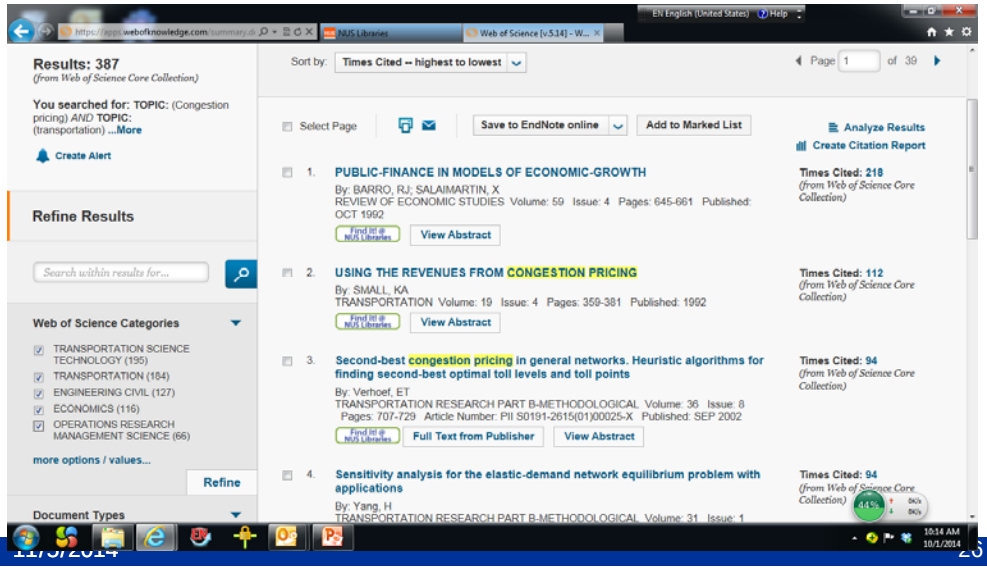
The initial idea of road pricing was put forward by Pigou (1920), who use the example of a congested road to make points on externalities and optimal congestion charges.

❑ **Congestion Pricing Fundamental**

- System optimum is the theoretical target
- Mitigate traffic congestion at some congested urban areas is a practical target
  - Congestion price are higher under congestion conditions, and lower at less congested times and locations to deter excessive users.
- **Key Issues of Congestion Pricing**
- How to choose the congestion pricing locations?
- How to choose an appropriate congestion?
- What different impacts would the congestion pricing scheme bring to different users?

Theoretical Developments (3/3)

❑ **Literature Review – 387 Papers Published Since 1989**



Classification for Congestion Pricing Studies

The congestion pricing studies can be generally classified into two categories:

➢ **First-best Congestion Pricing Principle**

(also named marginal-cost pricing problem). The marginal congestion price will be charged on every road in the network to get a system optimum.

➢ **Second-best Congestion Pricing Principle**

Due to unreality of the first-best pricing, the second-best pricing is proposed from a practical perspective and have received ample attention.

The key issues for the second-best pricing:

- Where to levy the toll and how much?
- What is the impact of value to times (VOT)?

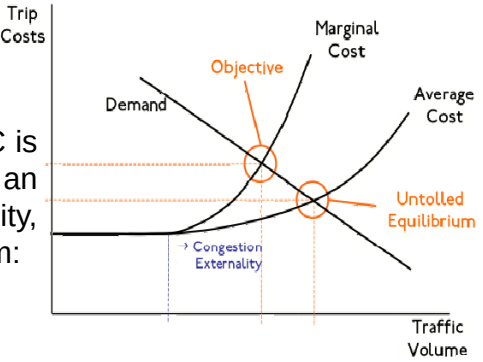
First-best Congestion Pricing Principle (1/2)

The differences between AC and MC curves at any traffic flow reflects the economic cost of congestion at that flow.

(1) Total cost: $TC(v) = vt(v)$

(2) The marginal social cost:

$$MC(v) = \frac{dTC(v)}{dv} = t(v) + v\frac{dt(v)}{dv}$$



Conclusion: The first term of MC is average cost AC, then to make an efficient use of available capacity, the toll is equal to the second term:

$$\tau(v) = v\frac{dt(v)}{dv}$$

Optimal toll: $x(v) = MC(v) - AV(v)$

First-best Congestion Pricing (2/2)

General Network Setting

Assume that behavior of drivers in their route choice from an origin to a destination follows user equilibrium (UE) principle.

UE Model:

$$\min z(v) = \sum_a \int_0^{v_a} t_a(v)dv$$

$$\sum_{p \in p_w} f_p^w = d_w, w \in W$$

$$\sum_{w \in W, p \in P_w} f_p^w \delta_{ap}^w = v_a, a \in A,$$

$$f_p^w \geq 0, p \in P_w, w \in W$$

$$\tau(v) = v \frac{dt(v)}{dv}$$

System Optimum Model:

$$\min z(v) = \sum_a t_a(v_a) v_a$$

$$\sum_{p \in p_w} f_p^w = d_w, w \in W$$

$$\sum_{w \in W, p \in P_w} f_p^w \delta_{ap}^w = v_a, a \in A,$$

$$f_p^w \geq 0, p \in P_w, w \in W$$

Second-best Congestion Pricing Principle (1/3)

Four Congestion Charging Schemes

(1) Link-based charging

(2) Cordon-based charging

(3) Travel distance based charging

(4) Travel time or travel-delay based charging

Second-best Congestion Pricing Principle (2/3)

Bi-level Programming Model Building

Upper-level Objectives

- social welfare maximization
- total revenue maximization
- total travel time and delay minimization
- System optimization

Lower-level Model: traffic assignment

- User equilibrium
- Stochastic user equilibrium
- Variable demand user equilibrium

➢Under elastic demand, the upper-level model is to determine toll pattern to optimize system performance, shown as:

$$\min F_1 = \sum_{w \in W} \int_0^{d_w(\tau)} D_w^{-1}(w)dw - \sum_{a \in A} t_a(v_a(\boldsymbol{\tau}))v_a(\boldsymbol{\tau})$$

$$s.t \quad \tau_a^{\min} \leq \tau_a \leq \tau_a^{\max}, a \in \overline{A}$$

➢The lower-level traffic assignment elastic demand model is given as:

$$\min z(v) = \sum_a \int_0^{v_a} \tilde{t}_a(w, \tau_a)dw - \sum_{w \in W} \int_0^{d_w} D^{-1}(w)dw$$

$$\sum_{p \in p_w} f_p^w = d_w, w \in W$$

$$\sum_{w \in W, p \in P_w} f_p^w \delta_{ap}^w = v_a, a \in A,$$

$$f_p^w \geq 0, p \in P_w, w \in W$$

Second-best Congestion Pricing Principle (3/3)

Solution Algorithm Design

➢Sensitivity analysis based algorithm

Tobin and Friesz (1988) developed the original sensitivity formulas; then based on their research, the row/link-based reduction method for sensitivity analysis of network equilibrium.

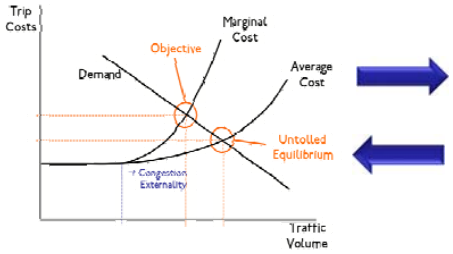
➢Heuristic algorithms

There are many heuristic algorithm that have been used at the second-best congestion pricing solution, mainly including genetic algorithm, simulated annealing algorithm, particle swarm optimize algorithm.

-Tobin, R. L., Friesz, T.L., 1988, Sensitivity Analysis for Equilibrium Network Flow. Transport Sci. 22(4), 542-550.

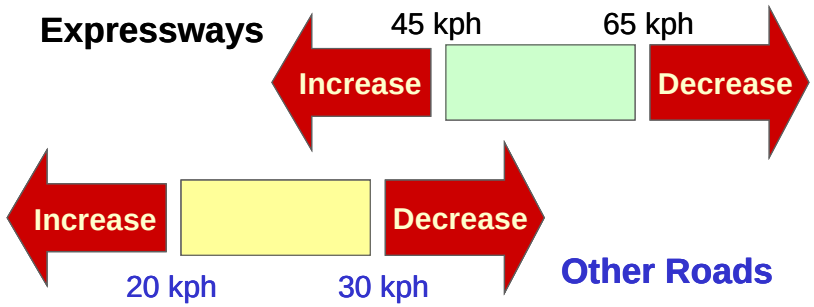
PART III

Bridge GAP Between Academic Studies and Practices



Practice for ERP Toll Fares Adjustment

- **Reviewed every 3 months according to a survey on the average travel speed**
  - To ensure optimal use of road space
- **Increment: 0.5 S$ (Changed to 1 S$ from July 2008)**



Three Primary Elements for Theoretical Congestion Pricing Determination

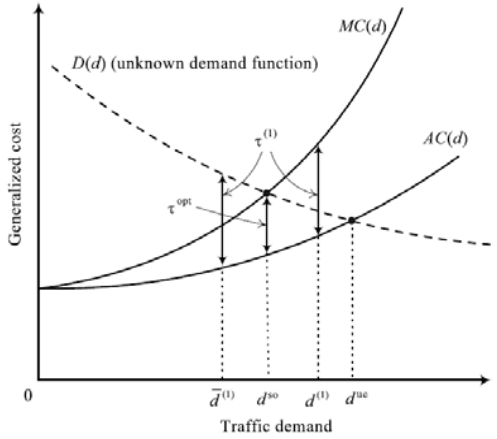
- **Conventional analysis of optimal congestion pricing relies on three primary elements: speed-flow relationship, demand function, generalized disutility.**
- **Analytical demand functions tailed for congestion pricing are, however, difficult to establish in practice even with advanced transport modeling techniques.**
- **How to choose the optimal charge level of congestion tolls in a simple yet practical manner?**
- **A trial-and-error implementation methods are proposed, especially for demand function (and or value of time) are unknown.**

Vickrey, W. (1993). Point of view: principles and applications of congestion pricing. TR News, 4-5.

William Spencer Vickrey was a Canadian-born professor of economics and Nobel Laureate of Economics in 1996.

Trial-and-Error Implementation (1/4)

- The optimal toll to be charged is equal to τ_{opt};
- The demand function is generally unknown, so the optima toll cannot be determined analytically.
- What we know is that the revealed demand or traffic flow for a given toll.
- Based on the responses of traffic flow to alternative toll charges, the optimal toll charge can be found through iterative trial-and-error procedure.



Trial-and-Error Implementation (2/4)

- **The trial-and error for marginal cost pricing**
  - **The theory first-best pricing equals:** $\tau_a = v_a t_a'(v_a), a \in A$
  - **Trial-and error procedure for the first-best pricing scheme:**

Step 0- Initialization: Set an initial set of feasible link flows

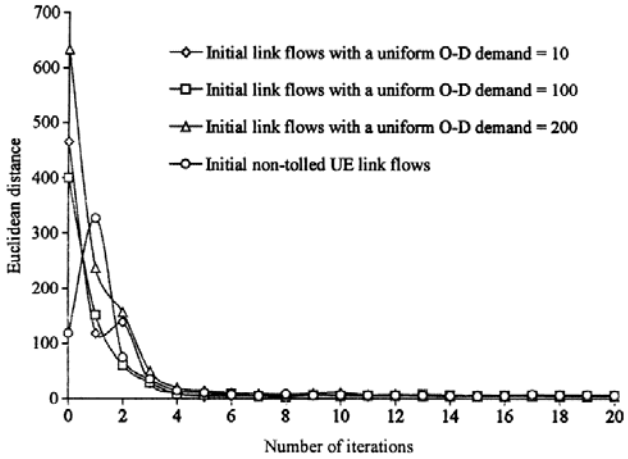
Step 1-Estimate link tolls Based on the current link flow, calculate link toll using first-best pricing formula.

Step 2-Observe link flows Get link flow after the imposition of the step 1 given tolls.

Step 3- Check convergence If result satisfy convergence, stop; else, go to step 4

Step 4- Update link toll Use updating models to get the new link toll, go to step 1.

Trial-and-Error Implementation(3/4)



Change of the Euclidean distance with iterations for various initial link flows

Trial-and-Error Implementation (4/4)

- **Relevant References**

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- Wang, X., & Yang, H. (2012). Bisection-based trial-and-error implementation of marginal cost pricing and tradable credit scheme. Transportation Research Part B: Methodological, 46(9),1085-1096.

PART V

Future Asia-oriented Research

Future Asian-oriented Research(1/3)

❑ Tradable travel credits for congestion management

- One of the major concerns with congestion pricing is the equality debates, that it is perceived as unfair or just another flat tax.
- In recent years, a more sophisticated quantity control method scheme has been proposed: the tradable driving permit/right/credit or the emission cap-and-trade scheme.
- In a tradable credit scheme, a policy target is defined in terms of quantity and the associated consistent equilibrium price of credits is determined by the market through free trading.

The government initially issues credits to all eligible travelers. → The government predetermines the charge or the consumption rate for each roadway link. → Credits can then be traded freely in a competitive market without government intervention.

Future Asia-oriented Research (2/3)

❑ Advantage of Tradable Credits Scheme

- If there is an initial uniform distribution of credits to all registered travelers, the scheme involves **the same equity**.
- Link-specific (or cordon-based) **charges regulate traffic flow as pricing does in both static and dynamic control** settings by allowing for unrestricted trading of credits.
- With the free credit allocation and trading travelers have a **supplementary incentive to limit their vehicle use**, because they can sell their extra credits.
- The scheme confines transfers to within a predefined group of travelers throughout the whole exercise. The scheme is clearly **revenue-neutral**.

Future Asia-oriented Research (3/3)

❑ Recent Studies

- Yang, H., Wang, X., 2011. Managing network mobility with tradable credits. *Transportation Research Part B: Methodological ,* 45, 580-594.
- Wang, X.L., Yang, H., Zhu, D.L., Li, C.M., 2012. Tradable travel credits for congestion management with heterogeneous users. *Transportation Research Part E,* 48 (2), 426–437.
- Wu, D., Yin, Y., Lawphongpanich, S., Yang, H., 2012. Design of more equitable congestion pricing and tradable credit schemes for multimodal transportation networks. Transportation Research Part B, 46, 1273-1287.
- Nie, Y., Yin, Y., 2013. Managing rush hour travel choices with tradable credit scheme. Transportation Research Part B: Methodological, 50, 1-19.
- Xiao, F., Qian, Z., Zhang, H.M., 2013. Managing bottleneck congestion with tradable credits. Transportation Research Part B: Methodological ,56, 1-14.
- Wang, X., Yang, H., 2012. Bisection-based trial-and-error implementation of marginal cost pricing and tradable credit scheme. Transportation Research Part B: Methodological 46, 1085-1096.

THANK YOU