Modelling & Simulation: Plenary II

**Advanced trip-related road pricing schemes based on transport accessibility and their impacts on equity**

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FUTURE MOBILITY

**Outline**

1. Background
2. Acceptance and equity in road pricing schemes
3. Transport-related *acceptance* & *equity* measures for road pricing schemes
4. Exploratory results on a test network
5. Conclusions and research perspectives
1. Background

The idea of introducing a toll (pricing) for the use of a road infrastructure and/or a service in urban areas is one of the most common TDM policies aimed to reduce traffic congestion and/or pollutant emissions

**Most common road-pricing schemes** *(Ecola and Light, 2009; Levinson, 2010)*

- **toll** (pay for using a single road infrastructure or lane)
- **cordon/area pricing** (pay for crossing a cordon or entering in an area, e.g. Historic city center)

**Several applications of road-pricing across the world**

- Singapore – Cordon, Time (peak vs. off-peak hours), Distance of the trip and Vehicle based
- London (UK) Cordon and Time-Based
- Milan (Italy) Cordon, Time and Vehicle-based
- New York (USA) Bridge and tunnel crossing and Time-based
- ... even though the number of applications is definitely lower than its potential benefits due to the consensus difficulties in introducing it *(acceptance)*

1. Background

**ITS technologies and road pricing**

allow to extend and apply more sophisticated pricing schemes connecting the price to:

- **trip characteristics** (OD-based; path-based; service-based)
- **distance of the trips** (e.g. $/km)
- **travel time** (e.g. $/minutes of network usage)
- **congestion level** (e.g. peak-hour vs. off-peak our)
- **vehicle consumption/emission** characteristics (e.g. electric vs. traditional)
- **vehicle loading factor** both for passenger and for freight (e.g. one passenger vs. more than one passenger)
1. Background

State of the art

Impacts of road-pricing schemes:

- **Internal to the transportation system**
  - changes in travel demand (e.g. path, mode, departure time, trip frequency)
  - changes in flows and level of service attributes (e.g. travel time, reliability, generalized cos)
  - Safety (e.g. accidents reduction)

- **External to the transportation system**
  - Environmental impacts (e.g. pollutants emission reduction)
  - Land use impacts (e.g. residences and activities localization)
  - Economic impacts (e.g. cost of living, value of houses/offices)
  - Social impacts (e.g. Equity)

All the available applications aim to reduce car use and their impacts using different pricing strategies through different methodologies aimed to define the price:

- **Unconstrained optimization problem** (e.g. first-best congestion pricing/marginal cost pricing)
  (Ferrari, 2005; Tsekeris and VoB, 2009; Vickrey, 1969; Walters, 1961)

- **Constrained multi-objective optimization problem** (e.g. second-best pricing)
  - reducing/constraining traffic congestion
  - reducing/constraining traffic emissions (e.g. PM10, CO2, CO)
  - reducing/constraining travel time
  - constraining (generalized) travel cost
2. Acceptance and equity in road pricing schemes

a) Acceptance

Many papers deals with the problem related to the consensus in introducing road-pricing schemes
(Levinson, 2010; Grisolia et al. 2015; Taylor et al., 2010; Viegas, 2001)

No measures proposed in the literature

Consolidated strategies for increasing acceptance are:

- **Public engagement** (e.g. Cascetta et alii, 2015)
- **Simplicity of the proposed schemes** (e.g. Li and Hensher, 2013)
- **Information about the characteristics of the schemes** (familiarity – e.g. Cools et al., 2011)
- **Information about the social benefits** (Alhalate and Bol, 2009; Odeck and Kjerkreit, 2010; May et al, 2010; Noordergraaf et al, 2014)
- **Perception of an equitable policy**: e.g. use revenues raised by toll for
  - Improve public transport (Ferrari, 2005; Grisolia et al, 2015)
  - New infrastructures and services for the users of the road-pricing (trust in government use of funds – e.g. De Palma et al, 2007; Kim et al., 2013)
2. Acceptance and equity in road pricing schemes

b) Equity

**Equity** is concerned with the distribution of costs and benefits among members/users. Such benefits and costs (monetary or not) can be distributed in ways that people may see as reasonable or not (**acceptance**), depending on different criteria (Ecola and Light, 2009)

- Economists tend to use **welfare-based measures of equity** based on microeconomic theory to characterize the impacts
- Transportation planners tend to evaluate congestion pricing in terms of **transportation accessibility and environmental impacts** as measures of equity

**Horizontal Equity**

is concerned with how individuals from the same group (e.g. the poor, the elderly, the users with low transport accessibility) fare relative to one another. All people in a group are equal and should enjoy equal opportunities (e.g. activities, transport services) (Ecola and Light, 2009)

**EXAMPLE:** all people in a study area, **pay the same fare/km (toll proportional to the distance traveled)**

**Vertical Equity**

refers to the distribution of costs and benefits across groups. The vertical equity concept often differentiates between groups based on ability to pay, which is typically measured by individual’s income or through transportation accessibility (opportunities) (Ecola and Light, 2009)

**EXAMPLE:** all travelers in a study area, **pay the same fare/inclusive transport cost**
Aims of the research

- Acceptance and equity measures are not used for road-pricing design (in short-term applications)

- Acceptance and equity are at most used for ex-post evaluations in real case applications (long-term effects)

The aims of the research are:

a) Propose transport-related acceptance & equity measures for road-pricing schemes

b) Propose to use acceptance & equity measures for road-pricing design (short-term)

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3. Transport-related acceptance & equity measures for road pricing schemes
4. Exploratory results on a test network
5. Conclusions and research perspectives
3.1 A transport-related acceptance measure

The change in OD net perceived utility (or surplus) deriving from a road-pricing scheme could be considered as an inverse measure of acceptance (the smaller the change the larger the acceptance)

In RUM (Random Utility Models), the EMPU (Expected Maximum Perceived Utility) variable $s$ related to an OD pair can be considered as a measure of the OD net perceived utility (surplus) (Cascetta, 2009):

$$s = s(V) = E[\max_j(U)] = E[\max_j(V + e)] = \max_j(V + e) f(e) \, de$$

Where $U$ is the vector of the perceived utility function related to all alternatives, $V$ is the vector of the systematic utility and $e$ is the vector of the residuals.

If the residuals $e$ are i.i.d. Gumbel variables, the EMPU can be expressed in closed form as a logsum (or inclusive) variable:

$$s = s(V) = \theta \ln \sum_j \exp(V_j/\theta)$$

**EXAMPLE**

**NO PRICING ($\theta=1$)**

$$\begin{align*}
V_1 &= -5 \\
V_2 &= -2 \\
s &= -1.95
\end{align*}$$

**PRICING ($\beta\cdot c = -2$)**

$$\begin{align*}
V_1 &= -5 \\
V_2 &= -4 \\
s &= -3.69 \\
|\Delta s| &= 1.74
\end{align*}$$

Pricing OD pairs with more opportunities (e.g. modes, services, paths) generally increase acceptability.

| $|\Delta s|$ | (more acceptable) |
|-----------|-------------------|
| $|\Delta s|$ | $0.94$            |

**EXAMPLE**

**NO PRICING ($\theta=1$)**

$$\begin{align*}
V_1 &= -5 \\
V_2 &= -2 \\
V_{\text{train}} &= -3 \\
s &= -1.95
\end{align*}$$

**PRICING ($\beta\cdot c = -2$)**

$$\begin{align*}
V_1 &= -5 \\
V_2 &= -4 \\
V_{\text{train}} &= -3 \\
s &= -2.59 \\
|\Delta s| &= 0.94 \\
&= (more \ acceptable)
\end{align*}$$
### 3.2 A transport-related equity measure

**The dispersion (scatter) of OD net perceived utilities (surplus) as a measure of equity** for transport accessibility

- **Some possible indicators:**
  - Mean Absolute Deviation (MAD)
  - standard deviation
  - GINI coefficient
  - ...

**EXAMPLE**

**NO PRICING** → MAD = 0.66

**PRICING** ($\beta \cdot c = -2$)

- **MAD=0.16 (-76%)**
- **MAD=1.66 (+152%)**

*Pricing OD pairs with more opportunities generally increase equity*

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4. Exploratory results on a test network

A. “Traditional” road-pricing design models (e.g. Unconstrained vs. Constrained optimization problem), generally have multiple solutions

- **Dominated solutions**: the performance of the system decreases wrt all the indicators not considered in the design model (e.g. gen. transport cost; environmental impacts; equity; acceptance)
- **Not dominated solutions**: the performance of the system increases wrt some indicators
  - Dominance analysis
  - Multicriteria analysis
  - ...

B. Transport-related **acceptance&equity measures as additional criteria for choosing/designing the solution**

### Test network

**the topology**
- 4 OD pairs
- 8 arcs
- 2 modes (car and train)
- 6 paths (for car mode)

<table>
<thead>
<tr>
<th>OD pair</th>
<th>Path</th>
<th>Link</th>
<th>Mode alternatives</th>
<th>OD group</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-C</td>
<td>1</td>
<td>1, 2, 3</td>
<td>Car, train</td>
<td>Long distance</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1,4,7,5,3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-C</td>
<td>3</td>
<td>6,4,2,3</td>
<td>Car</td>
<td>Long distance</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6,7,5,3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-C</td>
<td>5</td>
<td>8,5,3</td>
<td>Car, train</td>
<td>Short distance</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8,7,6</td>
<td>Car</td>
<td>Short distance</td>
</tr>
</tbody>
</table>

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4. Exploratory results on a test network

**Supply model**

BPR separable cost functions

\[ c_i(f_i) = c_{0,i} \cdot \left[ 1 + \alpha \left( \frac{f_i}{Q_i} \right)^\gamma \right] \]

where:
- \( c_i \) be the travel time (minutes) on arc \( i \)
- \( c_{0,i} \) be the free-flow travel time on arc \( i \)
- \( Q_i \) be the capacity of arc \( i \)
- \( f_i \) be the flow on arc \( i \)
- \( \alpha = 1.5 \)
- \( \gamma = 2 \)

**Demand model**

Assignment model

Elastic Stochastic User Equilibrium (SUE) for congestion road network

**Table: Mode choice attributes**

<table>
<thead>
<tr>
<th>model</th>
<th>attributes</th>
<th>parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train</td>
<td>In-vehicle travel time</td>
<td>-1.8 (1/h)</td>
</tr>
<tr>
<td></td>
<td>Waiting time</td>
<td>-2.0 (1/h)</td>
</tr>
<tr>
<td></td>
<td>Access time</td>
<td>-2.2 (1/h)</td>
</tr>
<tr>
<td></td>
<td>Fare</td>
<td>-0.12 (1/k)</td>
</tr>
<tr>
<td></td>
<td>Alt. Specific Constant</td>
<td>+0.20</td>
</tr>
<tr>
<td>Car</td>
<td>Logsum&lt;sub&gt;min&lt;/sub&gt;</td>
<td>0.85</td>
</tr>
<tr>
<td>path 1</td>
<td>Travel time</td>
<td>-1.8 (1/h)</td>
</tr>
<tr>
<td>path 2</td>
<td>Monetary Cost</td>
<td>-0.12 (1/k)</td>
</tr>
</tbody>
</table>

**Within-day Static models with variable demand**

4. Exploratory results on a test network

Road-pricing performance indicators

- **Transportation system**
  - Total Travel Time  \( TT = \Sigma_k Time_k \cdot h_k \) (all modes)
  - Total Generalized Car Cost  \( GCC = \Sigma_k (VTTS \cdot Time_k + Cost_k) \cdot h_k \)

  *WHERE: VTTS is the value of the Travel Time Saved; Time, is the total travel time per the path \( k \); Cost \( k \) is the total monetary cost (fuel + pricing); \( h_k \) is the car flow on the path \( k \)*

- **Acceptance**
  - Average absolute variation (\( \Delta_s \)) of OD net perceived utility \( s \)

  \[ \Delta_s = \Sigma_j \left| s_j^{\text{price}} - s_j^{\text{base}} \right| / N_{OD} \]

  *WHERE: \( s_j^{\text{price}} \) is the EMPU variable relative to the OD pair \( j \) and to a road-price scheme; \( s_j^{\text{base}} \) is the EMPU variable relative to the base scenario; \( N_{OD} \) is the total number of OD pairs*

- **Vertical Equity**
  - Mean Absolute Deviation (MAD)  \( = \Sigma_j \left| s_j^{\text{price}} - s_m^{\text{price}} \right| / N_{OD} \)

  where:
  \( s_m^{\text{price}} = \Sigma_j s_j^{\text{price}} / N_{OD} \)
4. Exploratory results on a test network

A. Generally multiple solutions for a Road-pricing model

**EXAMPLE**

- \( \text{Argmin Total Travel Time} \) (objective function)
- constraining waited average variation of the OD Generalized Cost - GC
  \[ \frac{G_{\text{pricing},i}}{G_{\text{base},i}} < +100\% \]

\( P \) is a vectors of the path-based pricing values (6 values of prices for 6 car paths)

![Graph showing multiple solutions for road pricing](image)

\[ \forall P = \begin{bmatrix} 5 \\ 1 \\ 11 \\ \text{price5} \\ 2 \end{bmatrix} \]

Min Total Travel Time (%var. GC<100%)

B. Acceptance & equity measures for choosing the solution

**Road-pricing model** (Constrained Min Total Travel Time)

Some possible solutions

- Not dominated solutions
- Dominated solutions

Not considering Acceptance & Equity measures could choose the wrong solution
4. Exploratory results on a test network

Road-pricing scheme *(Argmin Total Travel Time)*

<table>
<thead>
<tr>
<th>OD pair</th>
<th>Modes available</th>
<th>Number of Car paths</th>
<th>SOLUTION a Average path Price (€)</th>
<th>SOLUTION b Average path Price (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-C</td>
<td>Car, train</td>
<td>2</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>B-C</td>
<td>Car</td>
<td>2</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>D-C</td>
<td>Car, train</td>
<td>1</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>D-B</td>
<td>Car</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

To increase acceptability and equity: price the OD pairs with more opportunities (e.g. modes, services, paths)

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a) **Measures** of transport-related **acceptance&equity** for road-pricing schemes can be proposed using EMPU variables.

b) Given the same values of other Performance Variables, "optimal" pricing vectors may **differ significantly** with respect to acceptance&equity indicators.

c) For increasing acceptability and equity, **paths connecting price OD pairs with more opportunities** (e.g., modes, services, paths), **should be priced more**, given anything else.

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Research perspectives (1/2)

a) Formulation of optimal pricing using **acceptance&equity variables**

\[
\max \quad E(P) \\
C(P) \leq 0
\]

Where \( E(P) \) is some measure of acceptance&equity, conditional to the vector of constraints \( C(P) \) (e.g., maximum increase of the general transport cost, minimum reduction of the traffic congestion and/or environmental impacts).

b) Application to a real case study

- Some preliminary results relative to the case study of Naples (Italy) confirm the results obtained.
5. Conclusions and research perspectives

Research perspectives (1/2)

d) Study the relationships between acceptability and equity

e) Mathematical proprieties for the acceptance&equity measures and for the design problem (e.g. monotonicity of the function; domain of the solutions)

f) Comparison of alternative pricing schemes (link based; OD-based; path-based) wrt acceptability/equity measures.

References


References


