Demand Modeling for Congestion Pricing Analysis: An Overview

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Outline

• Motivation
• Activity-based demand models
• Enhancements relevant to congestion pricing
  – Value of time heterogeneity
  – Travel time reliability
  – Choice of time-of-travel
• Conclusion
Motivation

Global Toll Road Sample (2005)
Average = 0.76; Standard Deviation = 0.26; N = 104

Motivation (2)

• Toll road traffic forecasts characterized by large errors and optimism bias
• Most of these forecasts are based on 4-step demand models
• Need for better demand forecasts that capture human decision-making in response to policies (e.g. tolls)
4-step demand models

• Classic 4-step (trip based)
  – Trip Generation (Frequency)
  – Trip Distribution (Destination)
  – Modal Split (Mode)
  – Assignment (Route)

• Congestion pricing affecting the AM trip to work also affects other trips in the day
Representing activity/travel behavior

Activity based demand models

Land-use and Economic Development

Mobility and Lifestyle

Activity and Travel Scheduling

Activity and Travel Rescheduling

Transportation System Performance

Activity schedule approach

Long Term Choices
(residential/workplace locations, auto ownership, lifestyle)

Activity Pattern
number/purpose/sequence of tours

Primary Tours
timing, destination

Secondary Tours
timing, destination
Enhancements relevant to congestion pricing

- Value of time (VOT) heterogeneity
- Value of reliability
- Choice of time-of-travel
VOT heterogeneity:
Motivation

• Variation in VOT affects all travel related decisions

• Value of time (VOT) or willingness to pay for travel time savings varies by
  – Trip purpose
  – Travel mode
  – Trip length, income, etc.

• But there also exists significant unexplained heterogeneity
VOT heterogeneity: Hybrid with attitudinal indicators

- Quantify latent attitudes and their effect on VOT using the hybrid choice model

![Diagram]

- Attributes of Alternatives ($X$)
- Characteristics of the Traveler ($X$)
- Attitudes ($A$)
- Indicators ($I$)
- Utility ($U$)
- Choice (i)

Interactions with cost and/or time
VOT heterogeneity: Hybrid with attitudinal indicators (2)

- Model (Behavioral Mixture):

\[ P(i | X) = \int P(i | X, A) f(A | X) dA \]

- Likelihood (choice & attitudinal Indicators):

\[ f(i, I | X) = \int P(i | X, A) h(I | A) f(A | X) dA \]
VOT heterogeneity: Hybrid with attitudinal indicators (3)

- 2005 survey in Stockholm, N= 2400
- Choice (SP): car vs public transportation
- Questions indicating car-loving attitude:
  - $I_1$: It is comfortable to go by car to work.
  - $I_2$: It feels safe to go by car
  - $I_3$: It is very important that traffic speed limits are not violated
  - $I_4$: Increase the motorway speed limit to 140 km/h

VOT heterogeneity: Hybrid with attitudinal indicators (4)

CDF of VOT by Income (SEK/hour) group

7,500 < Income < 15000  
25,000 < Income < 30,000  
Income >50,000

Base model  
Model with latent attitudes

VOT heterogeneity: Conclusion

• Considerable heterogeneity in Value of Time
• Methods based on Logit mixtures:
  – Continuous mixture (aka Mixed Logit)
  – Latent class (discrete mixture) performs better as the mixing distribution includes covariates and introduces correlations
  – Hybrid with attitudinal indicators enhances the power of mixture models
Travel time reliability: Expected utility methods

• Conventional approach: risk attribute
  – Mean / variance of travel time
  – Mean schedule delay
Travel time reliability: Non-expected utility methods

- Delays with probability near 0 or 1 are not well-perceived (Avineri and Prashker 2004)
  - Overweigh small probabilities
  - Underweigh large probabilities

- Methods:
  - Rank-dependent (RDEU)
  - Cumulative prospect theory (CPT) (Tversky and Kanheman 1992)
  - Latent-class model of risk seeking heterogeneity
Time-of-travel choice:
Motivation

• Time-of-travel choice is highly elastic with respect to congestion pricing
Time-of-travel choice: Schedule delay

• Difference between desired and actual time-of-travel due to congestion, reliability, and non-continuous public transportation schedules

• Key explanatory variable of time-of-travel choice

• Travelers trade off disutilities of schedule and congestion delays
Time-of-travel choice:
Schedule delay disutility specification

- $t = \text{time-of-travel}$
- $t^* = \text{desired time-of-travel}$
- $TT(t) = \text{travel time at } t$
- $\alpha(t) = \text{ASC for time-of-travel } t$
- $SD_{\text{early}}(t,t^*) = \text{early schedule delay for time-of-travel } t$
- $SD_{\text{late}}(t,t^*) = \text{late schedule delay for time-of-travel } t$

\[
V(t) = \alpha(t) + \beta TT(t) + \gamma_{1_{\text{early}}} SD_{\text{early}}(t,t^*) + \gamma_{1_{\text{late}}} SD_{\text{late}}(t,t^*) + \cdots
\]
Time-of-travel choice:
Accounting for Schedule Delay When Desired Departure or Arrival Times Are Unknown

• Assume $t^*$ is (unknown) constant for individuals in a market segment
• Schedule delay functions become arrival and departure time preference functions by market segment
Time-of-travel choice: The 24 hour cycle

- Need cyclic functions: $V(0) = V(24)$

- Trigonometric Function - based on the idea of Fourier series
  
  $$V(t) = \beta_1 \sin\left(\frac{2\pi t}{24}\right) + \beta_2 \sin\left(\frac{4\pi t}{24}\right) + \ldots + \beta_K \sin\left(\frac{2K\pi t}{24}\right)$$
  
  $$+ \gamma_1 \cos\left(\frac{2\pi t}{24}\right) + \gamma_2 \cos\left(\frac{4\pi t}{24}\right) + \ldots + \gamma_K \cos\left(\frac{2K\pi t}{24}\right)$$

- Truncation at $K$ is determined empirically
Time-of-travel choice: Illustration of Trigonometric Function

Time-of-travel choice: Continuous Logit (CL)

- \( t \) is the continuous time-of-travel variable, bound by \( b_1 \) and \( b_2 \) (e.g. 0, 24h)

\[
f(t) = \frac{\exp(V(t))}{b_2} \int_{b_1}^{b_2} \exp(V(r)) dr
\]

Time-of-travel choice: Continuous cross-nested logit (CCNL) formulation (Lemp et al. 2010)

- Cross-nested formulation to handle correlation between adjacent time periods
- Each nest contains a set of sequential elemental alternatives

Time-of-travel choice: CCNL (2)

Nests are centered at $w$ with an interval $2h$ contains alternatives $w-h$ to $w+h$, $\alpha(t,w)$ is the allocation parameter of alternative $t$ to nest $w$

$$f(t) = \frac{\left[ \alpha(t,w) \exp(V(t)) \right]}{\int_{w-h}^{w+h} \left[ \alpha(r,w) \exp(V(r)) \right] dr} \times \left( \int_{w-h}^{w+h} \left[ \alpha(r,w) \exp(V(r)) \right] dr \right)^{\mu} dw \int_{b_1}^{b_2} \left( \int_{q-h}^{q+h} \left[ \alpha(r,q) \exp(V(r)) \right] dr \right)^{\mu} dq$$

Scale parameter: $1 \geq \mu > 0$

$\Rightarrow$ Assumes similar correlation structure across the day

Time-of-travel choice: CCNL (3)

\[ \int_w \alpha(t, w) dw = 1 \]

Conclusion

• Activity-based demand models
• Enhancements relevant to congestion pricing
  – Value of time heterogeneity
  – Travel time reliability
  – Choice of time-of-travel
Appendix
VOT heterogeneity: Continuous logit mixture

\[ U_i = \mu [c_i + \beta'X_i + \nu(t_i + \gamma'Z_i)] + \epsilon_i \]

- \( \nu = \text{value of time} \)
- \( c_i = \text{travel cost of alternative } i \)
- \( t_i = \text{travel time of alternative } i \)
- \( X_i = \text{vector of additional variables for alternative } i \)
- \( Z_i = \text{vector of additional variables} \)
- \( \epsilon_i = \text{additive error term} \)
- \( \mu = \text{scale parameter} \)
- \( \beta, \gamma = \text{unknown parameters} \)

VOT heterogeneity: Continuous logit mixture (2)

- Choice probability for a lognormal distribution of VOT

\[ \ln \nu : \mathcal{N}(\omega, \sigma^2) \]

\[ P(i) = \frac{1}{\sigma \sqrt{2\pi}} \times \int_{0}^{\infty} \frac{\exp\{\mu[c_i + \beta'Y_i + \nu(t_i + \gamma'Z_i)]\}}{\sum_{j=1}^{\infty} \exp\{\mu[c_j + \beta'Y_j + \nu(t_j + \gamma'Z_j)]\}} \times \frac{1}{\nu} \exp\left\{-\frac{1}{2} \left( \frac{\ln \nu - \omega}{\sigma} \right)^2 \right\} d\nu \]

- where \( \mu, \beta, \gamma, \omega, \sigma \) are the parameters to be estimated simultaneously using maximum likelihood

VOT heterogeneity: Latent class

- Discrete distribution of value of time
- Segment population based on unobserved sensitivity through ordered levels
- Each individual belongs to exactly one class

VOT heterogeneity: Latent class (2)

- Class membership model: \( Q(s|X; \theta) \)
- Class-specific choice model: \( P(i|X; \beta_s) \)
- Unconditional choice probability: \( P(i|X) = \sum_{s=1}^{S} P(i|X; \beta_s)Q(s|X; \theta) \)
  
  - \( i \) = travel alternative
  - \( s \) = latent class
  - \( X \) = vector of alternative attributes and individual characteristics
  - \( \theta, \beta_s \) = vectors of unknown parameters

Travel time reliability: Motivation

Travel time reliability: Motivation (2)

- Travel time reliability accounts for 5-35% of trunk road scheme economic benefits (SACTRA 1999)
- Scheduling delay accounts for 30-40% of total time cost (Ettema and Timmermans 2006)
- Ratio of reliability \( \left( \frac{\hat{\beta}_{\sigma_{tt}}}{\hat{\beta}_{E[tt]}} \right) \) estimated to be > 1
  - Commuter car travel: 1.3 (Bates et al. 2003)
  - Public transit: 1.4 (de Jong et al. 2009)

Travel time reliability: 
CPT vs. EU performance (Gao et al. 2010)

- Synthetic data
- Lowest travel time chosen as reference
  - Delays are considered losses
  - CPT is applied only in loss domain

Travel time reliability: CPT vs. EU performance (2)

Travel time reliability:
Latent-class Logit model (Razo and Gao 2011)

- PC-based experiment
- Accounts for both strategic and non-strategic behavior
- Estimates overall probability that an observation is the result of strategic choice behavior
- Choice set at the origin with two alternatives
  - \{safe (I-93), risky route (I-90)\} if non-strategic
  - \{safe (I-93), risky branch (I-90 and Rt.2)\} if strategic

Travel time reliability:

Latent-class Logit model (2)

• Latent-class logit mixture model form:

\[ P(i) = P(\text{strategic}) \times P(i \mid V_{\text{saf}} \& V_{\text{risky,strategic}}) \]
\[ + [1 - P(\text{strategic})] \times P(i \mid V_{\text{saf}} \& V_{\text{risky,non-strategic}}) \]

choice: observed choice at the origin (safe or risky)

• Systematic utility of the risky branch \((V_{\text{risky}})\) in the strategy map

  • Large delay not included if strategic
  • Large delay included if non-strategic

Travel time reliability:

Latent-class Logit model (3)

• Estimated strategic class probability (0.880-0.934) is significantly different from 0 and 1

• The same individual exhibits strategic and non-strategic route choice behavior depending on the situation

• Probability weighing function has a pronounced inverse S-shape

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