Demand Modeling for Congestion Pricing Analysis: An Overview

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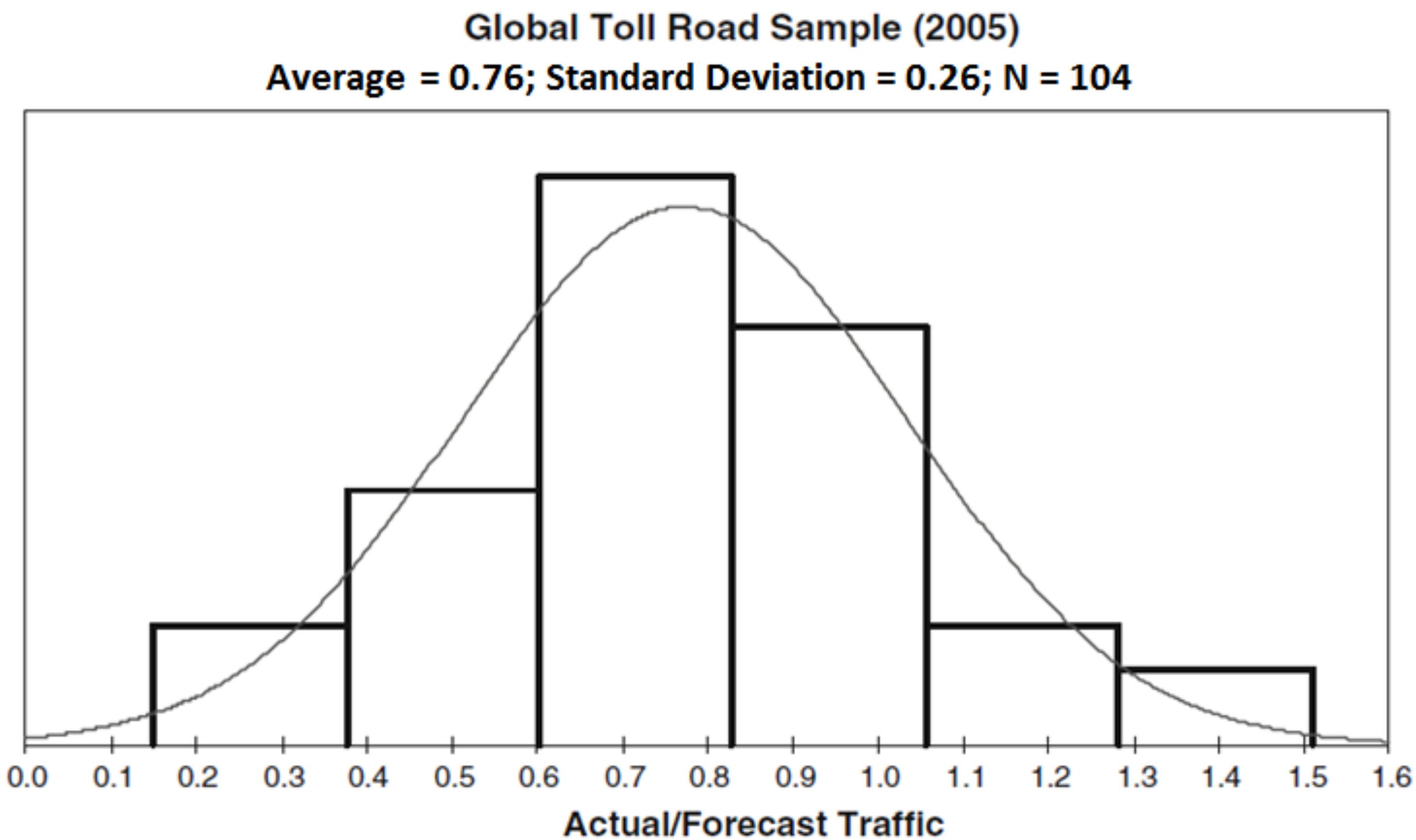
Outline

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

Motivation



Source: 1. Bain, R. (2009) , "Error and optimism bias in toll road traffic forecasts," *Transportation*, vol. 23, pp. 241-266

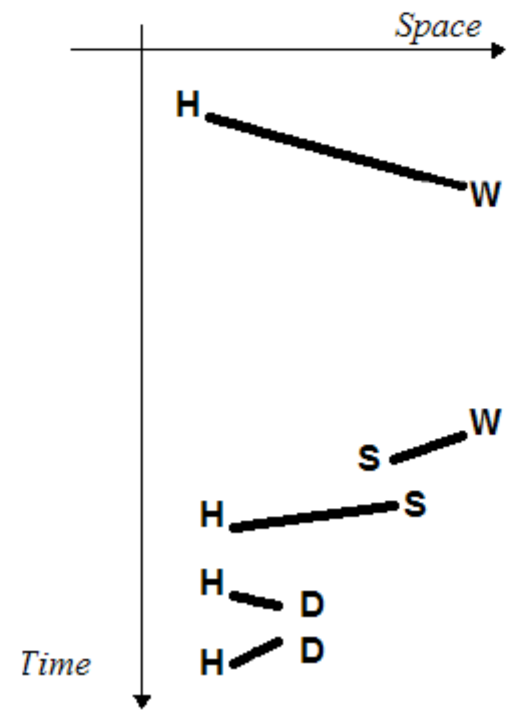
Motivation (2)

- 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)

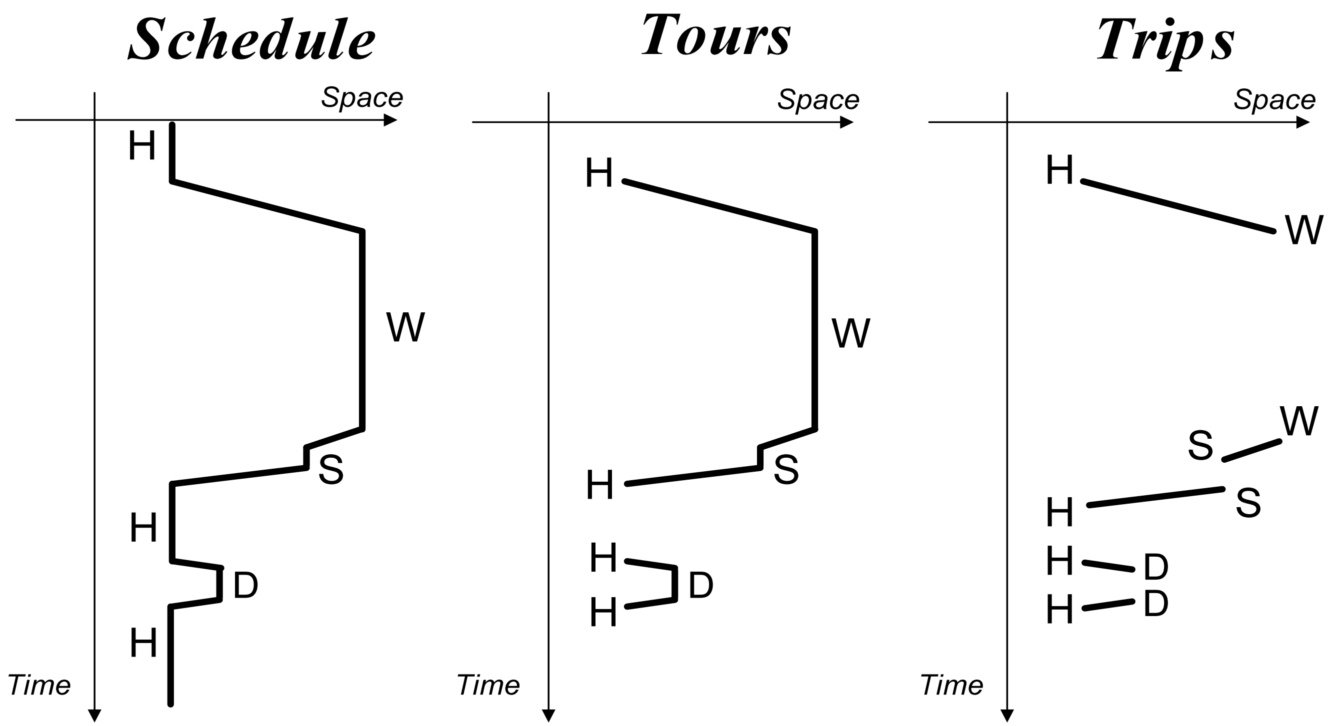
4-step demand models

- 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



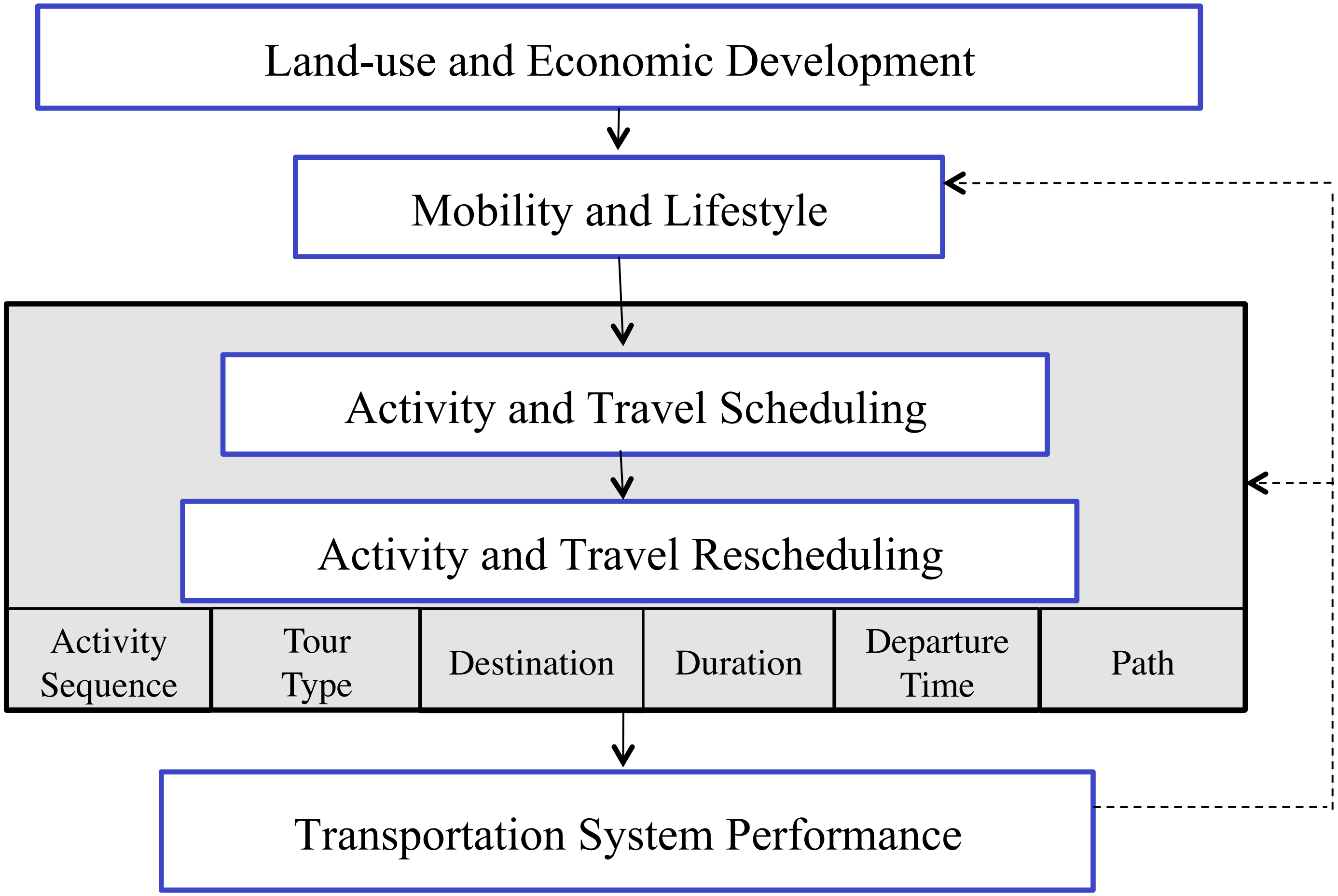
Representing activity/travel behavior



H: *Home* **W:** *Work* **S:** *Shop* **D:** *Dinner out*

Source: 1. Ben-Akiva, M. and Bowman, J. (1998), "Activity based travel demand model systems," in *Equilibrium and Advanced Transportation Modeling*, eds. P. Marcotte and S. Nguyen, Kluwer Academic Publishers.

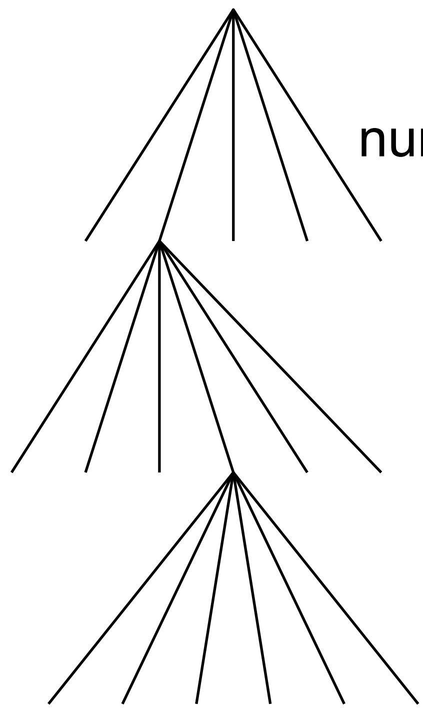
Activity based demand models



Source: 1. Ben-Akiva, M., Bowman, J. and Gopinath, D. (1996), "Travel demand model system for the information era," *Transportation*, vol. 23, pp. 241-266.

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

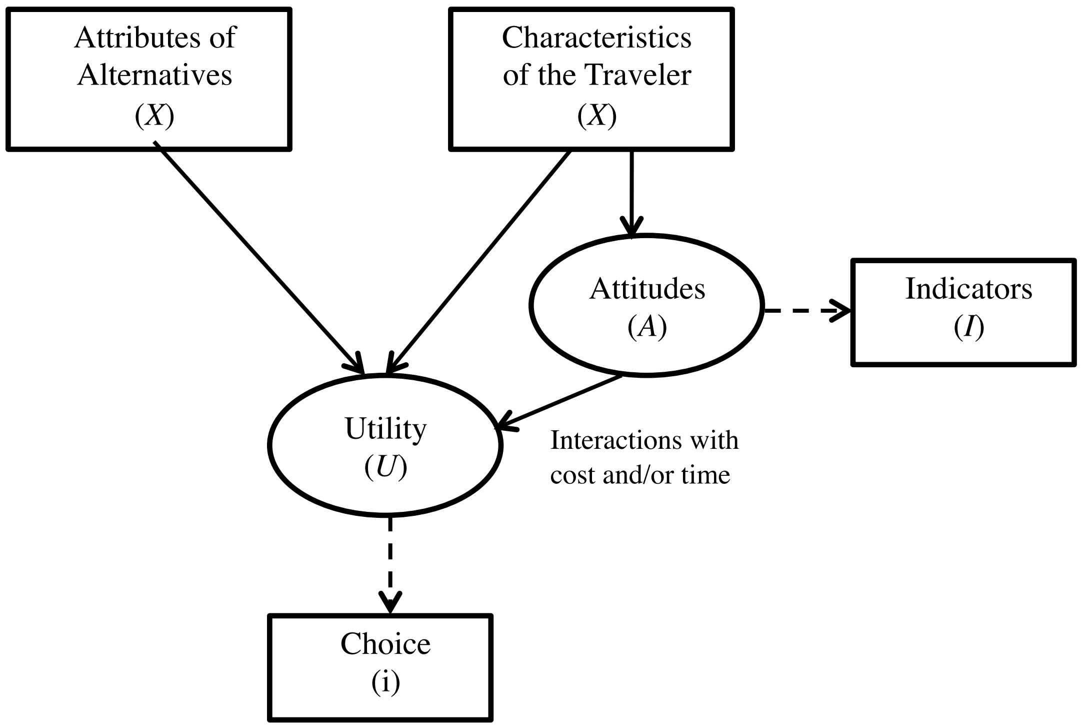
- Value of time (VOT) heterogeneity
- Value of reliability
- Choice of time-of-travel

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



VOT heterogeneity: Hybrid with attitudinal indicators (2)

- Model (Behavioral Mixture):

$$P(i \mid X) = \int_A P(i \mid X, A) f(A \mid X) dA$$

- Likelihood (choice & attitudinal Indicators):

$$f(i, I \mid X) = \int_A P(i \mid X, A) h(I \mid A) f(A \mid X) dA$$

VOT heterogeneity: Hybrid with attitudinal indicators (3)

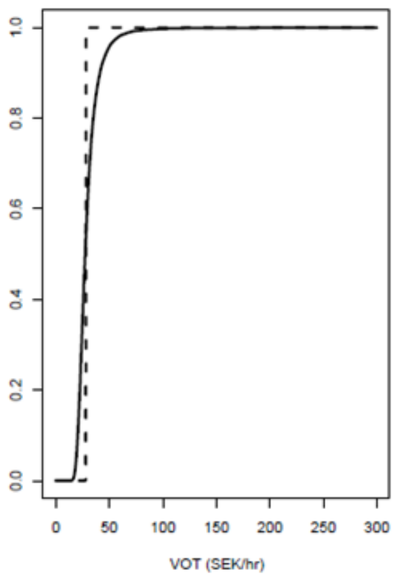
- 2005 survey in Stockholm, N= 2400
- Choice (SP): car vs public transportation
- Questions indicating car-loving attitude:
  - I_1: It is comfortable to go by car to work.
  - I_2: It feels safe to go by car
  - I_3: It is very important that traffic speed limits are not violated
  - I_4: Increase the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

Source: 1. Abou-Zeid, M., Ben-Akiva, M., Bierlaire, M., Choudhury, C. and Hess, S. (2010). "Attitudes and value of time heterogeneity" in *Applied Transport Economics: A Management and Policy Perspective*. eds. E. Van de Voorde, T. Vanelslander. Uitgeverij De Boeck nv, Antwerp, Belgium, pp. 523-545.

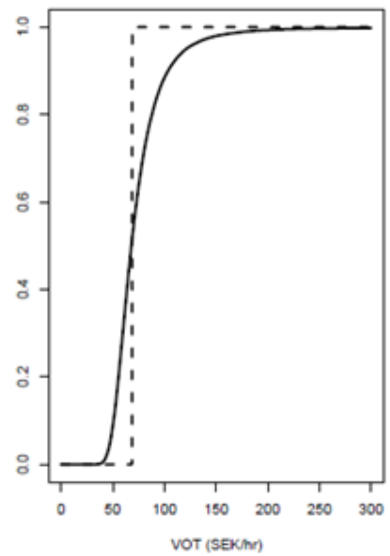
VOT heterogeneity: Hybrid with attitudinal indicators (4)

CDF of VOT by Income (SEK/hour) group

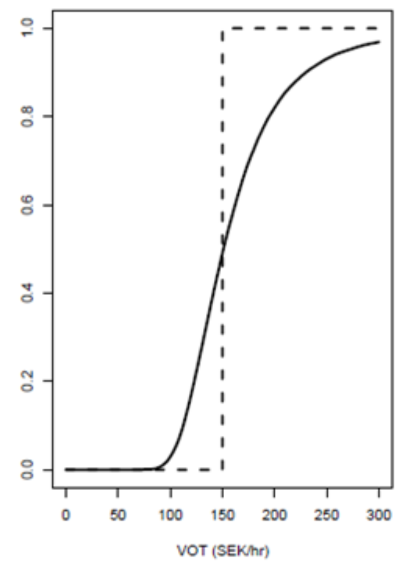
7,500 < Income < 15000



25,000 < Income < 30,000



Income >50,000



- - - - - Base model

———— Model with latent attitudes

Source: 1. Abou-Zeid, M., Ben-Akiva, M., Bierlaire, M., Choudhury, C. and Hess, S. (2010*)*. "Attitudes and value of time heterogeneity" in *Applied Transport Economics: A Management and Policy Perspective*. eds. E. Van de Voorde, T. Vanelslander. Uitgeverij De Boeck nv, Antwerp, Belgium, pp. 523-545.

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

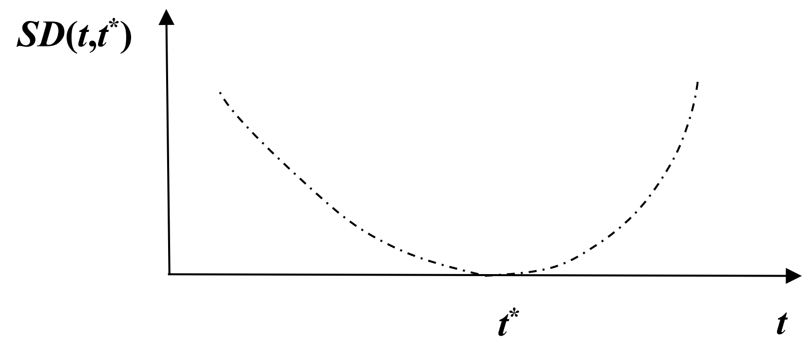
Time-of-travel choice: Motivation

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

$$\mathrm{V}(t) = \alpha(t) + \beta TT(t) + \gamma_{1\_early} SD_{early}(t,t^*) + \gamma_{1\_late} SD_{late}(t,t^*) + \cdots$$

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

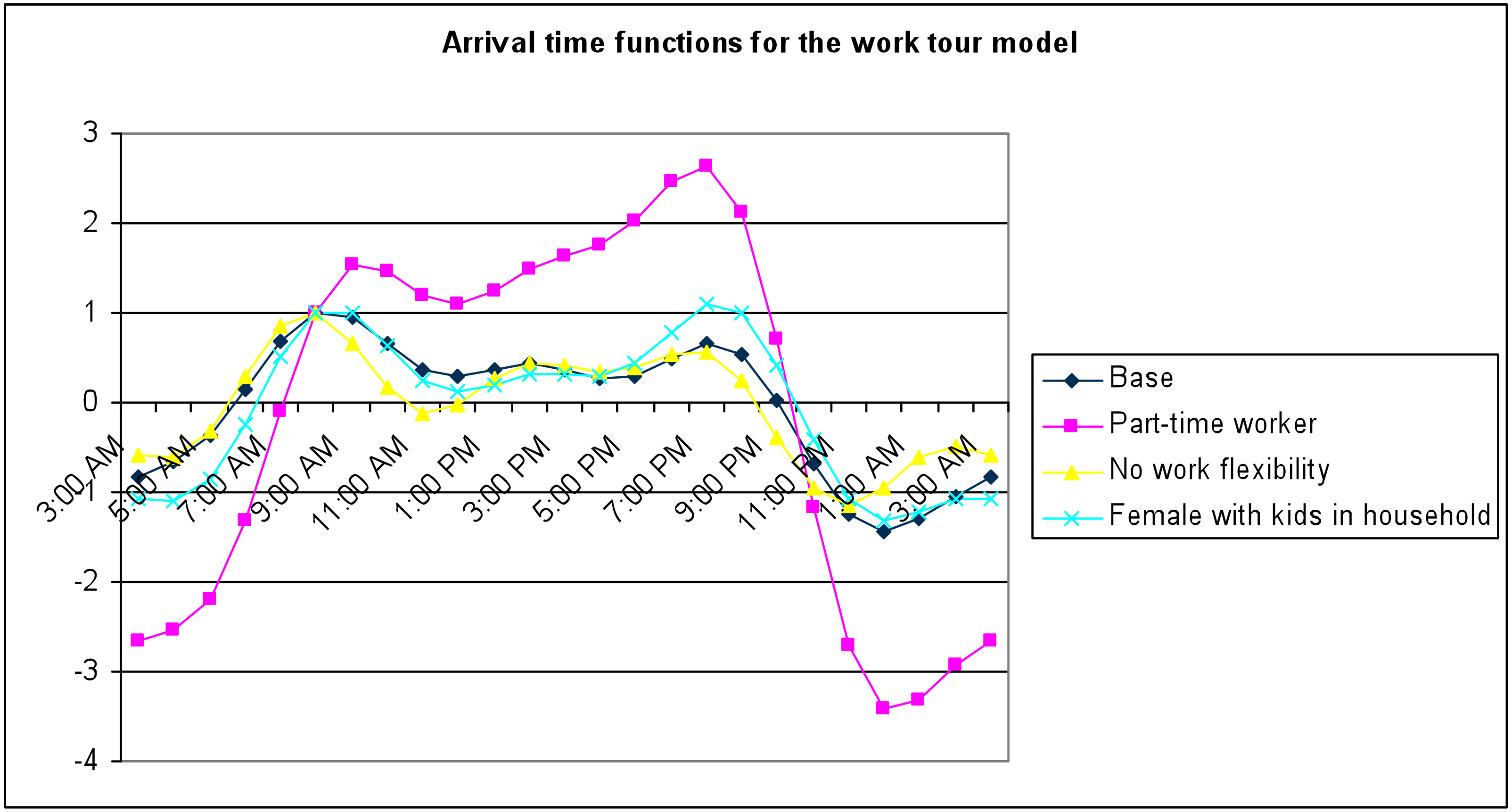
- Need cyclic functions: V(0) = V(24)

- Trigonometric Function - based on the idea of Fourier series

$$\mathrm{V}(t) = \beta_1 \sin\left(2\pi t/24\right) + \beta_2 \sin\left(4\pi t/24\right) + \cdots + \beta_K \sin\left(2K\pi t/24\right)$$
$$+ \gamma_1 \cos\left(2\pi t/24\right) + \gamma_2 \cos\left(4\pi t/24\right) + \cdots + \gamma_K \cos\left(2K\pi t/24\right)$$

- Truncation at *K* is determined empirically

Time-of-travel choice: Illustration of Trigonometric Function



Source: Ben-Akiva, M. and Abou-Zeid, M. (2007) "Methodological issues in modeling time-of-travel preferences", in *11th World Conference on Transport Research,* Berkeley, CA.

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)

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

Source: Ben-Akiva, M. and Watanatada, T. (1981) "Application of a continuous spatial choice logit model". in *Structural Analysis of Discrete Data with Economic Applications*. eds. C.F. Manski, D. McFadden, MIT Press, Cambridge, pp. 320-343

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

Source: Lemp, J., Kockelman, K. and Damien, P. (2010). "The continuous cross-nested logit model: Formulation and application for departure time choice", *Transportation Research Part B: Methodological* , vol. 44, no. 5, pp. 646-661.

Time-of-travel choice: CCNL (2)

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

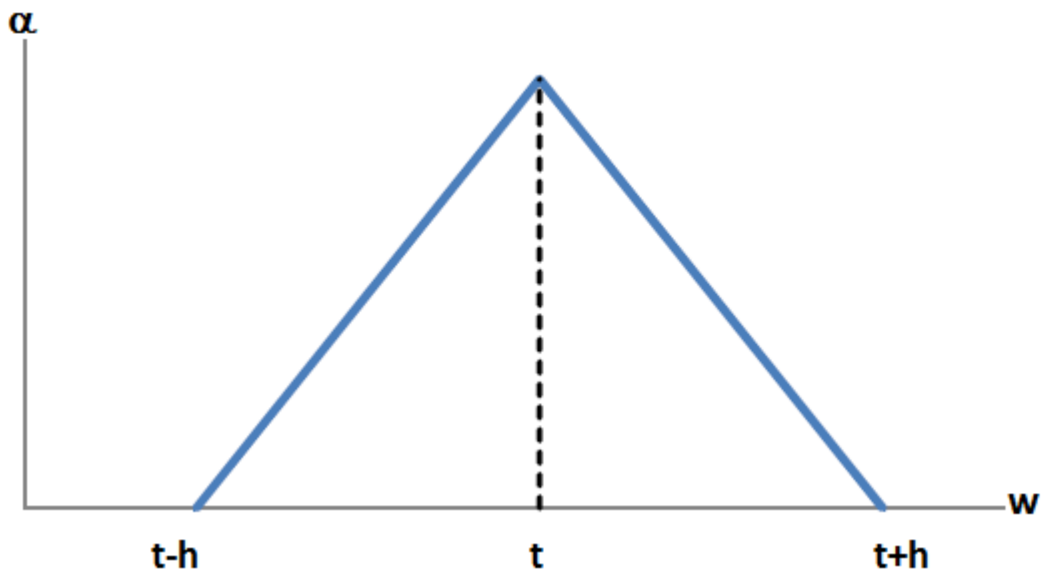
$$f(t)=\int_{b_1}^{b_2} \frac{[\alpha(t,w)\exp(V(t))]}{\int_{w-h}^{w+h}[\alpha(r,w)\exp(V(r))]\,dr} \times \frac{\left(\int_{w-h}^{w+h}[\alpha(r,w)\exp(V(r))]\,dr\right)^{\mu}}{\int_{b1}^{b2}\left(\int_{q-h}^{q+h}[\alpha(r,q)\exp(V(r))]\,dr\right)^{\mu} dq}\,dw$$

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

$\Longrightarrow$ Assumes similar correlation structure across the day

Source: Lemp, J. , Kockelman, K. and Damien, P. (2010). “The continuous cross-nested logit model: Formulation and application for departure time choice,” *Transportation Research Part B: Methodological* , vol. 44, no. 5, pp. 646-661.

Time-of-travel choice: CCNL (3)



$$\int_w \alpha(t,w)dw = 1$$

Source: Lemp, J. , Kockelman, K. and Damien, P. (2010). "The continuous cross-nested logit model: Formulation and application for departure time choice", *Transportation Research Part B: Methodological* , vol. 44, no. 5, pp. 646-661.

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

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

- v = value of time
- c_i = travel cost of alternative i
- t_i = travel time of alternative i
- X_i = vector of additional variables for alternative i
- Z_i = vector of additional variables for alternative i, whose coefficients vary proportionally to the time coefficient
- ε_i = additive error term
- μ = scale parameter
- β, γ = unknown parameters

Source: 1. Ben-Akiva, M., Bolduc, D. and Bradley, M. (1993), "Estimation of travel choice models with randomly distributed value of time," *Transportation Research Record*, vol. 1413, pp. 88-97.

VOT heterogeneity: Continuous logit mixture (2)

- Choice probability for a lognormal distribution of VOT

$$\ln \nu : N(\omega, \sigma^2)$$

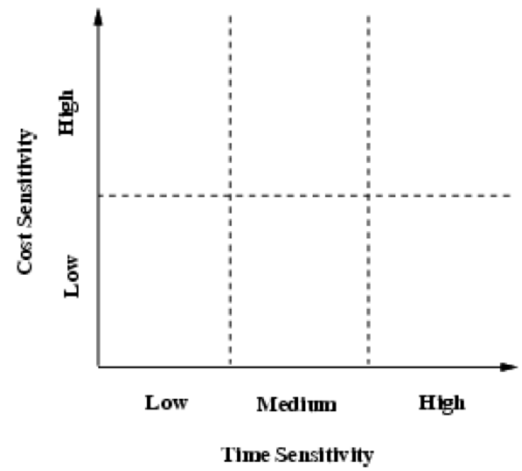
$$P(i) = \frac{1}{\sigma\sqrt{2\pi}} \times \int_0^\infty \frac{\exp\{\mu[c_i + \beta' Y_i + \nu(t_i + \gamma' Z_i)]\}}{\sum_{j=1}^{J} \exp\{\mu[c_j + \beta' Y_j + \nu(t_j + \gamma' Z_j)]\}} \times \frac{1}{\nu} \exp\left\{-\frac{1}{2}\left(\frac{\ln \nu - \omega}{\sigma}\right)^2\right\} d\nu$$

  – where $\mu, \beta, \gamma, \omega, \sigma$ are the parameters to be estimated simultaneously using maximum likelihood

Source: 1. Ben-Akiva, M., Bolduc, D. and Bradley, M. (1993), "Estimation of travel choice models with randomly distributed value of time," *Transportation Research Record*, vol. 1413, pp. 88-97.

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



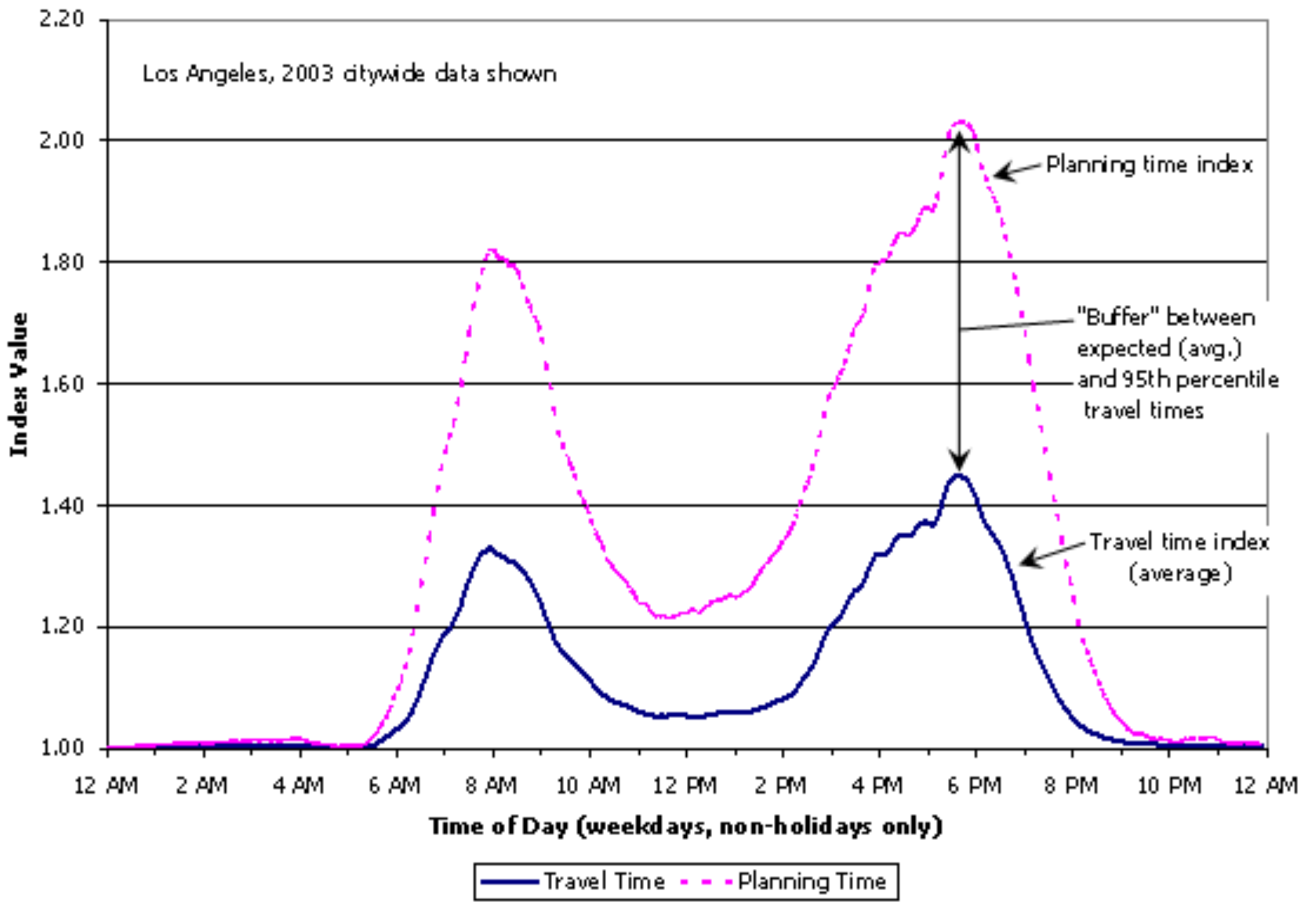
Source: 1. Gopinath, D. and Ben-Akiva, M. (1997), "Estimation of randomly distributed value of time," Working paper, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology

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
  - θ,β_s = vectors of unknown parameters

Source: 1. Gopinath, D. and Ben-Akiva, M. (1997), "Estimation of randomly distributed value of time," Working paper, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology.
2. Hess, S., Ben-Akiva, M., Gopinath, D. and Walker, J. (2009), "Advantages of latent class choice models over continuous mixed logit models," presented at the *12th International conference on travel behavior research*, Jaipur.

Travel time reliability: Motivation



Source: US DOT FHA, Travel Time Reliability, 2006, http://ops.fhwa.dot.gov/publications/tt_reliability/

Travel time reliability: Motivation (2)

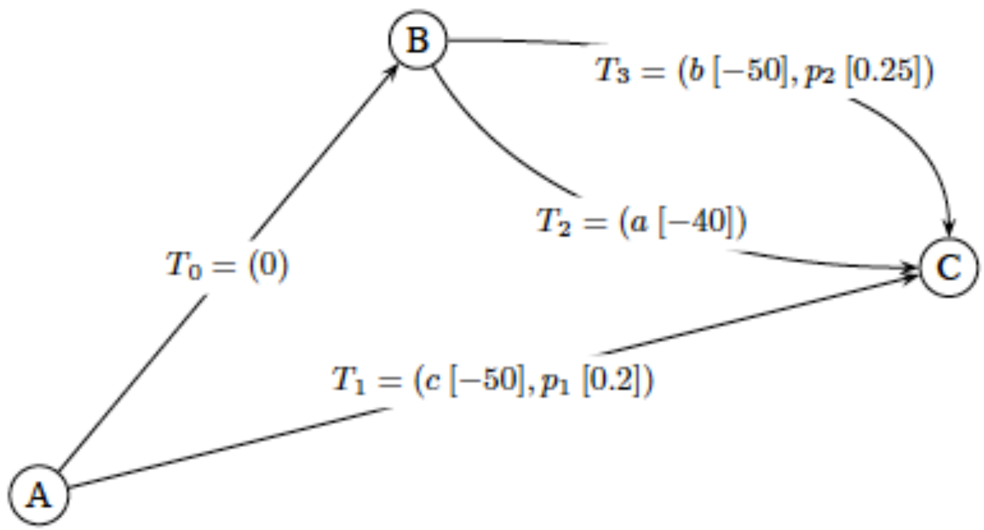
- Travel time reliability accounts for 5-35% of trunk road scheme economic benefits (SACTRA 1999)
- Scheduling delay accounts for 30-40% of total time cost (Ettema and Timmermans 2006)
- Ratio of reliability $\left(\hat{\beta}_{\sigma_{tt}} / \hat{\beta}_{E[tt]}\right)$ estimated to be > 1
  - Commuter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

Source: Li, Z., Hensher, D. and Rose, J. (2010). "Willingness to pay for travel time reliability in passenger transport: A review and some new empirical evidence". *Transportation Research Part E: Logistics and Transportation Review,* vol. 46, no. 3, pp. 384-403

Travel time reliability:

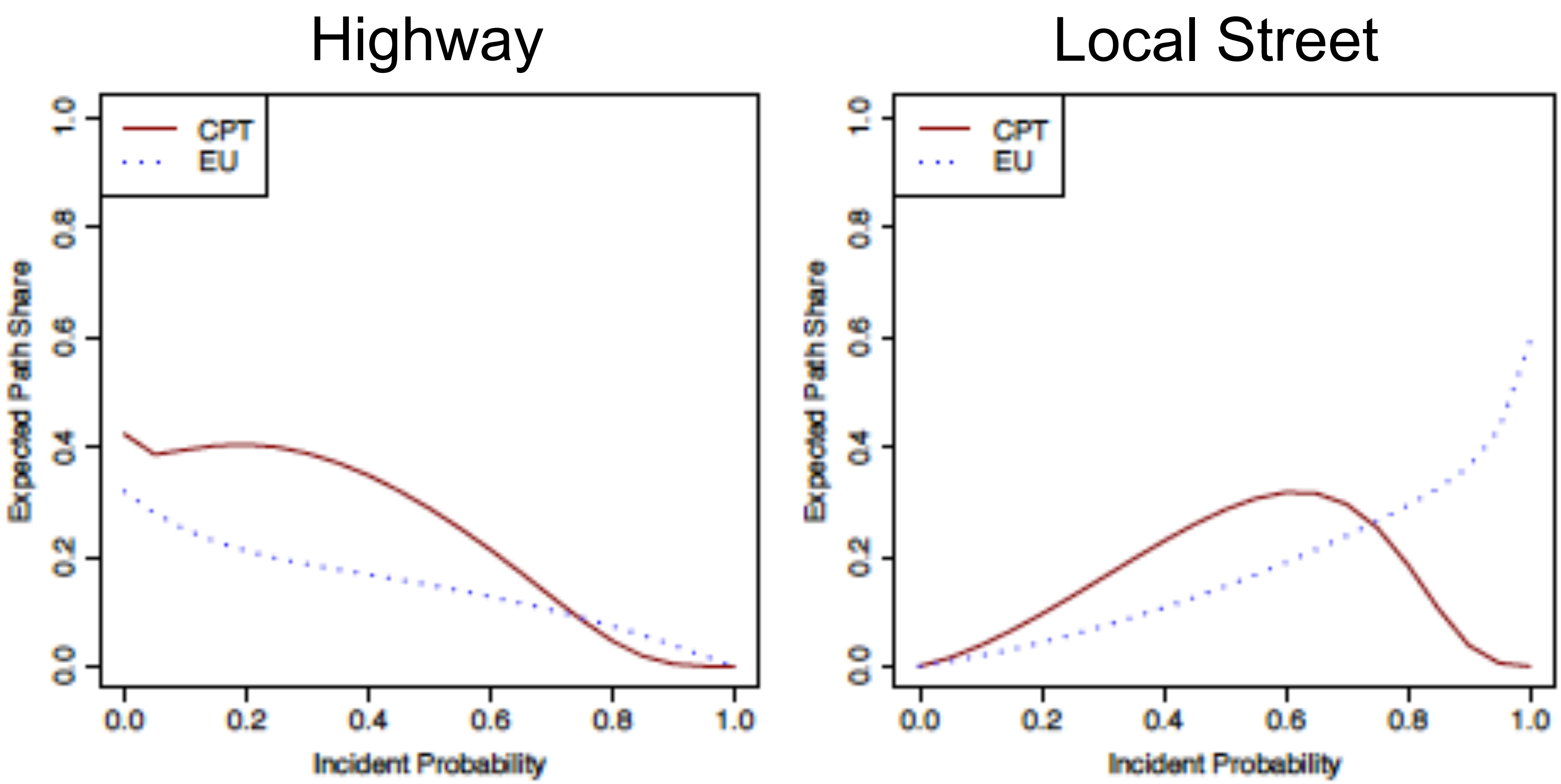
CPT vs. EU performance (Gao et al. 2010)

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



Source: Gao, S., Frejinger, E. and Ben-Akiva, M. (2010). "Adaptive route choices in risky traffic networks: A prospect theory approach". *Transportation Research Part C: Emerging Technologies* vol. 18, no. 5, pp. 727-740.

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



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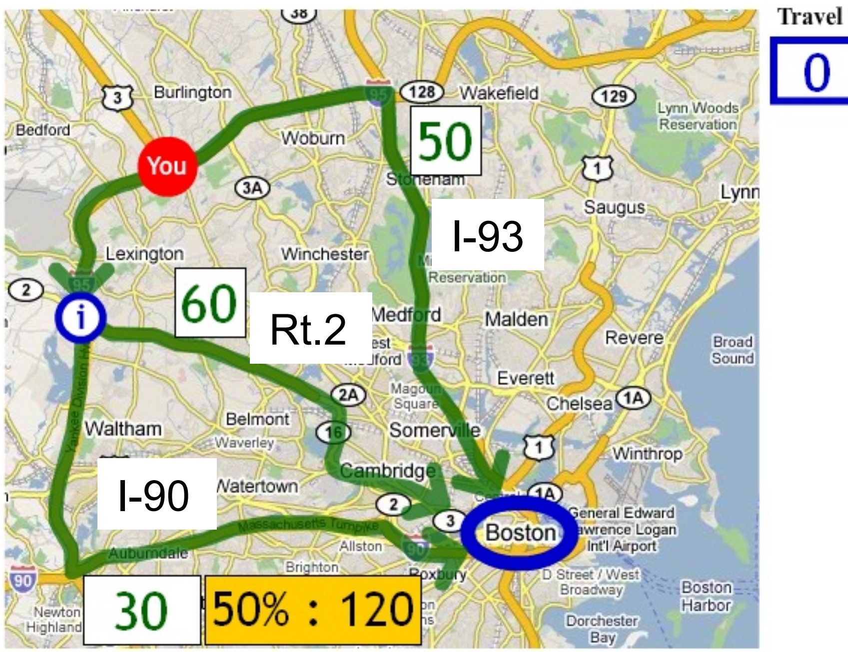
Travel time reliability:

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



Source: Razo, M. and Gao. S. (2010). A Rank-Dependent Expected Utility Model for Strategic Route Choice with Stated Preference Data: 1-27. http://www.ecs.umass.edu/~songgao/NewPaperv13.pdf.

Travel time reliability:

Latent-class Logit model (2)

- Latent-class logit mixture model form:

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

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

- Systematic utility of the risky branch (V_{risky}) in the strategy map
    - Large delay not included if strategic
    - Large delay included if non-strategic

Source: Razo, M. and Gao. S. (2010). A Rank-Dependent Expected Utility Model for Strategic Route Choice with Stated Preference Data: 1-27. http://www.ecs.umass.edu/~songgao/NewPaperv13.pdf.

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

Source: Razo, M. and Gao. S. (2010). A Rank-Dependent Expected Utility Model for Strategic Route Choice with Stated Preference Data: 1-27. http://www.ecs.umass.edu/~songgao/NewPaperv13.pdf.

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