

# Advanced Integrated Demand- Network Equilibrium Models: New Challenges and Implementation with Emme

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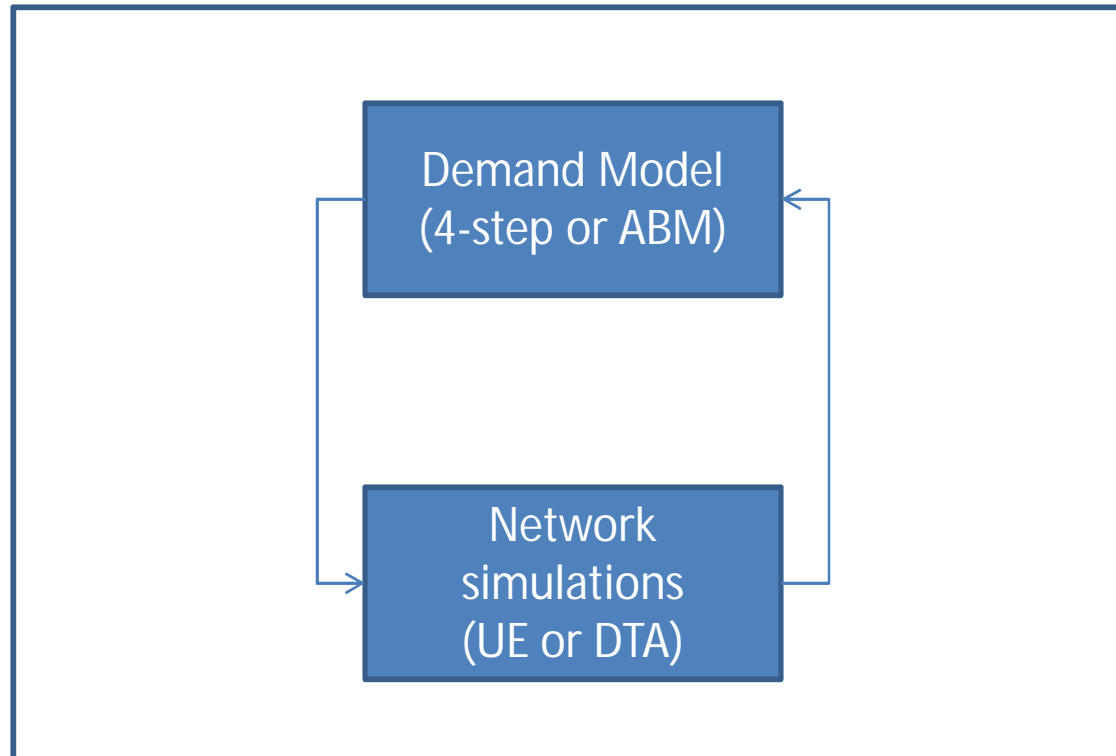
Parsons Brinckerhoff, New York, NY

# Proud Emme Macro-Writer

- Complete 4-step models implemented as nested macros:
  - Tel-Aviv, 1995
  - Jerusalem, 1997
  - Ottawa TRANS, 2007
- Advanced ABMs integrated with Emme network procedures:
  - Montreal, 2004
  - Chicago, 2011
  - Jerusalem, ongoing
- My favorite 😊:
  - %%%A%%rx%%%



# Integrated Regional Travel Model



From  
Stephen  
Hawking's  
"Grand  
Design"



"Putting a box around it, I'm afraid,  
does *not* make it a unified theory."

# 4 Major Options

Demand Model	UE	DTA
4-Step	1=Conventional well-explored	3=Usual for DTA in practice (demand is stretched)
ABM	2=Usual for ABM in practice (UE is stretched)	4=Most promising avenue (first attempts)

# 1. Conventional Integration Scheme – 4-Step with UE

Basic theory

Choice hierarchy

Consistent segmentation

# Fundamentals – Origins

$a$  =links,  $i$ =origins,  $j$ -destinations,  $r$ =routes

UE – Beckmann, 1956

$$\min_{\{x_{ijr}\}} \left\{ \sum_a \int_0^{v_a} c_a(w) dw \right\}$$

Subject to:

$$\sum_r x_{ijr} = d_{ij}$$

$$v_a = \sum_{ijr} \delta_{ar} x_{ijr}$$

$$x_{ijr} \geq 0$$

Solution:

$$x_{ijr} (c_{ijr} - \min_r c_{ijr}) = 0$$

Entropy max – Wilson, 1967

$$\max_{\{y_{ij}\}} \left\{ - \sum_{ij} y_{ij} \ln y_{ij} \right\}$$

Subject to:

$$\sum_j y_{ij} = P_i \quad \sum_i y_{ij} = A_j$$

$$\sum_{ij} c_{ij} y_{ij} = C$$

$$y_{ij} > 0$$

Solution:

$$y_{ij} = P_i \alpha_i A_j \beta_j \exp(-\theta c_{ij})$$

# Combined UE & Trip Distribution, Evans, 1976

$$\min_{\{x_{ijr}\}} \left\{ \sum_a \int_0^{v_a} c_a(w) dw + \frac{1}{\theta} \sum_{ij} y_{ij} \ln y_{ij} \right\}$$

Subject to:

$$\sum_r x_{ijr} = y_{ij}$$

$$\sum_j y_{ij} = P_i$$

$$v_a = \sum_{ijr} \delta_{ar} x_{ijr}$$

$$\sum_i y_{ij} = A_j$$

$$x_{ijr} \geq 0$$

Solution:

$$x_{ijr} (c_{ijr} - \min_r c_{ijr}) = 0$$

$$y_{ij} = P_i \alpha_i A_j \beta_j \exp(-\theta \min_r c_{ijr})$$

# Combined UE & Mode Choice, Florian et al, 1977

$$\min_{\{x_{ijmr}\}} \left\{ \sum_{am} \int_0^{v_{am}} c_{am}(w) dw + \frac{1}{\theta} \sum_{ijm} y_{ijm} (\ln y_{ijm} - \gamma_m) \right\}$$

Subject to:

$$\sum_r x_{ijmr} = y_{ijm}$$

$$\sum_m y_{ijm} = d_{ij}$$

$$v_{am} = \sum_{ijr} \delta_{amr} x_{ijmr}$$

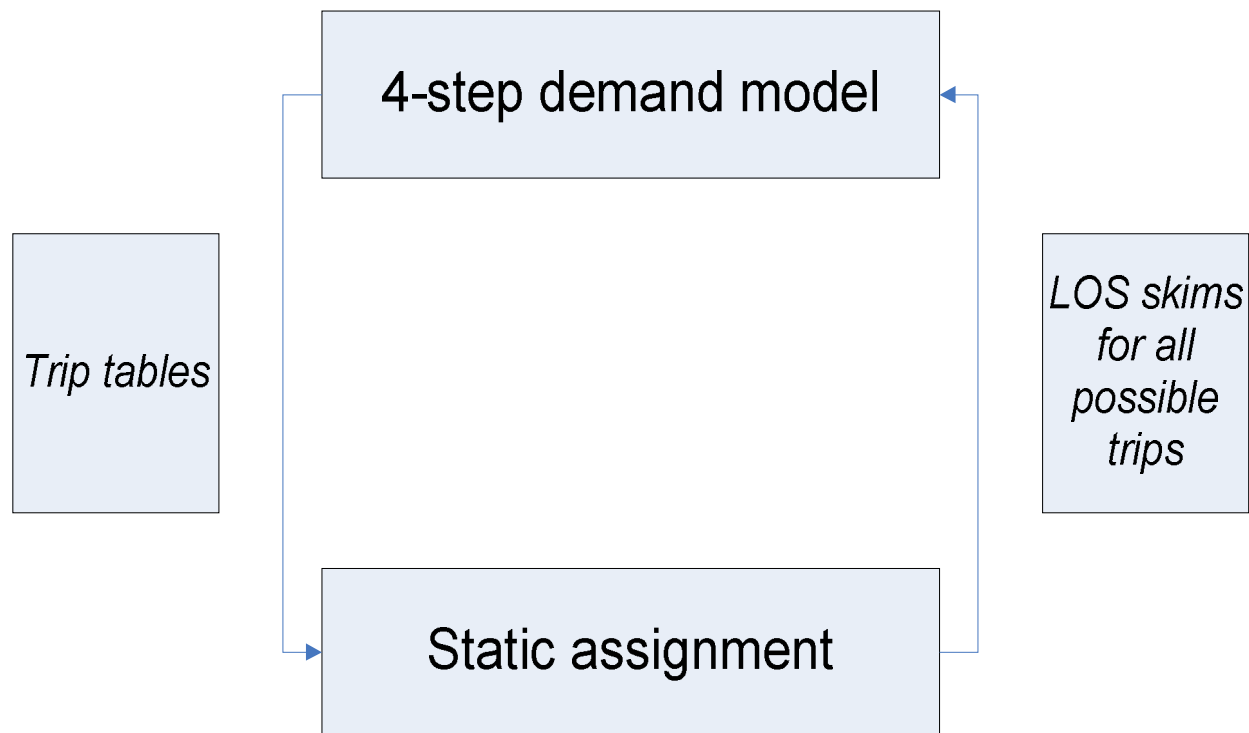
$$x_{ijmr} \geq 0$$

Solution:

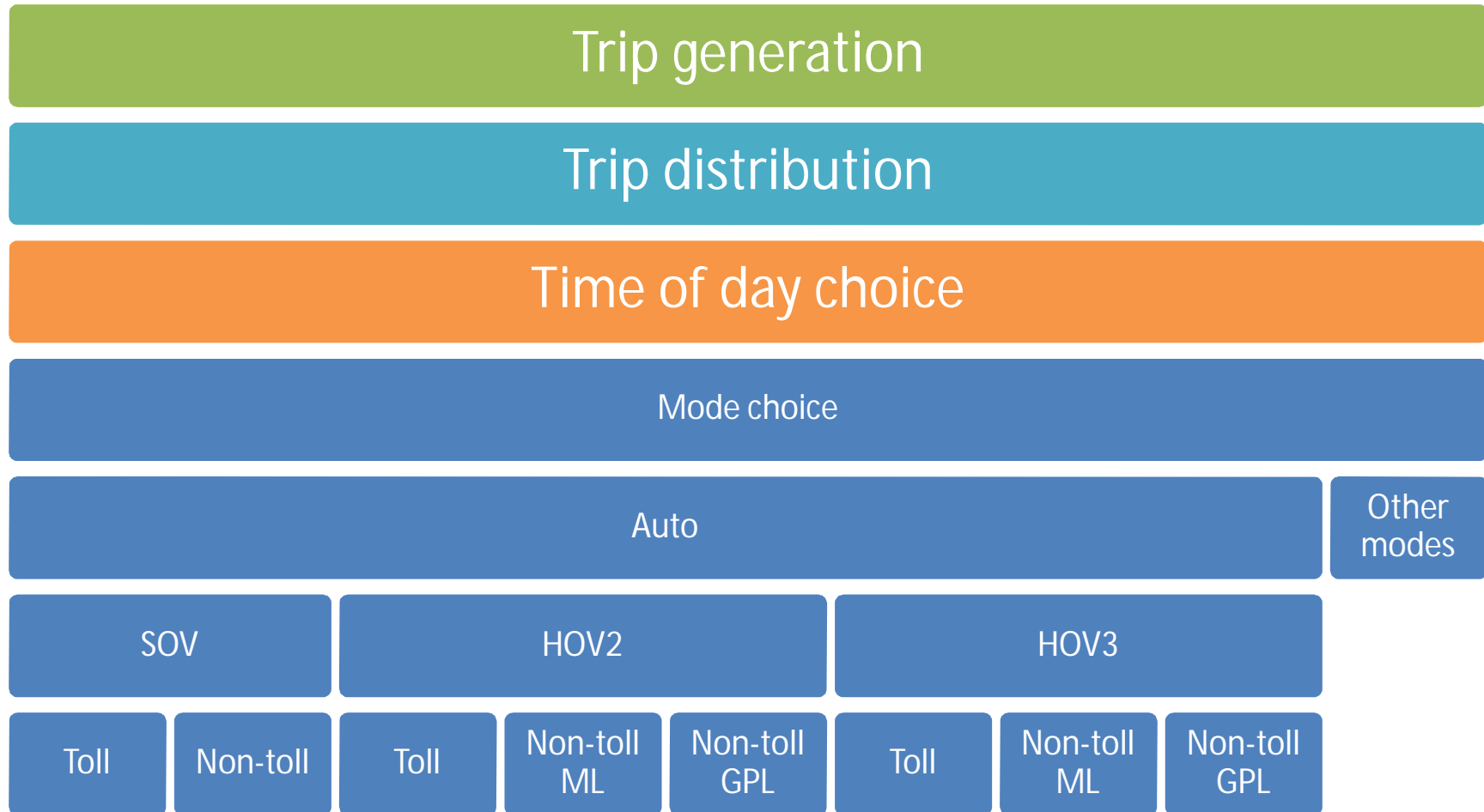
$$x_{ijmr} (c_{ijmr} - \min_r c_{ijmr}) = 0$$

$$y_{ijm} = d_{ij} \frac{\exp(\gamma_m - \theta \min_r c_{ijmr})}{\sum_n \exp(\gamma_n - \theta \min_r c_{ijnr})}$$

# Actual Implementation



# Extended Hierarchy of Travel Choices



# Route Type Choice

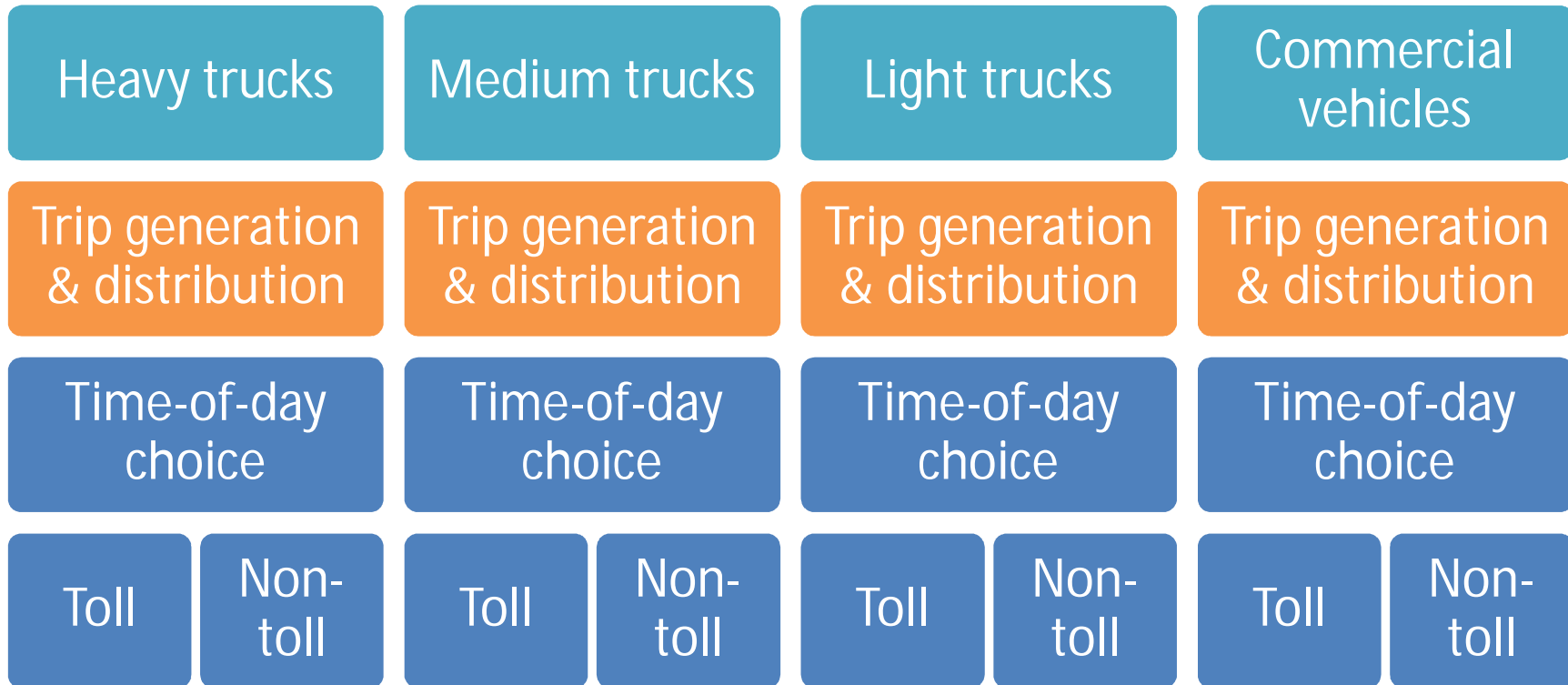
- Overcomes AON nature of UE that manifests itself strongly in uncongested conditions
- Explicit modeling and analysis of toll and ML users at OD level
- Accounts for (negative) toll bias beyond time and cost trade-off
- Allows for VOT variation / segmentation beyond 12 assignable classes

# Typical Demand Segmentation

Dimensions	Trip generation	Trip distribution	Time of day choice	Mode choice	Route choice / assignment
	Aggregate or disaggregate	Aggregate OD matrix structure			
Purpose	X	X	X	X	VOT
Income	X	X	X	X	VOT
Car ownership	X	X	X	X	
Any other	X	?	?	?	VOT?
Car occupancy				Choice alternative	X

# Freight Choices

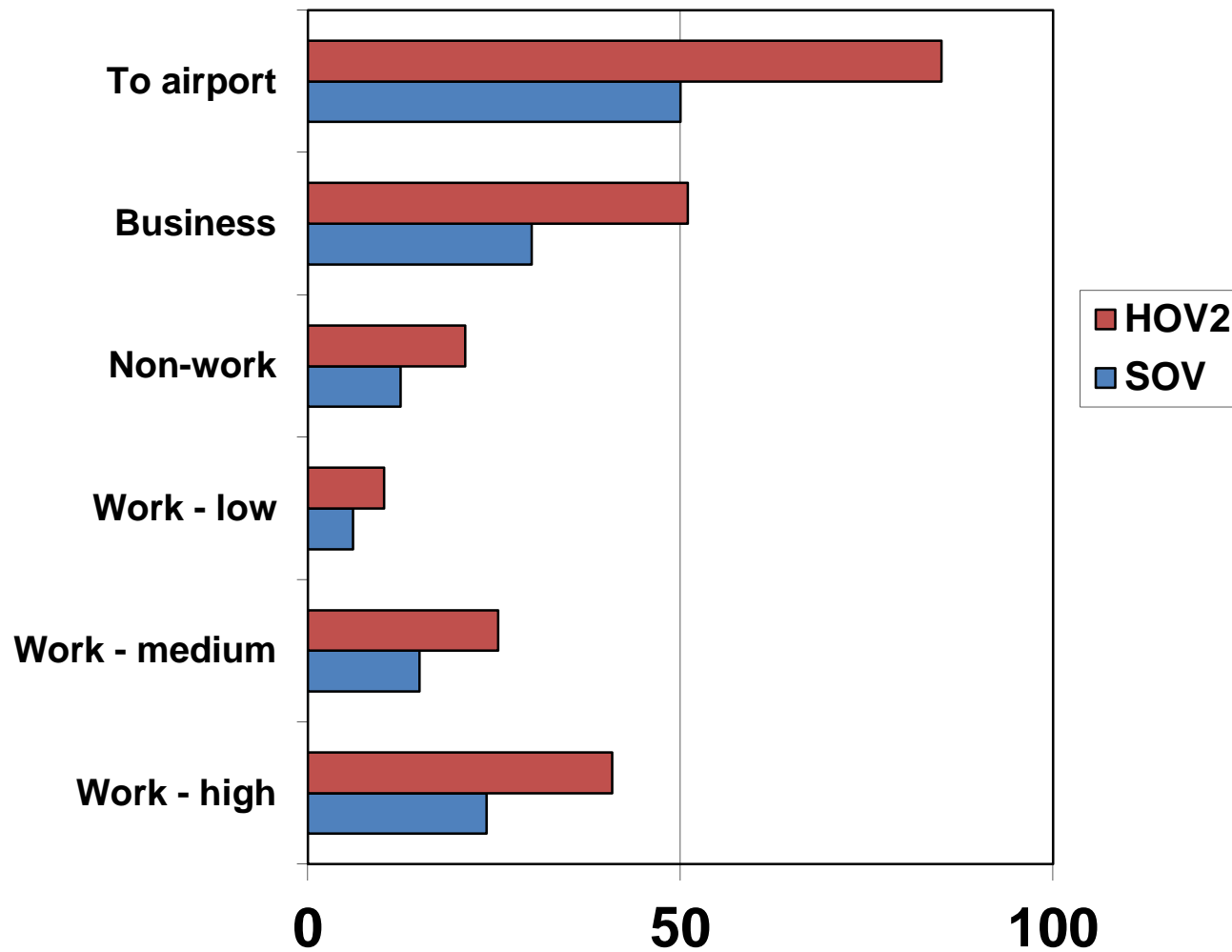
## Commodity flow



# Reasons for Multi-Class Assignment

<b>Class</b>	<b>Prohibitions</b>	<b>Differential tolls</b>	<b>Differential VOT</b>
SOV	X	X	X
HOV2	X	X	X
HOV3+		X	X
Commercial	X	X	X
Light truck	X	X	X
Medium truck	X	X	X
Heavy truck	X	X	X
Travel purpose			X
Income			X
Other			X

# Typical VOT, \$/h



# Inevitable Compromise

- Core demand model has multiple travel and population segments
- Multiple segments are aggregated into feasible number of classes for assignment
- VOT is averaged within each class:
  - Aggregation bias in network simulation and
  - Discrepancy between demand model and network simulation

# Conclusions on Integration of 4-Step and UE

- What do modelers want?
  - Large regional networks w/high level of spatial resolution (4,000-5,000 zones and even more)
  - Numerous travel and population segments for better representation of behavior (purpose, income, gender, etc)
- Probably a dead end:
  - Both 4-step and UE are inherently limited
  - Integration is hampered by incompatible segmentation

## 2. Advanced ABM integrated with UE

What is different from 4-step?  
Equilibration with microsimulation  
Segmentation issues

# What is Different with ABM?

- Complicated chains of choices with structural changes in the list of agents instead of predetermined matrix of choices pertinent to 4-step
- Entropy-maximizing formulation for demand terms is theoretically possible but impractical because of dimensionality
- Microsimulation of crisp choices instead of fractional probabilities

# Theoretical Formulation

$$\min \left\{ \sum_p \sum_a \int_0^{v_{pa}} c_a(v) dv + \mu \sum_n \sum_\theta p_{n\theta} \ln \frac{p_{n\theta}}{U_{n\theta}} \right\}$$

Link volumes

Route flows

$$v_{pa} = \mathcal{G}(f_{pr}^{od})$$

Trip table

Individual schedules

$$M_p^{od} = \sum_r f_{pr}^{od} = \psi(\{p_{n\theta}\})$$

# Practical Methods: Enforcement & Averaging

- Simple feeding back LOS variables does not ensure convergence
- 2 ways to ensure convergence by iterating:
  - Enforcement to ensure replication of “crisp” individual choices:
    - Theoretical foundation
    - Empirical strategies
  - Averaging:
    - Continuous LOS variables (skims)
    - Link volumes (before skimming)
    - Trip tables

# Enforcement Methods

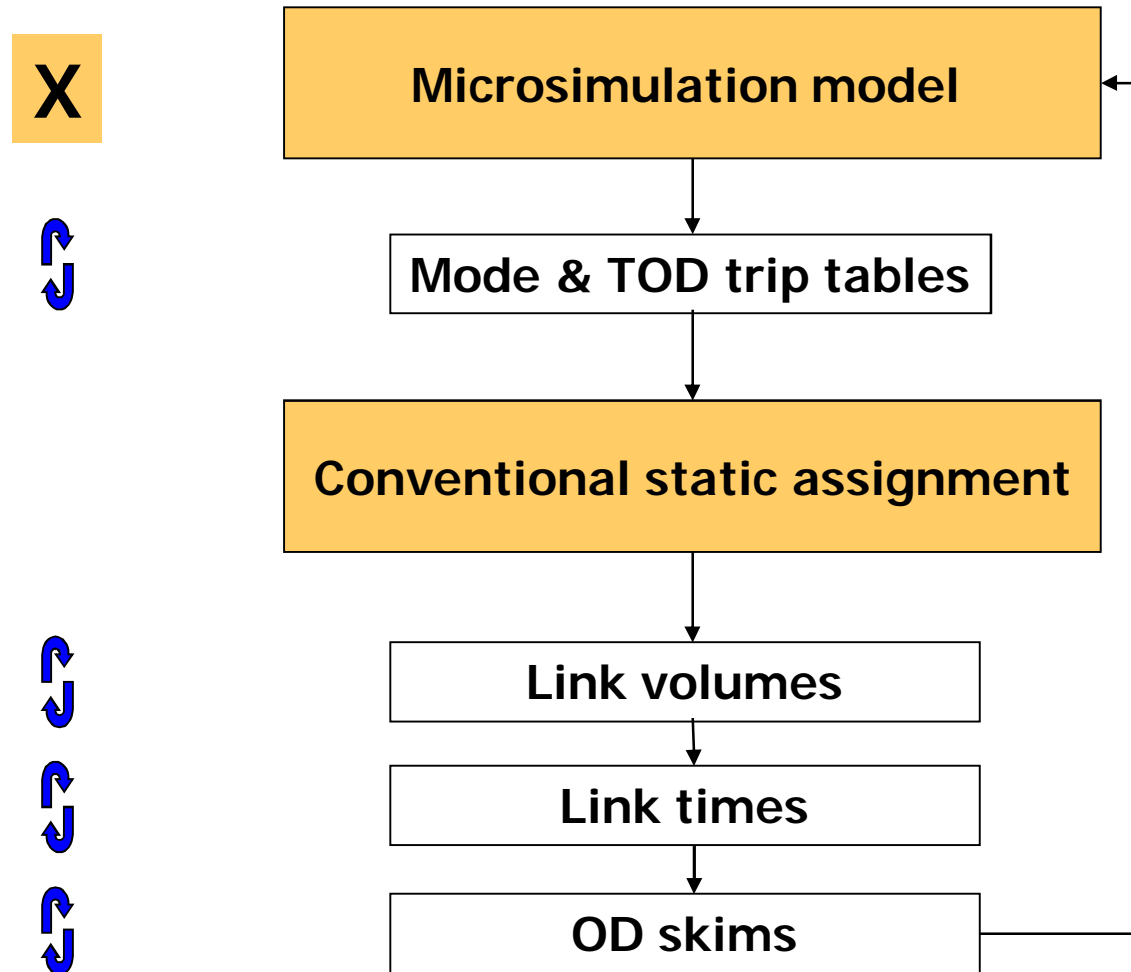
- Re-using same random numbers / seeds:
  - Each household / person has a fixed seed
  - Structural stability of decision chains by reserving choice placeholders
- Gradual freezing of travel choices:
  - Subsets of households
  - Travel dimensions
- Analytical discretizing of probability matrices:
  - Avoiding Monte-Carlo (no random numbers!)

# Stable Structure

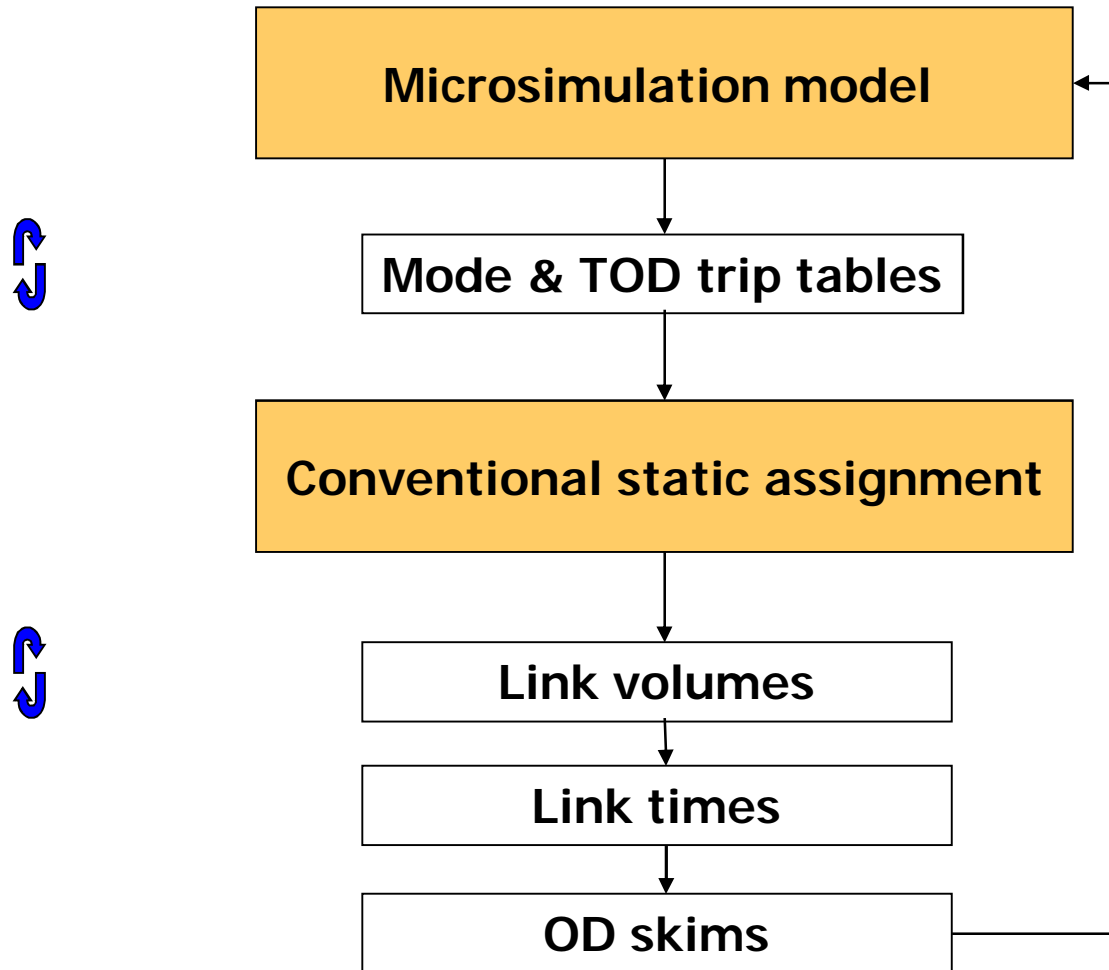
Same list of agents	Same random sequence	Same choices with convergent probabilities			
		Mode 1	Mode 2	Mode 3	Mode 4
Tour 1	0.7543267	0.5354	0.5540	0.7374	<b>1.0000</b>
Tour 2	0.2635498	<b>0.6623</b>	0.8632	0.8944	1.0000
Tour 3	0.1135645	<b>0.2231</b>	0.5678	0.6633	1.0000
Tour 4	0.9797613	0.8988	0.8989	<b>0.9800</b>	1.0000

**With the same list of agents facing the same choices, using the same random numbers with convergent probabilities will ensure convergence of the individual choices**

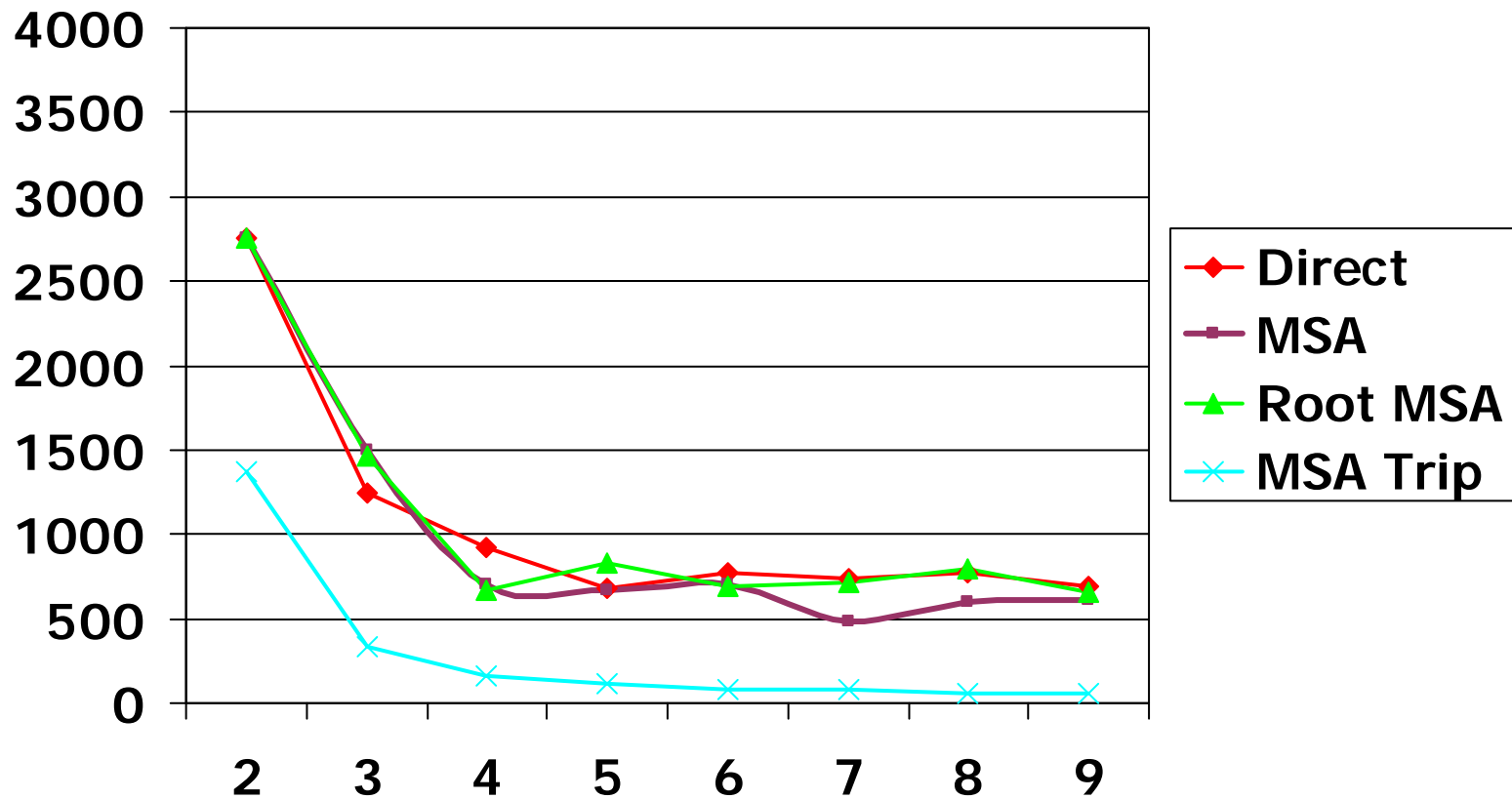
# Averaging Methods



# Most Effective



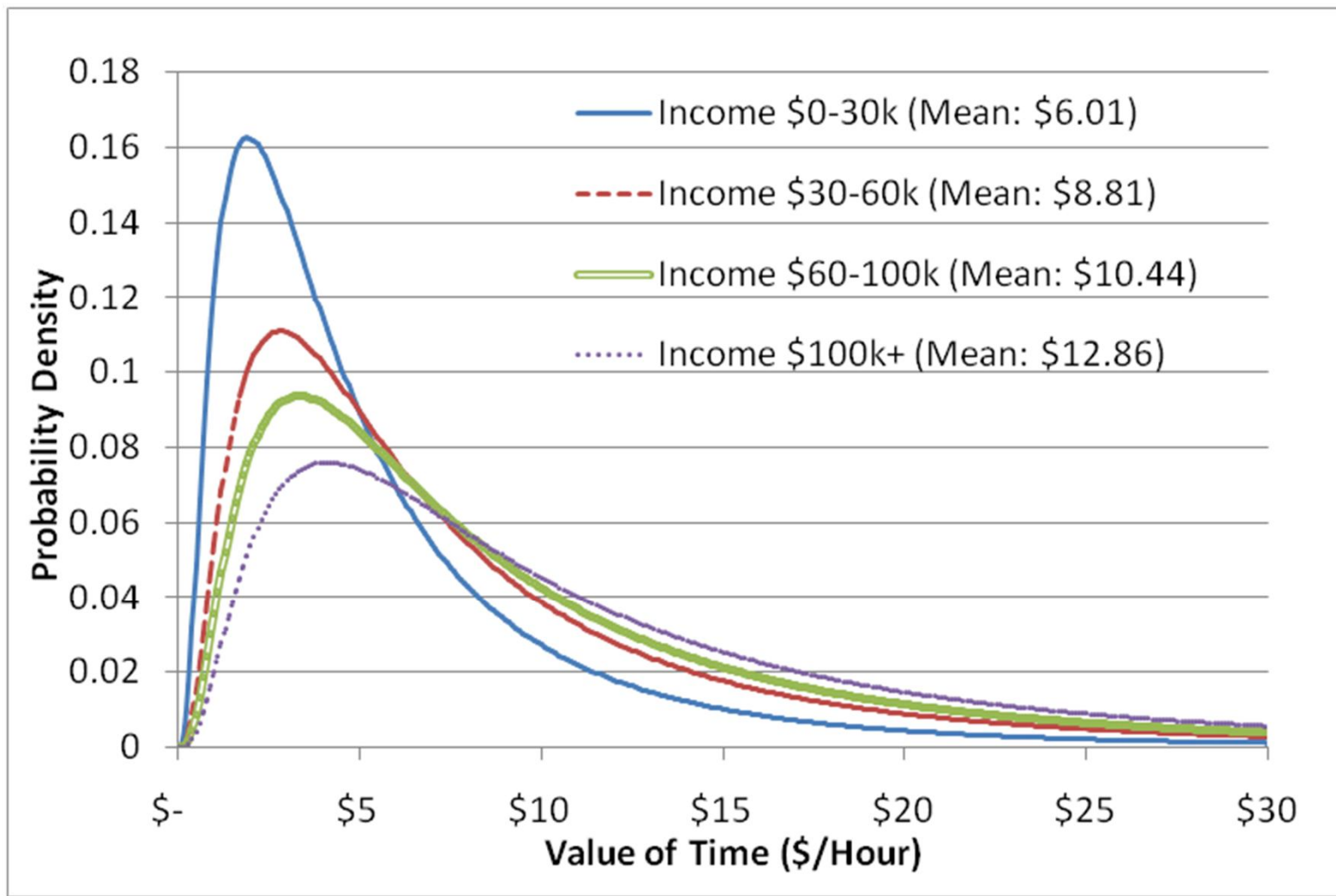
# NY ABM: RMSE for AM Highway Trip Table (29×29)



# New Challenge – Continuously Distributed VOT: Chicago Pricing ABM

- Basic VOT estimated for each travel purpose and person type
- Situational variation of VOT applied for each person based on lognormal distribution – essential for pricing studies
- Car occupancy accounted by cost sharing:
  - VOT for HOV2 is 1.6 of highest participant VOT
  - VOT for HOV3+ is 2.3 of highest participant VOT
- For static assignments VOT has to be aggregated across individuals into discrete vehicle classes

# Example of VOT Distribution



# Resulted Classes for Assignment

Vehicle type & VOT	Non-toll SOV	Non-toll HOV2	Non-toll HOV3+	Toll SOV	Toll HOV2	Toll HOV3+
Auto low	1	3	5	2	4	6
Auto high	7	9	11	8	10	12
Commercial	13			14		
Light truck	15			16		
Medium truck	17			18		
Heavy truck	19			20		
External low	21	23	25	22	24	26
External high	27	29	31	28	30	32
Airport low	33	35	37	34	36	38
Airport high	39	41	43	40	42	44

# Emme Implementation Constraints

- Currently multi-class-assignment is limited to 12 classes (will be extended soon to 30)
  - It will be beneficial to consider more than 2 VOT classes, for example (Low, Medium, High)
- Possible implementation scheme:
  - Pre-assign heavy and (possibly) medium trucks since they follow planned routes (4 classes)
  - Assign the rest of classes with heavy and medium trucks preloaded

# Conclusions on Integration of ABM and UE

- Theoretical elegance is lost due to complex chains of choices and microsimulation
- Effective & efficient practical strategy:
  - MSA of link volumes and
  - MSA on trip tables
- Enforcement can be applied effectively
- Segmentation incompatibility is exacerbated due to continuous VOT and other individual variables of ABM

# 3. 4-Step Integrated with DTA

Incompatible temporal resolution

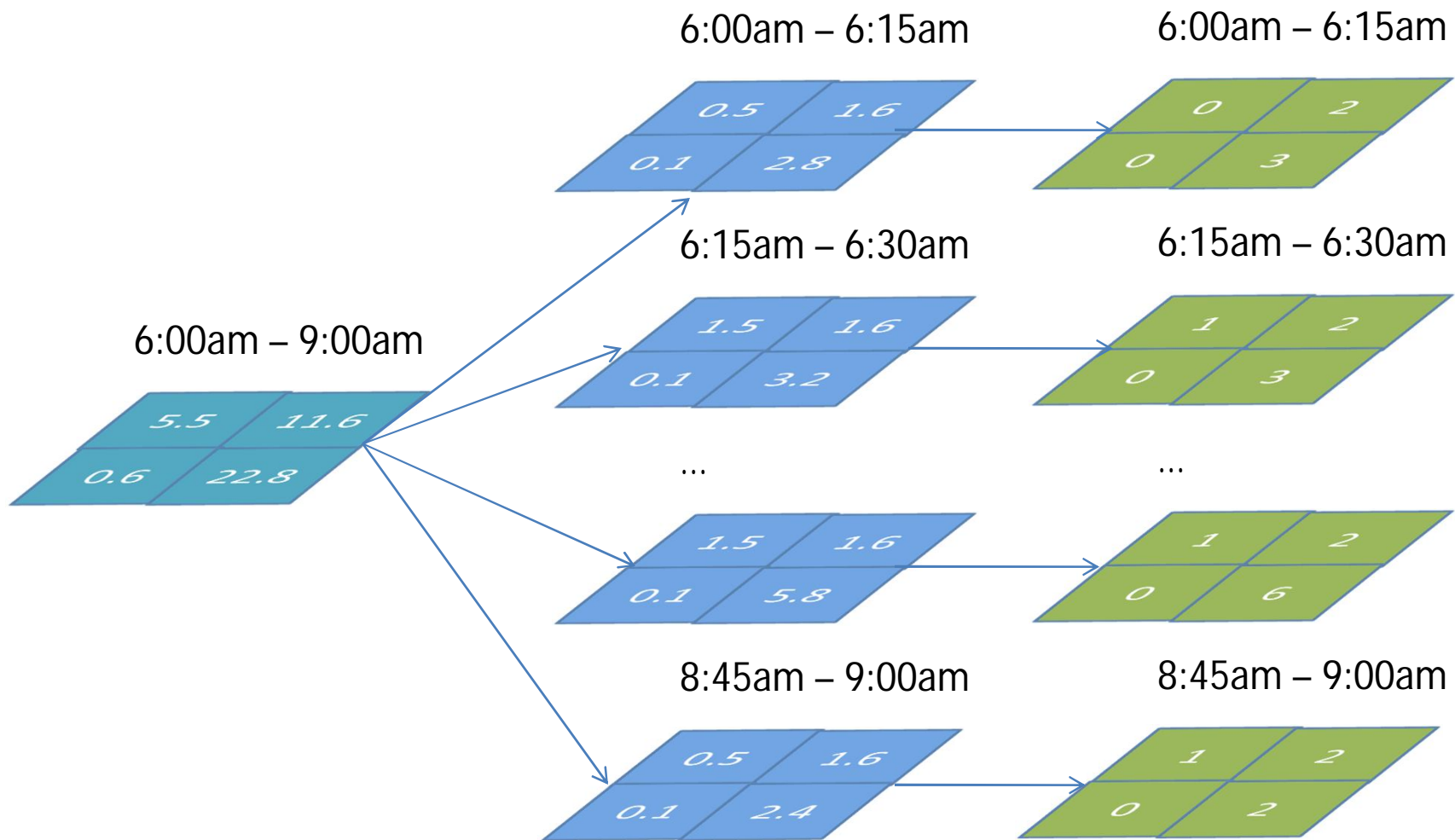
Adjustment of trip tables

Conceptual problem of integration

# Incompatible Temporal Resolution

- 4-step operates with broad time-of-day periods and fractional trips
- DTA requires finer demand slices (15 min) and discrete trips
- Split factors are applied (developed from household survey or traffic counts) with subsequent rounding up the number of trips

# Slicing & Integerizing Trip Tables



# “Massaging” Trip Tables

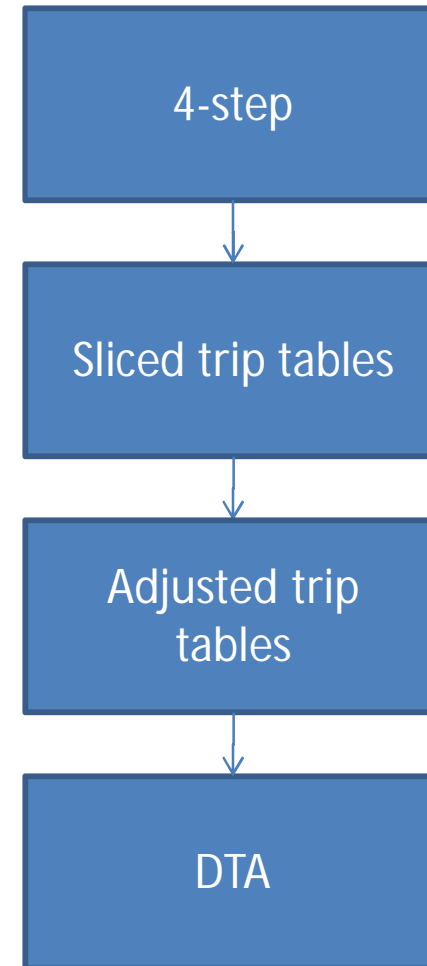
- Trip tables from 4-step model after slicing and integerizing do not replicate traffic counts with fine temporal resolution
- Matrix adjustment is common practice to match link & turn counts
- Static & dynamic matrix adjustment algorithms are improving

# Matrix Adjustment Methods

- Start with seed matrix (daily, period-specific, hour-specific)
- Define targets to match and closeness function:
  - Link & turn counts (total or by vehicle class; daily, period-specific, hourly)
- Define structural preservation criteria:
  - Preserve trip distribution (daily, period, hour)
    - TAZ-to-TAZ
    - District-to-district
  - Preserve marginals (daily, period, hour)
  - Preserve TLD (daily, period, hour)
- Form optimization program and find a solution (or step towards optimum)
- Equilibrate optimization with assignment

# Limited Value of Trip Table Adjustment

- This is a short term solution for certain projects (highway operations) when demand can be considered fixed
- Problematic for long-term planning studies:
  - How adjustments could be carried over to future?
  - Replace demand model with simple trip table factoring?
  - Feedback?



# Equilibration is Essential for Long-Term Studies

- Future demand growth can exceed highway capacity:
  - UE allows for  $V/C > 1$
  - DTA with unrealistic demand would not work
- Equilibration can solve this problem:
  - Only if elastic trip generation and time-of-day choice models are applied (problematic with 4-step)
  - trip distribution and mode choice may not be enough

# Conclusions on Integration of 4-Step and DTA

- DTA is used as complementary tool for certain studies most frequently short-term
- 4-step is equilibrated with UE and then trip tables are additionally adjusted for DTA
- No promising avenue for 4-step & DTA integration and equilibration:
  - Inherent limitations of 4-step with respect to fine temporal resolution and time-of-day choice
  - Feedback from DTA to 4-step is not clear

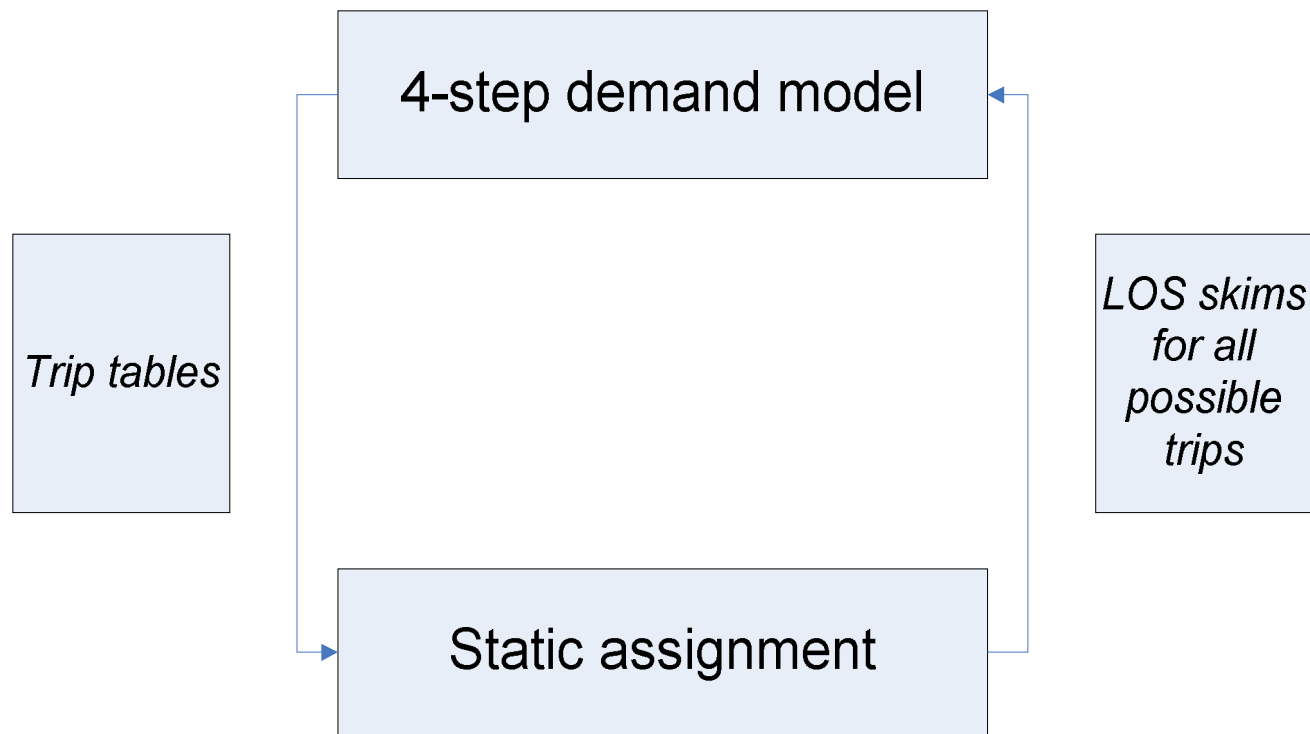
# 4. ABM integrated with DTA

Conceptual problem with LOS feedback

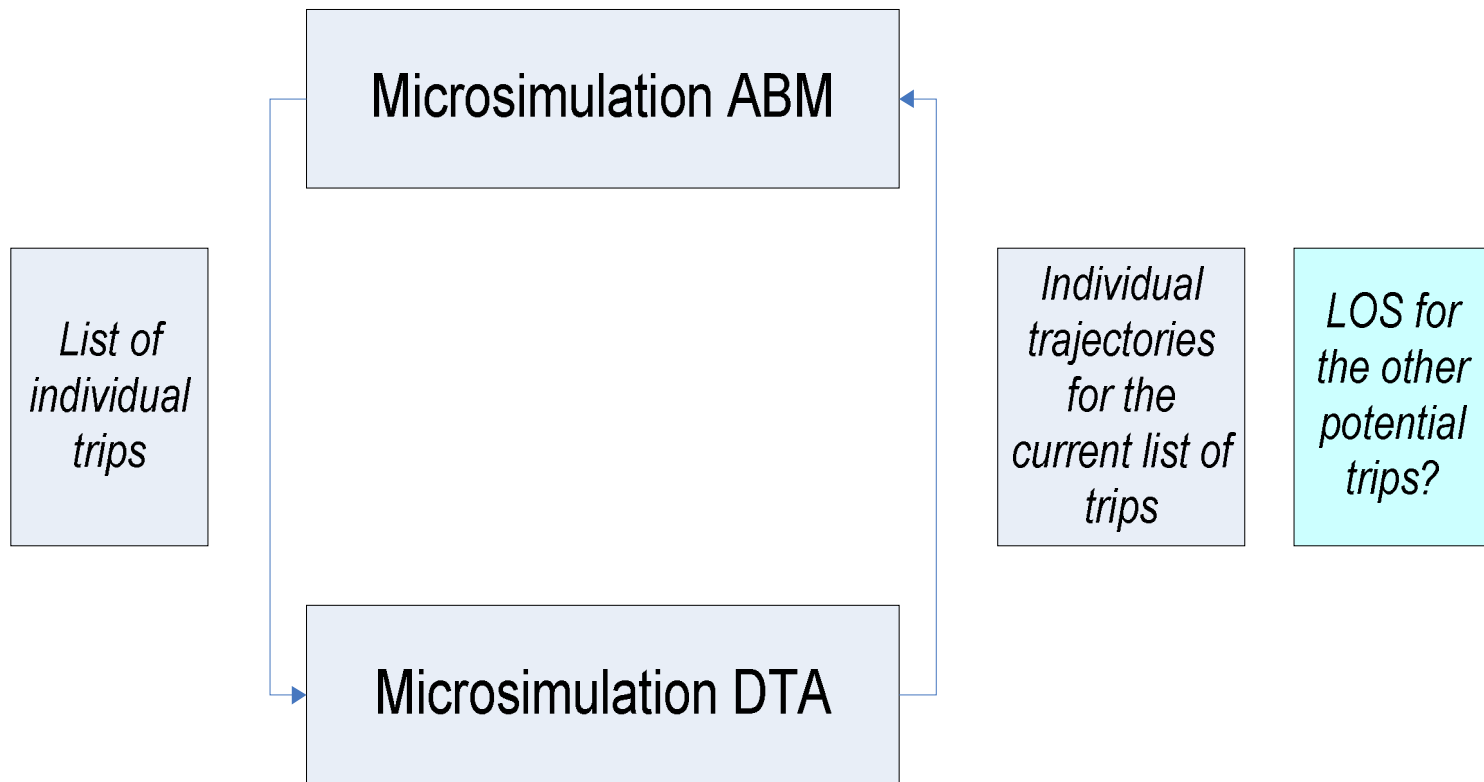
Individual schedule consistency

Temporal equilibrium

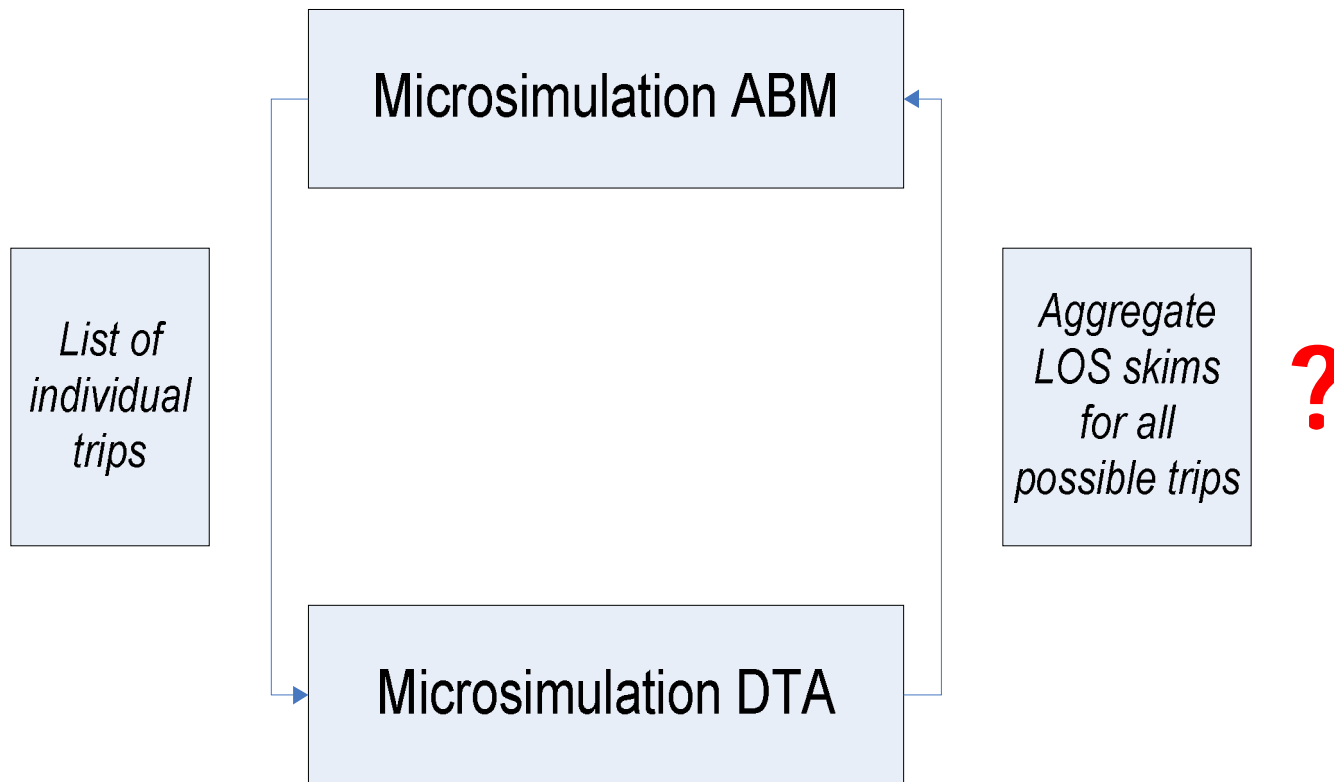
# Conventional Integration Scheme Reminder



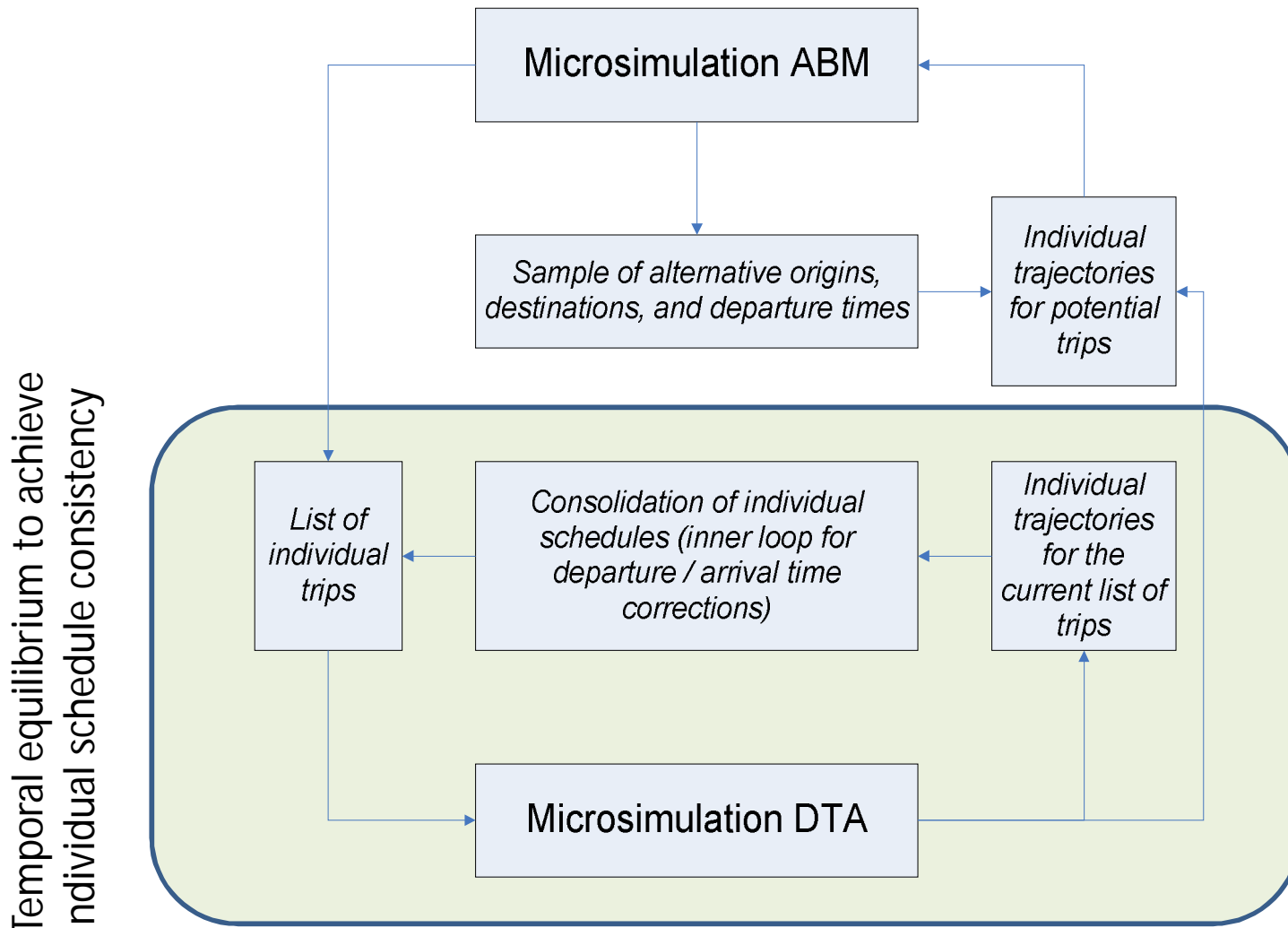
# Integration Issue DTA-to-ABM



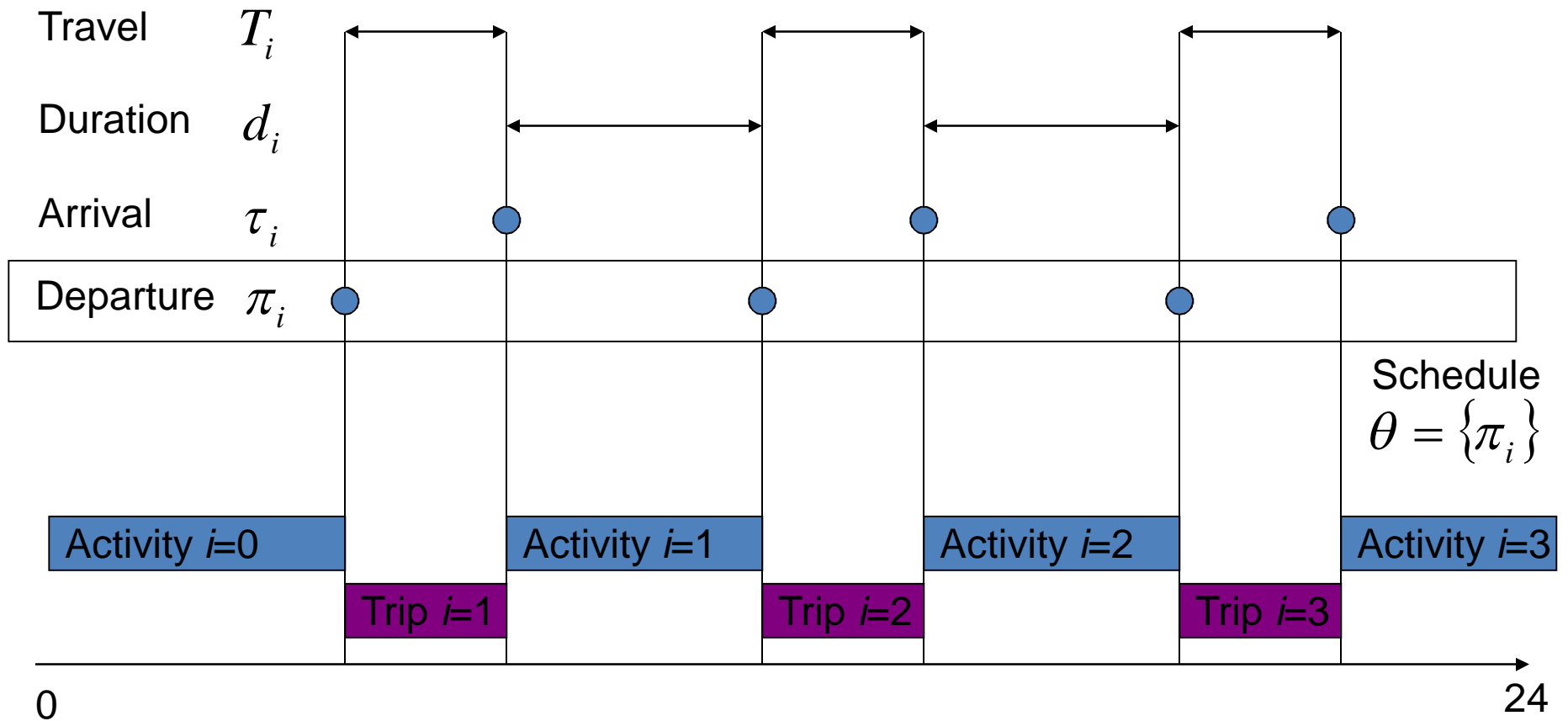
# Possible Surrogate



# Suggested 2-Level Approach



# Schedule Consistency



# Schedule Adjustment

Find new schedule close to previous durations and departures

$$\min \left\{ \sum_i \left( x_i \ln \frac{x_i}{d_i} + y_i \ln \frac{y_i}{\pi_i} \right) \right\}$$

New durations (points to  $x_i$ )  
New departures (points to  $y_i$ )  
Previous durations (points to  $d_i$ )  
Previous departures (points to  $\pi_i$ )

Daily consistency

$$\sum_i (x_i + t_i) = 24$$

Departure time

$$y_i = \sum_{j \leq i} (x_j + t_j)$$

Changed travel times

Solution

$$x_i = k \times d_i \times \prod_{j \geq 1} \frac{\pi_j}{y_j}$$

# Pre-Sampling of Trip Destinations

- Primary destinations are pre-sampled:
  - 300 out of 30,000 for each origin and travel segment,
  - 30 out of 300 for each individual and travel segment
- Stop locations are pre-sampled:
  - 300 out of 30,000 for each OD pair and travel segment
  - 30 out of 300 for each individual and travel segment
- Importance sampling w/o replacement from expanded set of destinations  $300 \times 30,000$  and  $30 \times 300$  to ensure uniform unbiased samples
- Efficient accumulation of individual trajectories in microsimulation process

# LOS Variables for Outer Loop

- Individual trajectories by departure time period for the same driver (personal learning experience), if not:
  - Individual trajectories by departure time period across individuals (what driver can hear from other people through social networks), if not:
    - Aggregate OD skims by departure time period (advice from navigation system)

# Conclusions on Integration of ABM and DTA

- ABM-DTA integration is the most promising avenue
- Recommended to start developing both components pivoting off 4-step and UE
- For small metropolitan areas under 1 million ABM-DTA integration is already realistic
- For large metropolitan areas ABM still has to be integrated with UE; partial implementation of DTA (subarea, specific time-of-day) is possible

# Thank you for your attention!