Integrating Dynamic Traffic Assignment and Activity-Based Demand Models for Large Scale Network Applications

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OUTLINE

1. Motivation and Key Issues
2. Reliability, Pricing and User Heterogeneity in Dynamic Equilibrium Framework
   - Challenges
   - Formulation and Algorithms
   - Large-Scale Issues
3. Application to New York Regional Network
4. Concluding Remarks
• Why do we need integrated dynamic network models?
• Why capture behavior?
• Responses to congestion, interventions (pricing, information, management actions…) three key objectives:
  MOBILITY, RELIABILITY, SUSTAINABILITY
• Support strategic and operational planning decisions by agencies
• Next generation of interventions: information-based, personalized, dynamic, predictive, multimodal
DELIVERING THE METHODS: SIX KEY CHALLENGES

- ADVANCED BEHAVIOR MODELS
- HETEROGENEOUS USERS
- INTEGRATION WITH NETWORK MODELS: THE PLATFORM—SIMULATION-BASED MICRO-ASSIGNMENT DTA
- GENERATE THE ATTRIBUTES: RELIABILITY IN NETWORK LEVEL OF SERVICE
- CONSISTENCY BETWEEN BEHAVIOR (DEMAND) AND PHYSICS (SUPPLY): EQUILIBRATION
- PRACTICAL LARGE NETWORK APPLICATION: INTELLIGENT IMPLEMENTATION
User Behavior and Heterogeneity
Choice Frameworks

Upper-level models of activity generation

Tour primary destination & intermediate stops

Main mode: auto, transit, non-motorized

Detailed mode & occupancy

Tour TOD combination of departure and arrival times

Trip departure time within 2-3 hour window

Auto route type: toll vs. free

Source: Peter Vovsha (2010); SHRP2-C04
Travel Time Reliability

• Travel time reliability is manifested in that a trip maker may be willing to pay a premium (toll) to achieve greater reliability in travel time.
Individual’s Path Choice Decision
User Heterogeneity

• Recognize user heterogeneity in the path choice model
  ➢ Conventional traffic assignment models consider a **homogeneous perception** of tolls by assuming a **constant VOT** in the path choice model.
  ➢ Empirical studies (e.g. Hensher, 2001; Brownstone and Small 2005; Cirillo et al. 2006) found that **the VOT varies significantly across individuals.**
User Heterogeneity

• Present in valuation of key attributes, and risk attitudes
  – Value of schedule delay (early vs. late, relative to preferred arrival time), critical in departure time choice decisions.
  – Value of reliability.
  – Risk attitudes.

Causes significant challenge in integrating behavioral models in network simulation/assignment platforms
Integration Issues
DEMAND

SUPPLY

INTEGRATE

? 

INTERFACE
DEMAND

SUPPLY

INTEGRATE

JUXTAPOSE
DEMAND

SUPPLY

INTEGRATE?
THE KEY IS THE PLATFORM: SIMULATION-BASED DTA

DIS INTEGRATING DEMAND AND SUPPLY

CRITICAL LINK 1: LOADING INDIVIDUAL ACTIVITY CHAINS

CRITICAL LINK 2: MODELING AND ASSIGNING HETEROGENEOUS USERS

CRITICAL LINK 3: Multi-scale modeling: consistency between temporal scales for different processes
• Simulation-based DTA, e.g. DYNASMART-P: A dynamic network modeling capability, to represent demand and supply dynamics, along with operational measures

• Overcomes limitations of conventional planning tools, and provides combined network assignment and traffic simulation capability for large networks, with micro-level representation of agent decisions

• Meso simulation enables application to practical large networks
1. Ignore: route choice main dimension captured; replace travel time by travel cost in shortest path code, assuming constant VOT.

2. When multiple response classes recognized, discrete classes with specific coefficient values are used; number of classes can increase rapidly; not too common in practice.

2. Recent developments with simulation-based DTA:

   *Heterogeneous users with continuous coefficient values; made possible by Breakthrough in parametric approach to bi-criterion shortest path calculation.*

   *Include departure time and mode, in addition to route choice, in user responses, in stochastic equilibrium framework*

   *Efficient implementation structures for large networks: Application of integrated model to New York Regional Network.*
• Multi-criterion Stochastic Dynamic User Equilibrium (MSDUE) model, which integrates:
  ➢ Traffic Flow Dynamics;
  ➢ Heterogeneous Users
  ➢ Three essential decision attributes: travel time, out-of-pocket cost, and travel time reliability in path choice framework
  ➢ Higher-level mode choice and activity timing dimensions

• Applicable to transportation networks of practical size.
Model Challenges

• **Reliability Measure in path choice framework** → increase complexity of the path finding/calculation procedure

• **Heterogeneous Users** in terms of continuously distributed VOT and/or VOR → create an infinite-dimensional problem

• **Large-Scale Network Applications** → impose computational burdens on the solution algorithm
Divide and Conquer I: Generate Reliability Measures

• Foundation: a robust relation between s.d. and mean values of the TT per unit distance at path level.

• In this study:

\[ TTSD_{\tau,m} = a + b \times \frac{TT_{\tau,m}}{TD_{\tau,m}} \]

➢ Future improvements: actual observations of vehicle trajectories

• Generally, any relation relying on path-level attributes, could be incorporated in the procedure followed.

*based on Herman, Mahmassani and co-workers’ research*
Travel Time Reliability

• Model: standard deviation vs. mean

\[(t) = a + b \times E(t)\]

where

- \(t\) = travel time per unit distance
- \(\sigma(t)\) = standard deviation of \(t\)
- \(E(t)\) = mean value of \(t\)
- \(a, b\) = coefficients

• Model calibration
  - GPS probe data
  - Vehicle trajectory data output from simulation

*based on Herman, Mahmassani and co-workers’ research in ‘80’s*

*Hou, Mahmassani and Dong (2012)*
GPS probe data analysis

- GPS data from Traffic Choice Study at Puget Sound area (Seattle)
- Data from July 2005 to March 2007 (~18 months)
- 275 households, 415 vehicles involved
- Network size:
  - ~3000 OD pairs
  - ~1700 paths
  - ~6000 links
GPS probe data analysis

OD level

Path level

Link level

$y = 1.0665x - 1.6728$
$R^2 = 0.577$

$y = 0.7323x - 1.1286$
$R^2 = 0.3861$

$y = 0.9936x - 0.4736$
$R^2 = 0.6675$
Robust Relation

- Models are calibrated for different sizes of networks at different aggregation levels
- Three model forms are tested
  - Linear model
  - Square root model
  - Quadratic model
- Linear model gives best results
- Model parameters are estimated by Weighted Least Square (WLS) to accommodate heteroscedasticity

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<th>Network</th>
<th>Irvine</th>
<th>CHART</th>
<th>New York City</th>
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<td>Number of Zones</td>
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<td>Demand Duration (hr)</td>
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<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
Network-Level SD vs. Mean of Trip Time per Mile

(a) Irvine

(b) Baltimore-Washington

(c) New York
Path-Level SD vs. Mean of Trip Time per Mile

Irvine

Baltimore-Washington

New York
Model Challenges

• **Reliability Measure in path choice framework** → increase complexity of the path finding/calculation procedure

• **Heterogeneous Users** in terms of continuously distributed VOT and/or VOR → create an infinite-dimensional problem

• **Large-Scale Network Applications** → impose computational burdens on the solution algorithm
Divide and Conquer II: Solve for Random Coefficients (VOR and VOT)

Parametric Analysis Method (PAM)\(^1\)

- Solves multi-objective shortest path problems with random variables.
- Outputs: Segments of random variables on the run instead of given a priori and time-dependent shortest path trees.

\(^1\)Mahmassani et al. (2006); Lu, & Mahmassani, (2008).
Parametric Analysis Method (PAM)

Input: from traffic simulator
- Time-dependent travel time (TT)
- Time-dependent travel cost (TC)

Output: for each dest. \( j \)
- A path tree
- VOT Breakpoints

\[ c_{odp}^{\tau} (\alpha) = TC_{odp}^{\tau} + \alpha \times TT_{odp}^{\tau} \]

- Initialize \( \alpha = \alpha_{\text{min}} \)
- Update link generalized Costs with \( \alpha \)
- Find time-dependent Least Cost (TT & TC) path tree \( T(\alpha) \)
- Obtain \( \alpha_{\text{ub}} \) by the parametric analysis
- Set new \( \alpha = \alpha_{\text{ub}} + \Delta \)

Stop

No \( \alpha < \alpha_{\text{max}} \)

Yes
**Parametric Analysis Method (PAM)**

**Input: from traffic simulator**
- Time-dependent travel time (TT)
- Time-dependent travel cost (TC)

**Output: for each dest. j**
- A path tree
- VOT Breakpoints

\[
c_{odp}^\tau (\alpha, \beta) = TC_{odp}^\tau + \alpha \times TT_{odp}^\tau + \beta \times TV_{odp}^\tau
\]

1. **Initialize** \( \alpha = \alpha_{\text{min}} \)
2. **Find time-dependent Least Cost (TT & TC)** path tree \( T(\alpha) \)
3. **Obtain** \( \alpha_{\text{ub}} \) by the parametric analysis
4. **Set new** \( \alpha = \alpha_{\text{ub}} + \Delta \)
5. **Update link generalized Costs with** \( \alpha \)
6. **Find** time-dependent Least Cost (TT & TC) path tree \( T(\alpha) \)
7. **Stop if** \( \alpha < \alpha_{\text{max}} \)

**Flowchart**:
- **Input** from traffic simulator
- **Output** for each dest. j
- 
  \[
c_{odp}^\tau (\alpha, \beta) = TC_{odp}^\tau + \alpha \times TT_{odp}^\tau + \beta \times TV_{odp}^\tau
\]
- Read VOT break points and path set for every \((i,j,t)\)
- Compute \( TV_{odp}^\tau \) for each path in the path set
- Start with the first VOT
- Find time-Dependent Least Generalized Cost Path
- And move to next interval
- Last int.? **Yes**
- Stop
- **No**

**Key Equations**

\[
c_{odp}^\tau (\alpha, \beta) = TC_{odp}^\tau + \alpha \times TT_{odp}^\tau + \beta \times TV_{odp}^\tau
\]
Output: for each dest. \( j \)
- A path tree
- VOT Breakpoints

Read VOT break points and path set for every \((i,j,t)\)

Compute \( TV_{odp} \) for each path in the path set

Start with the first VOT

Find time-Dependent Least Generalized Cost Path
And move to next interval

No

[Flowchart]

Yes

[Tree Index]

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c_{odp}^\tau (\alpha, \beta) = TC_{odp}^\tau + \alpha \times TT_{odp}^\tau + \beta \times TV_{odp}^\tau
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Start with the first VOT
Find time-Dependent Least Generalized Cost Path
And move to next interval

\[ \alpha_{min} \quad \alpha_{max} \]

\[ \text{Tree Index} \]

\[ \text{Int.} \quad \text{Int.} \quad \text{Int.} \quad \text{Int.} \quad \text{Int.} \quad \text{Int.} \]

\[ (1) \quad (2) \quad (3) \quad (4) \quad (5) \quad (6) \]
Column Generation-based Algorithm

A particle-based traffic simulator

Jiang, Mahmassani and Zhang (2011): Multi-Criterion DUE model
Algorithm: Outer Loop

\[ TTSD_{odp}^{\tau,m} = a + b \times \frac{TT_{odp}^{\tau,m}}{TD_{odp}^{\tau,m}} \]

\[ GC_{odp}^{\tau,m}(\alpha, \beta) = TC_{odp}^{\tau,m} + \alpha \times TT_{odp}^{\tau,m} + \beta \times TTSD_{odp}^{\tau,m} \]
Algorithm: Inner Loop

Outputs from Outer Loop:

Update Path Assignment: LOV

Update Path Assignment: HOV

\[ TTSD_{odp}^{\tau,m} = a + b \times \frac{TT_{odp}^{\tau,m}}{TD_{odp}^{\tau,m}} \]

\[ GC_{odp}^{\tau,m}(\alpha, \beta) = TC_{odp}^{\tau,m} + \alpha \times TT_{odp}^{\tau,m} + \beta \times TTSD_{odp}^{\tau,m} \]
Model Challenges

• **Reliability Measure in path choice framework** ➞ increase complexity of the path finding/calculation procedure

• **Heterogeneous Users** in terms of continuously distributed VOT and/or VOR ➞ create an infinite-dimensional problem

• **Large-Scale Network Applications** ➞ impose computational burdens on the solution algorithm
Bottlenecks of the Algorithm

Initialization: Outer Loop

PAM: LOV
PAM: HOV

Generate Reliability Measure

MDNL

Convergence Check?

YES → STOP

NO → Outer Loop: Path Generation

In Inner Loop: RMUDE

Update Path Assignment: LOV
Update Path Assignment: HOV

MDNL

Convergence Check?

YES → MDNL

NO → Initialization: Inner Loop

Implementation Techniques
Divide and Conquer III: Implementation Techniques for Large Network Applications

- **Gap-based Technique**: only activate PAM for a subset of destination nodes where the gaps are worse.

- **Adjust Step Size in PAM**: reduce the upper bound of number of segments found by PAM for each destination node.
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Application of Integrated Procedures to New York Regional Network

Apply demand and user response models developed in SHRP-2 Project C04 (w. P. Vovsha, PB Inc.) for NY Metro network:

- route choice model includes time-varying prices, and travel reliability measure
- random value of time (distributed across users)
- mode choice and departure time choice models

in conjunction with

MDUE (multi-criteria Dynamic User Equilibrium) with heterogeneous users and very large scale network

~30,000 Nodes
70,000 Links
3,700 Zones

5-hour AM peak period
5.2 M simulated vehicles
New York Network Application

How Big?

- TAZ: 3,697
- Node: 28,406
- Link: 68,490
- 5 hr (6-11am) demand
  - LOV: ~ 4.2 million
  - HOV: ~ 0.9 million
Convergence Patterns

AGap reduction at final iteration:

- E1: 72.36%; E2: 73.69%, and E3: 72.10%
Computational Time: PAM

E1: ~7min for each destination;
E2: 53% reduction of total time in E1;
E3: 64% reduction of total time in E1.
Flow Prediction: Toll Road Usage

Max flow difference: ~ 0.31%
Assumptions:
- Given network with discretized planning horizon
- Given time-dependent OD person demand
- Given calibrated mode choice model (LOV, HOV, and Transit)
- Given VOT distribution
- Given road pricing scheme

Solve for:
- Modal share for each mode (e.g., LOV, HOV, and Transit)
- Assignment of time-varying travelers for each mode (LOV, HOV) to a congested time-varying multimodal network under multi-criteria dynamic user equilibrium (MDUE) conditions

Methodology:
- Descent direction method for solving the modal choice problem
- Simulation-based column generation solution framework for the MDUE problem
Modal choice loop

Time-Varying Person OD Demand or trip chains

Initial Network Performance (Time, Toll, and Reliability etc.)

Modal Choice Model (LOV, HOV, and Transit)

Network (LOV and HOV)

Road pricing scheme

Time-Varying Vehicle Demand (LOV and HOV)

Time-Varying Transit Demand

Multi-Criteria Dynamic User Equilibrium Model (LOV and HOV)

Time-Varying Network (LOV and HOV) Performance (Time, Toll, Reliability etc.)

Time-Varying Network (LOV and HOV) Flow Pattern

Zhang, Mahmassani, and Vovsha (2011): Integrated Nest-Logit Mode Choice model
Nested Logit Mode Choice Model
Outer Loop Convergence Pattern: New York Regional Network
CONCLUDING COMMENTS

• We have seen advances in state-of-the-art in integrating user responses to dynamic pricing, congestion and unreliability in network modeling procedures.

• New methodologies are software independent and can be applied with any simulation-based DTA tool (caveats...)

• Application to very large New York regional network first successful application to network of this size of equilibrium DTA with heterogeneous users.

• Integration process could be improved with additional choice dimensions, and eventually fully-configured activity-based model.
KEY ISSUES and OPPORTUNITIES

• Theoretical constructs:
  – Notions of consistency in stochastic dynamic context
    ➔ convergence measures?
  – Path dependence in dynamic simulation forecasts
  – Consistency of attribute valuation throughout activity submodels—e.g. should travel time be valued similarly in route vs mode vs departure time choices?

• Methodological issues: multi-scale modeling, path finding, activity scheduling combinatorics, cooperation and competition in multi-agent system

• Application issues: Planning and Operations Decision Support System
  – Different applications/problems call for different capabilities: plug-and-play built on basic platform

• Major opportunity: more active tie in with trajectory data from probes and sensor information—responsive, calibrated, relevant platform for decision support