SHRPII Project C04:
Improving Our Understanding of How Congestion & Pricing Affect Travel Demand

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Integrating User Responses in Network Simulation Models

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EXECUTIVE SUMMARY

• Existing static assignment tools inadequate for incorporating user response models to dynamic prices and congestion: require time-varying representation of flows in networks

• Simulation-based DTA methods provide appropriate platform for integrating advanced user behavior models

• DTA tools used in practice still lack several key features
  – Limited to route choice as only user choice dimension
  – Do not capture user heterogeneity
  – Cannot generate travel time reliability measures as path LOS attributes
  – Do not produce distributional impacts of contemplated projects/ measures (social justice)
  – Limited applicability of dynamic equilibrium procedures to large-scale regional networks
This project is developing the methodologies to integrate user response models in network simulation procedures, for application over the near, medium and long terms.

The algorithms solve for a multi-criterion dynamic stochastic user equilibrium with heterogeneous users in response to dynamic prices, and congestion-induced unreliability.

The integrated procedures are demonstrated on the New York regional network, using advanced demand models developed by the project on the basis of actual data, coupled with the algorithmic procedures developed and adapted for large-scale network implementation.
1. Most agencies use static assignment models, often lacking formal equilibration, with very limited behavioral sensitivity to congestion-related phenomena (incl. reliability)

2. Some agencies use traffic microsimulation models downstream from assignment model output, primarily for local impact assessment

3. Time-dependent (dynamic) assignment models continuing to break out of University research into actual application—market relatively small, fragmented, with competing claims and absence of standards:
   - existing static players adding dynamic simulation-based capabilities,
   - existing traffic microsimulation tools adding assignment (route choice) capability, often in conjunction with meso-simulation
   - standalone simulation-based DTA tools
4. Applications to date complementary, not substitutes, for static assignment; primary applications for operational planning purposes: work zones, evacuation, ITS deployment, HOT lanes, network resilience, etc… Still not introduced in core 4-step process, nor integrated with activity-based models.

5. Existing commercial software differs widely in capabilities, reliability and features; not well tested.

6. Equilibration for dynamic models not well understood, and often not performed.

6. Dominant features, first introduced by DYNASMART-P in mid 90’s:
   - Micro-assignment of travelers; ability to apply disaggregate demand models
   - Meso-simulation for traffic flow propagation: move individual entities, but according to traffic flow relations among averages (macroscopic speed-density relations): faster execution, easier calibration
   - Ability to load trip chains (only tool with this capability, essential to integrate with activity-based models)
Responses to Pricing, in Existing Network Models

1. 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.

3. Reliability is almost never considered.
DELIVERING THE METHODS:
SIX KEY CHALLENGES

• ADVANCED BEHAVIOR MODELS  C04
• HETEROGENEOUS USERS  C04, C10
• INTEGRATION WITH NETWORK MODELS:
  THE PLATFORM—SIMULATION-BASED MICRO-ASSIGNMENT DTA  C04, L04, C10
• GENERATE THE ATTRIBUTES:  RELIABILITY IN NETWORK LEVEL OF SERVICE  L04
• CONSISTENCY BETWEEN BEHAVIOR (DEMAND) AND PHYSICS (SUPPLY):  EQUILIBRATION  C04, C10
• PRACTICAL LARGE NETWORK APPLICATION:  INTELLIGENT IMPLEMENTATION  C10
User Heterogeneity
Trip-makers choose their paths based on many criteria, including travel time, travel reliability and out-of-pocket cost, and with heterogeneous perceptions.

Empirical studies (e.g. Hensher, 2001; Cirillo et al. 2006) found that the VOT varies significantly across individuals.

Lam and Small (2001) measured the value of reliability (VOR) of $15.12 per hour for men and $31.91 for women based on SP survey data.
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
## Estimation Results Route Choice Model NYC Area

<table>
<thead>
<tr>
<th>Model Description</th>
<th>Lognormal [-1.00,1.00]</th>
<th>Lognormal [-1.00,1.00]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congested Time, Cost, Toll Bias and Std. Dev.</td>
<td>1694</td>
<td>1694</td>
</tr>
</tbody>
</table>

### Number of Observations

- 1694

### Likelihood with Zero Coefficients

- -1174.1913

### Likelihood at Convergence

- -1017.4036

### Parameter Estimates

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Coefficient</th>
<th>T-Statistic</th>
<th>Coefficient</th>
<th>T-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contant for Toll Route</td>
<td>-1.0155</td>
<td>-11.794</td>
<td>-1.0512</td>
<td>-14.041</td>
</tr>
<tr>
<td>Highway Cost (Dist*16+Tolls, cents) by Occupancy</td>
<td>-0.0010</td>
<td>-2.058</td>
<td>-0.0010</td>
<td>-2.350</td>
</tr>
<tr>
<td>Congested Time (minutes)</td>
<td>-0.0430</td>
<td>-5.569</td>
<td>-3.1732</td>
<td>-18.155</td>
</tr>
<tr>
<td>Congested Time on Highways (minutes)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Congested Time on Non-Highway Roads (minutes)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Congested Time on Roads with v/c =&gt; 0.9 (minutes)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Congested Time on Roads with v/c &lt; 0.9 (minutes)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Standard Deviation - Congested Time per Mile</td>
<td>-0.7344</td>
<td>-0.650</td>
<td>-0.7333</td>
<td>-1.312</td>
</tr>
</tbody>
</table>

### Error Term Parameters

| Varince log-Beta-Congested Time | 1.0142 | 6.357 |

### Values of Time ($/hr)

| Mean Based on Congested Time | 25.80 | 28.92 |
| Standard Deviation Based on Congested Time | --- | 15.42 |
Dealing with Heterogeneity in Existing Network Models

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
Integration Issues
Integration Issues

- As demand models reflect greater behavioral realism, supply side simulation models need to incorporate these improvements as well.

- Current travel choice models reflect the following:
  - Random heterogeneity and taste variations
  - Serial correlation among repeated choices
  - Non-IID substitution pattern among alternatives

- Incorporating these behavioral extensions into supply-side (network) models requires producing the attributes included in the estimated choice models.
INTEGRATING DEMAND AND SUPPLY

“GIVE ME SUPPLY MODEL THAT IS RICH ENOUGH FOR MY DEMAND MODEL”

“GIVE ME DEMAND MODELS THAT ARE PARSIMONIOUS ENOUGH TO FIT MY PLATFORM”
DISINTEGRATING DEMAND AND SUPPLY

THE KEY IS THE PLATFORM:
SIMULATION-BASED DTA
The key is the platform: Simulation-based DTA

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
Mode choice and multi-criteria dynamic user equilibrium model

• 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 Model
(LOV, HOV, and Transit)

Time-Varying Person OD Demand
Initial Network Performance (Time, Toll, and Reliability etc.)

Network (LOV and HOV)
Road pricing scheme
Time-Varying Vehicle OD Demand (LOV and HOV)
Time-Varying Transit OD 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

MDUE Loop
Model implementation

• Short-term Integration
  – Sequential Mode Choice and Dynamic Traffic Assignment
    • i.e. Initial Mode Choice -> DTA -> Mode Choice -> DTA
    – MNL-based mode choice model

• Medium-term Integration
  – Mode choice loop integrated in model framework
  – MNL, GEV, and Mixed Logit (random coefficients) based Mode Choice model

• Long-term Integration
  – Departure time choice dimension; activity-based models
  – MNL, GEV, Mixed Logit (Random coefficients), and Mixed Logit (Serial Correlation) based Mode Choice Model
Solution Algorithm for MDUE–UE with random VOT and VOR

For medium-term integration:
incorporate MNL/GEV mode choice
dimension and heterogeneous users for
mode and route choices
Generalized Cost

• Generalized cost is defined as a summation of travel monetary cost ($TC$), travel time ($TT$) and travel time variability/reliability ($TV$).

• VOT is considered as a continuous random variable distributed across the population of trip-makers with the density functions:

• $VOR$ is considered as a constant for all trip-makers
Input
OD demand, link tolls, VOT distribution, VOR and initial paths and path assignment

1. Initialization
Set k = 0
Perform a MDNL by traffic simulation to evaluate initial path assignment and obtain experienced path travel time (TT), and travel cost (TC)

2. PAM
Obtain the set of time-dependent extreme efficient path, breakpoints of VOT and their generalized costs to define the multi-user classes; augment the path set if new paths are found

Outer Loop: Path Generation

Return to outer loop with current link travel times. Set k = k+1

3. Convergence Checking
(a) no new path
(b) k = Kmax

4. Initialization
Set l = 0
Read output of Step 2 from PAM: current path set and path assignment r_l

5. Update Path Assignment
Determine path assignments r_{l+1} by multi-class path flow updating/equilibrating. Set l=l+1

6. Multi-class Dynamic Network Loading
Perform a MDNL by the traffic simulator to evaluate new path assignment r_{l+1} and obtain TC and TT.

Inner Loop: Solve RMDUE

7. Convergence Checking
(a) GAP
(b) l = I_{max}

YES
NO

Stop and output solution r_k
Input
OD demand, link tolls, VOT distribution, VOR and initial paths and path assignment

1. Initialization
Set k = 0
Perform a MDNL by traffic simulation to evaluate initial path assignment and obtain experienced path travel time (TT), and travel cost (TC)

2. PAM
Obtain the set of time-dependent extreme efficient path, breakpoints of VOT and their generalized costs to define the multi-user classes; augment the path set if new paths are found

Outer Loop: Path Generation

Return to outer loop with current link travel times. Set k = k + 1

3. Convergence Checking
(a) no new path
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(a) no new path
(b) k = Kmax

YES
Stop and output solution \( r^k \)

NO

4. Initialization
Set l = 0
Read output of Step 2 from PAM: current path set and path assignment \( r^l \)

5. Update Path Assignment
Determine path assignments \( r^{l+1} \) by multi-class path flow updating/equilibrating. Set \( l = l + 1 \)

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YES

NO

Inner Loop: Solve RMDUE
To overcome memory requirements and reduce computational time for a given large network to obtain initial path set.
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

- 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

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

**Flowchart:**
- Decision: $\alpha < \alpha_{\text{max}}$
- Path trees $T(\alpha)$
- VOT Breakpoints

**Variables:**
- $\tau$
- $\alpha$
- $\alpha_{\text{min}}$
- $\alpha_{\text{max}}$
- $\alpha_{\text{ub}}$
- $\Delta$

**Expression:**
$\tau = \tau_{\text{odp}} + \alpha \times C_{\text{odp}}$
Parametric Analysis Method (PAM)

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

Initialize \( \alpha = \alpha^{\text{min}} \)

- \( \alpha < \alpha^{\text{max}} \)
  - No
  - 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 \( \alpha = \alpha^{\text{ub}} + \Delta \)

- Yes
  - Stop

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

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

Compute \( T^{V_{odf}} \) 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.? 

No

Yes

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

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

Compute $TV_{od}$ for each path in the path set

Start with the first VOT

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

Check: Last int.? Yes / No

If Yes, Stop

If No, move to next interval and check again.

Diagram: VOT with intervals and tree structure.
Parametric Analysis Method (PAM)

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

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

Compute $T_{V_{odt}}$ 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

No

Stop

\[ \alpha_{\min} \quad \text{Int.} \quad \alpha_{\max} \]

Tree Index

Tree (1) Tree (2) Tree (3) Tree (4) Tree (5) Tree (6)

$\alpha_{\min}$ $\alpha_{\max}$

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

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

Compute $T_{V_{odt}}$ 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

No

Stop

\[ \alpha_{\min} \quad \text{Int.} \quad \alpha_{\max} \]

Tree Index

Tree (1) Tree (2) Tree (3) Tree (4) Tree (5) Tree (6)

$\alpha_{\min}$ $\alpha_{\max}$
Output: for each dest. j
- A path tree
- VOT Breakpoints

Read VOT break points and path set for every (i,j,t)
Compute $TV_{odt}$ 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

Yes

Last int.?
Numerical Results: Baltimore Network

Application of MDUE Procedure with Heterogeneous Users

- 6,825 nodes
- 14,317 links
- 570 zones
- Dynamic toll on I-95
- 2-hour (7-9Am) morning peak time-varying OD demand with 898,878 vehicles
General Specifications in DYNASMArt

Demand Level: 898,878 vehicles (100% PC)
Demand data: 2 hour OD-OD demand table
(morning peak period 7 am-9 am)

Simulation Mode: Iterative (100 % UE )
Demand loading mode: OD table
Planning horizon: 150 min
Departure time interval: 15 min
Assignment interval: 10 min
Aggregation Interval: 10 min
KSP number: 1
KSP calculation interval: 30 (5 min)
KSP updating interval: 5 (50 sec)
Convergence Pattern

![Graph showing the convergence pattern of AGAP(r) over iterations. The x-axis represents iteration numbers (1 to 10), and the y-axis represents AGAP(r) values from 3.5 to 0.]

\[
AGAP(r) = \sum \xi \in \tau \odot (AGap(r), \tau, \tau, \tau, \tau, \tau, \tau, \tau, \tau, \tau)
\]
Generate Reliability as Network LOS
Challenges in Characterizing Network Variability and Correlations

• Representation of the travel time variability through the network’s links and nodes
  – Variability of link travel times
  – Variability of delays associated with movements through the intersections, particularly left-turns

• Strong correlation between travel times in different parts of the network
  – Adjacent links are more likely to experience high delays in the same general time period than unconnected links
  – Difficult to capture these correlation patterns when only link level measurements are available
  – Difficult to derive path-level and OD-level travel time distributions from the underlying link travel time distributions
Travel Reliability Measure

• Given a path set for each \((i, j, \tau)\) for a given possible VOT range by PAM, we re-evaluate the path generalized cost by adding a travel time reliability measure \(TV_{i,j}^{\tau}\).

• In current implementation, exploit relation between std dev per unit distance and mean time per unit distance at network level.

• In future work, could estimate std dev per unit distance and mean time per unit distance for specific O-D’s and paths from simulation results.
Travel Time Reliability

Standard Deviation vs. Average Travel Time (per mile)

(Greater Washington, DC network: OD level variability)
Irvine Network

- **Network**
  - Freeways I-405, I-5, state highway 133
  - 326 nodes
  - 626 links
  - 61 TAZs

- **Demand**
  - Two hours morning peak (7-9AM)
Each data point represents the mean and standard deviation of travel times per mile for all vehicles departing in 5-minute interval.

24 data points for 2-hour demand
• Each data point represents the mean and standard deviation of travel times \textit{per mile} for all vehicles departing in 1-minute interval.

• 120 data points for 2-hour demand
Network Travel Time per Distance with Sampling Vehicles

- Each data point represents the mean and standard deviation of travel times per mile for all vehicles departing in 5-minute interval.
- 24 data points for 2-hour demand
Vehicle Trajectories: Unifying Framework for Micro and Meso Simulation

- Vehicle trajectory contains the traffic information and itinerary associated with each vehicle in the transportation network, including:
  - a set of nodes (describing the path)
  - the travel time on each link along the path
  - the stop time at each node
  - the cumulative travel/stop time
  - possibly lane information

```
**** Output file for vehicles trajectories ****
=================================================================
This file provides all the vehicles trajectories
Veh #  16645 Tag= 2 OrigZ= 5 DestZ= 9 Class= 5 UstmN= 103
DownN= 102 DestN= 11 STime= 70.20 Total Travel Time= 8.49 # of Nodes= 18 VehType 1 LOO 1
  102  160  102  103  151   97   89   4   3

  24
  5  27  28  32  35  39  40  11

  ==>Node Exit Time Point
  0.80  0.90  1.60  2.20  3.00  3.40  3.80  5.00  5.50
  5.90
  6.00  6.30  6.70  7.10  7.30  7.60  8.20  8.40

  ==>Link Travel Time
  0.80  0.10  0.70  0.60  0.80  0.40  0.40  1.20  0.50
  0.40
  0.10  0.30  0.40  0.40  0.20  0.30  0.60  0.20

  ==>Accumulated Stop Time
  0.60  0.60  1.20  1.36  1.42  1.44  1.47  2.22  2.57
  2.57
```
Obtain Vehicle Trajectories from Simulation Models

- Vehicle trajectories could be obtained from all particle-based simulations, regardless of whether the physics underlying vehicle propagation and interactions are captured through microscopic maneuvers or through analytic forms
  - Microscopic simulation models move traffic by capturing individual driver maneuvers such as car following, overtaking, lane changing and gap acceptance decisions.
  - Mesoscopic simulation models move vehicles as individual particles, albeit according to (macroscopic) relations among average traffic stream descriptors (e.g. speed-density relations).
- The realm between micro and meso has narrowed considerably over time—and will continue to do so.
- Trajectories could also be obtained from direct measurement in actual networks: video camera, cell-phone/GPS probes, etc...
- This enables consistent theoretical development in connection with empirical validation (for L04)
Apply demand and user response models developed in C04 in conjunction with MDUE and heterogeneous users to very large scale network.
New York Regional Network

~30,000 Nodes
95,000 Links
3,700 Zones
CONCLUDING COMMENTS

• This project has advanced 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.

• 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.