Transportation Networks and Operations

*From Models to Application*

*(in a Connected World)*

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Northwestern University

*NUTC 60th Anniversary Celebration: Technical Symposium*

November 13, 2014
Evanston, IL.
1954: Transportation Center is founded

1955: First publication, as a Rand Report, of


50-yr anniversary sessions at INFORMS and RSA meetings

In addition to its recognized contribution to formalizing the network equilibrium problem as a convex mathematical program (MP),

which provided the basis for the main class of solution algorithms that saw extensive development and refinement in the 1970’s and 1980’s, and found their way into the leading software packages used in practice for traffic assignment,

It turns out that **BMW actually contained the seeds for what would become the main directions for further development in network modeling for the next 60 years, namely:**

- variational inequality formulations (much more general than MP)
- dynamic (within day) equilibrium models
- stability analysis and user adjustment processes (day-to-day dynamics)
- congestion pricing
DID THEY MISS ANYTHING?

LINK PERFORMANCE FUNCTIONS
(volume-delay curves)

- Representation of traffic flow processes on roadway facilities (incl. junctions)
- Bone of contention between economists and traffic scientists
- Limited appreciation in both camps of interpretation
DID THEY MISS ANYTHING?

Traffic Science
(fundamental diagram)

Backward-bending curve
DID THEY MISS ANYTHING?

[Graph showing traffic flow versus density, with a breakdown point indicated.]
4-step Sequential Static

Behavioral Realism

Activity-scheduling, real-time response to information

Activity-based models

Trip chains

Disaggregate, choice models

Prospect theory, Cumulative PT

Learning dynamics

Bounded rationality, thresholds, heuristics, Computational process models

Attitudes, perceptions

Random utility

Consumer theory

4-step Sequential Static

Dynamics
Dynamics

Behavioral Realism

Learning dynamics

4-step Sequential Static

Within-day Day-to-day Long-term Evolution & Adaptation


Dynamics
Integration

Dynamics

Behavioral Realism

4-step Sequential Static

Process models of cognition and learning in networks

Integration

Static demand & network microsimulation
MULTI-SCALE MODELING of FLOW PROCESSES

**Micro level developments:** cognitive-based models of acceleration (car-following), lane changing,...:

Motivating applications: connected vehicles and associated V2V and V2I ITS strategies, e.g., INFLO (speed harmonization, coordinated driving), ATDM, DMA...

**Meso level developments:** “workhorse” of simulation-assignment (DTA) tools; developments: sensitivity to weather effects, better representation of flow breakdown, integrating user choices and dynamic controls.

Motivating applications: strategic planning/ABM integration (complement and replace static assignment and 4-step processes); operational planning (work zones, demand management, weather-related...); evacuation planning.

**Macro level developments:** rediscovery by worldwide traffic research community of network-level fundamental diagrams (original work by Herman, Mahmassani and Williams, mid 1980’s); dynamic properties of flow at network-level, with focus on hysteretic behavior, stability, network capacity and control applications. Signature relations for *reliability* analysis.
Complex interactions, Collective Effects:
Simple, robust linear relation between std. deviation and mean of trip time per unit distance

![Graph showing the relationship between network travel time per distance and standard deviation.](image-url)
Simulated Trajectory Data

- 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

<table>
<thead>
<tr>
<th>Network</th>
<th>Irvine</th>
<th>CHART</th>
<th>New York City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Zones</td>
<td>61</td>
<td>111</td>
<td>3697</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>326</td>
<td>2182</td>
<td>28406</td>
</tr>
<tr>
<td>Number of Links</td>
<td>626</td>
<td>3387</td>
<td>68490</td>
</tr>
<tr>
<td>Number of Vehicles</td>
<td>58385</td>
<td>151973</td>
<td>6766805</td>
</tr>
<tr>
<td>Demand Duration (hr)</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Mahmassani, Hou and Dong (2012)
Simulated Trajectory Data

- Model comparison – network level analysis

(a) Irvine; (b) CHART; (c) New York City
Simulated Trajectory Data

- Model comparison – path level analysis

(a) Irvine; (b) CHART; (c) New York City
GPS Probe Data

- Seattle network
MULTI-SCALE MODELING of FLOW PROCESSES (ctd.)

ALL LEVELS:

mixed flow processes (cars, peds, bicycles, buses...)

pedestrian and crowd dynamics

major role of *trajectories* (of vehicles, people) for calibration and validation of traffic relations and simulation tools.

\[
Q(\omega) = \frac{d(\omega)}{L_{xy}(\omega) \times \Delta t}
\]
and

\[
N(\omega) = \frac{t(\omega)}{L_{xy}(\omega) \times \Delta t}
\]

e.g. allows generalization of Edie’s 2D definitions of average flow density to 3D and networks

Saberi, Mahmassani, Hou and Zockaie (2014)
MAJOR INTEGRATION CHALLENGE:

Additional behavioral realism on the demand/activity side translates into major challenges for path finding and computational burden in network modeling side.

Examples:

1. Heterogeneous users—different values of time for different users, thus possibly different shortest paths; approach: parametric shortest path for continuously distributed VOT (in pricing applications).

1. Travel time reliability as attribute in choice models (of route, mode, departure time...): non-additive across links to obtain path disutilities or generalized costs.

2. Nonlinear utility function specifications—non-additivity.

3. Different behavioral rules (other than disutility minimization), especially for decisions under risk—path finding in stochastic dynamic networks.
DISINTEGRATING DEMAND AND SUPPLY

THE KEY IS THE PLATFORM:

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

DISTRACTING 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
Equilibrium Concept for ABM and DTA Integration

Current CMAP project, joint effort between NUTC and PB Americas
Definition of Equilibrated State

• Individual travelers cannot increase their utility by unilaterally changing their activity chain (activities, durations, schedule).

• An activity chain is defined by a sequence of activities with departure time and duration for each of activity in the chain.
Definition of Variables

- **ABM** outputs individual trip chain with activity chain, departure time, and activity durations:
  \[ a_i = [a_i^1, a_i^2, \ldots, a_i^M] \]
  \[ \tau_i^{ABM} = [\tau_i^{1,ABM}, \tau_i^{2,ABM}, \ldots, \tau_i^{M,ABM}] \]
  \[ d_i = [d_i^1, d_i^2, \ldots, d_i^M] \]

- **DTA** load individual trip chain and outputs experienced travel time and/or generalized travel cost:
  \[ a_i = [a_i^1, a_i^2, \ldots, a_i^M] \]
  \[ \tau_i^{DTA} = [\tau_i^{1,DTA}, \tau_i^{2,DTA}, \ldots, \tau_i^{M,DTA}] \]
  \[ d_i = [d_i^1, d_i^2, \ldots, d_i^M] \]
Fixed Point Formulation

\[ U(a, \tau, d) = S(P(A(U(a, \tau, d)))) \]

Experienced Utility or Generalized Cost
Fixed Point Formulation

\[ U(a, \tau, d) = S(P(A(U(a, \tau, d)))) \]

Experienced Utility or Generalized Cost

Activity Chain from ABM
Fixed Point Formulation

\[ U(a, \tau, d) = S(P(A(U(a, \tau, d)))) \]

Experienced Utility or Generalized Cost

Activity Chain from ABM

User path (trajectory) from assigning activity schedules
Fixed Point Formulation

\[ U(a, \tau, d) = S(P(A(U(a, \tau, d)))) \]

- Experienced Utility or Generalized Cost
- Activity Chain from ABM
- User path (trajectory) from assigning activity schedules
- Utility obtained from simulating user path (trajectory)
Fixed Point Formulation

\[ U(a, \tau, d) = S(P(A(U(a, \tau, d)))) \]

**Experienced Utility or Generalized Cost**

**Activity Chain from ABM**

**User path (trajectory) from assigning activity schedules**

**Utility obtained from simulating user path (trajectory)**
Possible Convergence Criteria

- **Traditional measures:** change in direct quantities (Trip table, travel time or cost) between successive iterations (k: iteration index; N: total population):

  - Trip table convergence (ABM)
    \[
    \text{Average Difference of Trip (\%)} = \frac{1}{N} \sum_{od\tau} \left| \frac{f_{od\tau}^{k,ABM} - f_{od\tau}^{k,DTA}}{f_{od\tau}^{k,ABM}} \right| \times 100
    \]
  
  - Travel time convergence (DTA)
    \[
    \text{Average Difference of Travel Time (\%)} = \frac{1}{N} \sum_{od\tau} \left| \frac{TT_{od\tau}^{k-1} - TT_{od\tau}^{k}}{TT_{od\tau}^{k}} \right| \times 100
    \]

Note that trip tables here are generated from chain of daily activities before and after DTA run.

These measures might lead to convergence and consistency but not necessarily to equilibrium.
Possible Convergence Criteria

- **Gap-based measures**: difference between individual experienced times or utilities and corresponding minimum values.
  - More directly related to equilibrium state properties
  - Provide consistent (reproducible) basis for comparing alternatives across different scenarios
  - Difficult to compute in certain cases
Linking the Variables

\[
\begin{align*}
\begin{pmatrix}
a_i & b & c
\end{pmatrix} & \longrightarrow ABM & \begin{pmatrix}
a_i & b & c
\end{pmatrix} \\
\begin{pmatrix}
a_i^\text{ABM} & b & c
\end{pmatrix} & \longrightarrow \text{Multi-Modal} & \begin{pmatrix}
\tau_i & a_i^\text{DTA}
\end{pmatrix} \\
\begin{pmatrix}
d_i & b & c
\end{pmatrix} & \longrightarrow \text{DTA} & \begin{pmatrix}
d_i & b & c
\end{pmatrix} \\
\begin{pmatrix}
\tau_i & a_i^\text{DTA}
\end{pmatrix} & \longrightarrow GC & \begin{pmatrix}
\tau_i & a_i^\text{DTA}
\end{pmatrix} \\
\begin{pmatrix}
U_i^\text{ABM}
\end{pmatrix} & \longrightarrow \text{Planned Individual Utility} & \begin{pmatrix}
U_i^\text{DTA}
\end{pmatrix} & \longrightarrow \text{Experienced Individual Utility}
\end{align*}
\]
Convergence Criteria: Gap Measure II

At equilibrated state, we have:

\[ U_{i,k}^{DTA} = U_{i,k}^* (a_k, \tau_k, d_k), \quad \forall i \in N \]

\[ GAP = \frac{1}{N} \sum_{i}^{N} \left| U_{i,k}^{DTA} - U_{i,k}^* (a_k, \tau_k, d_k) \right| \]
Schedule Consistency: Planned Activity Chain
Schedule Consistency: Experienced Activity Chain
Schedule Consistency: Experienced Activity Chain

The experienced arrival time is later than the planned depart time.
Schedule Consistency: Adjusted Activity Plan
Schedule Consistency: Adjusted Activity Plan

Adjust the depart time and duration time of the previous activity.
INTELLIGENT VEHICLE-HIGHWAY SYSTEMS

ITS 0.9
Vehicles
Highway infrastructure

ITS 1.0
Buses, trains, multimodal services
Urban mobility

ITS 2.0 = CS 2.0 CONNECTED SYSTEMS

FOCUS: THE USER
Mobility as an APP in seamless connected environment
**Connectivity**

Connected systems (internet of everything)

- Ad-hoc networks
- Peer-to-Peer (Neighbor)
- Receive only
- Isolated

**Automation**

- Fully manual Level 0
- Fully automated Level 4

**Coordinated**
- Optimized flow
- Routing
- Speed harmonization

**Connected**
- Real-time info
- Asset tracking
- Electronic tolling

**Cooperative Driving**

- INTELLIGENCE RESIDES ENTIRELY IN VEHICLE

**Smart Highways**
<table>
<thead>
<tr>
<th>CONVENTIONAL WORLD</th>
<th>CONNECTED WORLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Steady - state</td>
<td>– Time varying</td>
</tr>
<tr>
<td>– Equilibrium</td>
<td>– Evolutionary paths</td>
</tr>
<tr>
<td>– Static</td>
<td>– Dynamic</td>
</tr>
<tr>
<td>– Data poor</td>
<td>– Data rich</td>
</tr>
<tr>
<td>– Uncertainty about past/current events</td>
<td>– Known past/current events (to varying degrees)</td>
</tr>
<tr>
<td>– Component level</td>
<td>– System level</td>
</tr>
<tr>
<td>– Long lead time between solution and implementation</td>
<td>– Immediate action</td>
</tr>
<tr>
<td>– Limited “accountability” of decisions</td>
<td>– Performance monitoring and feedback</td>
</tr>
<tr>
<td>– “A priori” solutions</td>
<td>– Adaptive strategies</td>
</tr>
</tbody>
</table>
1994 to 2014

20 YEARS--
DEPLOYMENT OF A LOT OF
TECHNOLOGY

NOT AS MUCH INTELLIGENCE
PREDICTIVE ANALYTICS: Basis for Intelligent Control Strategies

Consistent anticipatory travel time Information and routing decisions

(Dong andMahmassani, 2010, 2014)

Dynamic pricing for managed lane operations

(Reference: Dong et al. 2012)
Weather-sensitive TrEPS

Weather-sensitive traffic operations model

**Estimation**: weather-sensitive traffic simulation-assignment model

**Prediction**: weather-sensitive traffic simulation-assignment model

Weather-responsive traffic management strategies

Weather data

Weather monitoring systems

Weather forecast

Alert weather conditions
Project Objectives

• Integrate and operationalize the weather-sensitive TrEPS models calibrated for Salt Lake City to support weather-responsive traffic signal timing implementation
  – Evaluate different possible signal timing strategies under weather-related scenarios
  – Determine when to deploy such weather-responsive signal timing plans

• Monitor the implementation of the TrEPS-based decision support system, and its effectiveness in terms of weather-responsive traffic management
Real-time Surveillance Data

- Freeway detectors
  - 30-second observation interval
  - occupancy, vehicle counts, speed

- Riverdale road cameras
  - Vehicle counts, speed
Real-time Traffic Management

Before implement management strategy

After implement management strategy

Time to implement traffic management strategy?
Dynamic Traffic Assignment Model and Simulator

Real-Time Traffic Data and Events
- Travel Times
- Traffic Incidents

State Prediction Module

Online Booking Processor

A Priori Requests

Real-Time Requests

A Priori Routing Planner

Service Network:
Nodes: Unserved customers and NEWLY accepted customers, locations of fleets
Links: time-dependent shortest paths linking nodes

Online Re-routing Planner

Lan and Mahmassani (2013, 2014)
PREDICTION essential in real-time traffic management and urban logistics

Considerable opportunities: new sources of personal information, emerging technologies

Computational challenges remain

User behavior: will remain moving target, because users will adapt hence need for adaptive schemes

Growing role of private sector as business models become more compelling
THANK YOU

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