REFLECTIONS ON TRANSPORTATION NETWORK MODELING

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ARPA-E TRANSPORTATION NETWORK OPTIMIZATION WORKSHOP, MARCH 10, SAN FRANCISCO
OUTLINE

• CLASSES OF TRANSPORTATION NETWORK MODELS
• COMMENTS ON THE MODELS
• PERSONAL EXPERIENCES
• CHALLENGES
TRANSPORTATION NETWORK MODELS

• TRANSPORTATION SYSTEM HAS A VARIETY OF MODES
  • (AIR, WATER), AUTO, BUS AND RAIL TRANSIT, NON-MOTORIZED

• TRAVELERS FACE COMPLEX CHOICES
  • WHETHER TO TRAVEL, WHERE TO TRAVEL, WHEN TO TRAVEL, HOW TO TRAVEL (MODE/ROUTE COMBINATIONS)

• (IN THIS TALK) : HOW TO TRAVEL

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PRINCIPLES OF CHOICE

• NON-COOPERATIVE (USER-OPTIMAL)
  • TRAVELERS CHOOSE A COMBINATION OF MODES/ROUTES/DEPARTURE TIMES TO MINIMIZE THEIR OWN TRAVEL COST
  • NASH EQUILIBRIUM

• CO-OPERATIVE (SYSTEM-OPTIMAL)
  • TRAVELERS COOPERATE TO REDUCE OVERALL SYSTEM COSTS, NOT NECESSARILY THEIR OWN
  • INCENTIVES OR CENTRAL CONTROL

• MIXED (ONE-SHOT DYNAMICS, MULTIPLE USER CLASSES)
(LINK) TRAVEL COST MODELS

• STATIC MODEL
  • TRAVEL COST IS A FUNCTION OF FLOW
  • BPR TYPE OF LINK COST FUNCTIONS (PLANNING)

• DYNAMIC MODELS
  • MICRO: CF OR CA MODELS (MICRO SIMULATION)
  • MACRO: QUEUING (PQ, SQ), FLUID MODELS (CTM, LWR), WHOLE LINK (CONVEYOR BELT) MODELS (DTA)
PROS AND CONS

• NETWORK MODELS WITH STATIC COST FUNCTIONS
  • PROS: LESS DATA, COMPUTATIONALLY EFFICIENT, WELL STUDIED
  • CONS: COARSE GRAINED, PEAK SPREADING/CONGESTION NOT ADEQUATE

• NETWORK MODELS WITH CF/CA MODELS
  • PROS: FINE GRAINED, DETAILED MODELING OF CONGESTION
  • CONS: DATA INTENSIVE, HARD TO SCALE UP, CALIBRATION IS DIFFICULT

• NETWORK MODELS WITH MACRO DYNAMIC MODELS
  • PROS: CONGESTION MODELING IS ADEQUATE (QUEUING, PEAK SPREADING)
  • CONS: DATA AND COMPUTATION INTENSIVE, CALIBRATION IS DEMANDING

Network models with macro dynamic flow models are good compromises
DYNAMIC LINK MODELS

• DTA NEEDS TRIP TIMES
• PERFORM NETWORK LOADING
  • FLOW CONSERVATION
  • FLOW PROPAGATION
    • CAUSALITY
    • QUEUING
    • FIFO

\[
\begin{align*}
\dot{x}(t) &= q(t) - e(t) \\
x(t) &= A(t) - E(t)
\end{align*}
\]

\[
A(t) = E(t + \tau(t))
\]

NC for FIFO
TRAFFIC FLOW MODELS COMMONLY USED IN DTA

• LINK TRAVEL TIME IS KNOWN **BEFORE** TRIP ENDS

  • THE DELAY FUNCTION MODEL:
    \[ \tau(t) = f(x(t)) \quad \tau(t) = f(x, q, e)(t) \]

• LINK TRAVEL TIME IS KNOWN **AFTER** TRIP ENDS

  • EXIT-FLOW MODELS
    • M-N
    • PQ/SQ/KW
  • OTHER FLUID-LIKE MODELS
  • CONVEYOR-BELT MODELS
    • GREENSHIELDS ETC
MODELING NETWORK FLOW WITH THREE QUEUING MODELS

• TRAFFIC EVOLUTION WITHIN LINKS
  • POINT-QUEUE MODEL
  • SPATIAL-QUEUE MODEL
  • THE KINEMATIC WAVE/CELL TRANSMISSION MODEL

• LINKS INTERACT THROUGH NODES
  • MERGE
  • DIVERGE
LINK MODEL I: POINT-QUEUE

\[
\dot{y}(t) = q(t - h) - e(t)
\]

\[
e(t) = \begin{cases} 
q(t - h) & \text{if } y(t) = 0 \text{ and } q(t - h) < c \\
c & \text{otherwise}
\end{cases}
\]

Queue will never spillover to upstream links!

Queue \( y \) at the exit point

Entrance

Travel at free flow speed

A link with bottleneck capacity \( c \) and free flow travel time \( h \)

Exit
Queue spillover occurs when $x=H$, at that time no vehicle can enter the link.

A link with bottleneck capacity $c$, free flow travel time $h$, and holding capacity $H$, its downstream link has holding capacity $G$.
**LINK MODEL III: KW/CTM**

\[ \rho_t + F(\rho, x)x = 0 \]

Cell Demand \( D = \min(\text{number of vehicles at the cell exit, cell flow capacity } c) \)

Cell Supply \( S = \min(\text{w (cell holding capacity } H(i) - \text{number of vehicles in the cell } x_i), \text{cell flow capacity } c) \)

Flow across cell boundary \( f = \min\{D \text{ of upstream cell, } S \text{ of downstream cell}\} \)

Queue spillover occurs when \( w(H(\text{Last}) - x_{\text{Last}}) < c \).

No vehicle can enter the link when \( H(\text{Last}) = x_{\text{Last}} \)
NODE MODEL I: MERGE

\[ e_{13} = a_{13} e \]
\[ e_{23} = a_{23} e \]

\[ v = \min\{ D_1 + D_2, S_3 \} \]

\[ a_{i3} = \frac{D_i}{\sum_i D_i}, \text{if } S_3 < \sum_i D_i \]
Turning percentage dependents on traffic composition, and hence vary with time and demand pattern.
LOADING RESULTS FOR A SYNTHETIC GRID NETWORK

19x19 grid network, 256 OD pairs, 1 hour loading. Base demand: 300 vehicles per OD (h=30~100 sec, jam density: 180 veh/mi/lane, free-flow speed 50 mph, w=12.5 mph, flow cap 1800 veh/hr/lane, 2 lanes)

<table>
<thead>
<tr>
<th>Delay (hours)</th>
<th>PQ</th>
<th>SQ</th>
<th>CTM</th>
<th>Delay func.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light load</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.6*base)</td>
<td>196</td>
<td>190</td>
<td>210</td>
<td>308</td>
</tr>
<tr>
<td>Medium load</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(base)</td>
<td>17,022</td>
<td>23,011</td>
<td>30,819</td>
<td>18,926</td>
</tr>
<tr>
<td>Heavy load</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2*base)</td>
<td>114,795</td>
<td>Gridlock</td>
<td>Gridlock</td>
<td>121,318</td>
</tr>
</tbody>
</table>
EXPERIENCES WITH REALISTIC NETWORKS

- 6 hours of Sunday (10AM-4PM)
- 582,606 total trips
- 2058 regular nodes
- 2711 regular links
- 21462 O-D pairs
WORK FLOW

- NETWORK CODING
  - IMPORT GIS NETWORK FILE USING SHAPEFILE
  - CLEAN UP (CORRECT ERRORS AND REVISE O/D AND O/D CONNECTORS)
- PREPARE INPUT DATA
  - TRAFFIC COUNTS, HISTORICAL O/D TABLE, FLOW PARAMETERS (SPEED LIMIT, CAPACITY, WAVE SPEED)
  - ESTIMATE O/D
- NETWORK DIAGNOSTIC
  - ERROR IN NETWORK CODING, INPUT DATA CAN ALL CAUSE ERRONEOUS FLOW PATTERNS
- NETWORK LOADING
  - ONE-SHOT DYNAMICS WITH MIXED USER CLASSES, NO EQUILIBRIUM
- ANALYSIS AND REPORT OF RESULTS

TOOK 4 (GRDUATE STUDENTS)+1 (MYSELF) 10 EQUIVALENT DAYS TO COMPLETE THE PROJECT
DATA AND TIME DEPENDENT O/D ESTIMATION
WHAT ABOUT SYSTEM-OPTIMAL DTA?

• IN SO-DTA, ONE HAS FULL CONTROL OF ALLOCATING TRIPS OVER SPACE AND TIME

• AT LEAST IN MANY-TO-ONE NETWORKS
  • ONE CAN SHOW THAT PQ, SQ, AND CTM PRODUCE THE SAME TOTAL SYSTEM COST IF BOTTLENECKS HAVE CONSTANT CAPACITIES
  • ONE SOLUTION IS TO ELIMINATE ALL INSIDE QUEUES IN THE NETWORK, AND LET THE VEHICLES QUEUE AT THE ENTRANCES

• PROOF FOR GENERAL NETWORKS IS HARD, IF THIS PROPERTY STILL HOLDS.
REFLECTIONS

• CODING EFFORT
  • LEVEL OF DETAIL
  • IN DYNAMIC MODELS, MINOR CODING ERROR CAN HAVE BIG CONSEQUENCES

• DATA NEEDS
  • DYNAMIC MODELS NEED MORE DATA!
    • TIME DEPENDENT O/D TABLES, MODEL PARAMETERS
    • MACRO MODELS ARE MORE PARSEMONIOUS

• CALIBRATION
  • ONE OF THE BIGGEST CHALLENGES
  • SMALL ERRORS IN CODING CAN LEAD TO LARGE ERRORS IN FLOW PATTERNS
  • THE SPREAD OF CONGESTION MASKS THE TRUE CAUSE OF THE PROBLEM

• COMPUTATIONAL CHALLENGES
  • TYPICALLY LOADING TAKES THE BULK OF THE CPU TIME IN EACH ITERATION