Reducing Energy Use in Multimodal Transportation System

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Outline

- Motivation
- Preliminaries
  - Research Statement
  - Interactions between Traffic Demand and Supply
  - Intermodal Network
- Mathematical Model
- Solution Methodology
- Case Study and Preliminary Results
- Future Work
- Other Research
Transportation Dominates Total U.S. Petroleum Consumption

- "Transportation" use: the use of petroleum products as vehicle fuels
- Transportation system accounts for 65-71% of the nation's gasoline consumption

Primary Energy Consumption By Source and Sector, 2011
quadrillion Btu

- Energy crisis becomes more and more urgent
- Non-renewable Oil provides 36% of energy sources in USA
- Transportation systems are highly oil dependent

Data Source: U.S. Dept. of Energy
Transportation Dominates Total U.S. Petroleum Consumption

Transportation Energy Use by Mode (2008)

- **Light-Duty Vehicles** (passenger cars, fleet vehicles, and light truck) account for most of the share, then Truck and Aviation

Data Source: U.S. Dept. of Energy
For passenger transportation, the order of energy efficiency is “Rail” > “Road” > “Air”
1. Focus on major modes

- Cars/light trucks, freight trucks, and aviation
  - Account for nearly all passenger and freight activity—will continue to account for the lion’s share for decades
- Other modes contribute very little to energy use/emissions
  - These modes may prove to be helpful as solutions

3. Develop system policy affecting both demand and supply

- Increase consumer demand for and manufacturer supply of efficient vehicles
- Enable more efficient transportation system operations
- Reduce demand for energy-intensive forms of travel
Policy Options

- **Fuel Taxes (higher fuel prices)**
  - Induces both consumer and supplier interest in vehicle efficiency
  - Motivates interest in reducing energy-intensive travel activity
  - Will prompt consumer demand for more efficient systems
  - Induces interest in alternative energy sources

- **Vehicle Efficiency Standards**
  - Compels development and supply of more efficient vehicles

- **Land Use/Transportation Coordination**
  - Better enables consumer reductions in energy-intensive travel activity (e.g., more travel alternatives)

- **Public Investments in Infrastructure and More Efficient System Operations**
  - Invests more energy efficient traffic mode
  - Reduces congestion to increase system energy efficiency
  - Valued by consumers when fuel prices are rising
Preliminary Research

- **Study** the interurban passenger trips in the multimodal transportation systems *aiming* to reduce the system energy consumption *considering* the interactions between policy makers, multimodal traffic facility suppliers, and traffic demand.

- **Develop** a mathematical model whose optimal solution provides the support/insights for the system policy makers to strengthen the energy sustainability in the multimodal transportation systems in *long-term planning*. 
Interactions between Traffic Demand and Supply

- Given a multimodal network, $G$
- Link traffic service described by waiting time, travel time, fare, service frequency
- Link traffic service leads to intermodal path traffic service
- Traffic supply further leads to traffic flow distribution among modes.
- Traffic flow distribution influences energy consumption

- Energy consumption should be considered as one of the most important factors which impact network design, traffic demand as well as the traffic supply in long term.

G: multimodal network; $\Omega$: distribution of travel demand; E: energy consumption; $t/c/w/r$: travel time/fare/waiting time/service frequency; T/C/W/R: corresponding path value; H: intermodal paths.
Intermodal Network

- Nodes: cities or mode transfer ports
- Directed links: the connections between cities/transfer ports
  - Multiple modes: private auto, transit, rail, and air
  - Links differentiated by modes instead of physical network
  - Aggregated link service level
- Interurban traffic demand
  - Deterministic, single O-D
  - Business and non-business trip
- Energy consumption per link, $\delta$

$w$: waiting time; $t$: travel time; $c$: fare; $r$: service frequency; $p$: seat capacity
Methodology: Bi-Level Mathematical Programming (MP)

Main Idea

1. Policy Maker
   Make policy to minimize energy consumption

2. Traffic Supplier (S)
   Adjust service level to sustain revenue

3. Traffic Demand (D)
   Maximize trip satisfaction

First Level MP

Traffic flow

Second Level MP

Cost, Profit

S-D: Ridership Change

• Fuel tax
  • Land use strategies
  • Allowance
  • Mandatory

• Service level (ticket fare, capacity, service frequency, ridership)
• Operation Cost
• Business profit

• Travel time (Waiting time)
• Service frequency
• Travel cost
• Comfort
Min Energy consumption

Supply-Demand (S-D) relation

Fare adjustment based on S-D relation, the traffic suppliers' profit limitations and the constraints in reality

Service frequency adjustment based on S-D relation, the traffic suppliers' profit limitations and the constraints in reality

The objective of system policy makers

More considerations to operation constraints from traffic suppliers

Other constraints of the decision variables; and the conversion from path flow (x) to link flow (y); x comes from the second level

Min \( \sum_i \sum_l r_{li} x_{li} \)

\[
\begin{align*}
\epsilon r_{li} p_{li} - y_{li} & \geq -B z_{li}, i \in \{2, 3, 4\}, l \in L \\
\epsilon r_{li} p_{li}^0 - y_{li} & \leq B s_{li}, i \in \{2, 3, 4\}, l \in L \\
z_{li} + s_{li} & \leq 1, i \in \{2, 3, 4\}, l \in L \\
c_{li} = c_{li}^0, l \in L \\
c_{li} = (1+\alpha_{li}^e z_{li} - \alpha_{li}^e s_{li}) c_{li}^0, i \in \{2, 3, 4\}, l \in L \\
b_{li}^c & \leq c_{li} \leq u_{li}^c, i \in I, l \in L \\
z_{li}^e \alpha_{li}^e z_{li} + y_{li}^e \alpha_{li}^e s_{li} & \geq (z_{li} + s_{li}) \pi_{li}^c, i \in \{2, 3, 4\}, l \in L \\
r_{li} = y_{li}, l \in L \\
r_{li} = (1+\beta_{li}^e z_{li} - \beta_{li}^e s_{li}) r_{li}^0, i \in \{2, 3, 4\}, l \in L \\
b_{li}^r & \leq r_{li} \leq u_{li}^r, i \in I, l \in L \\
\theta_{li}^e \beta_{li}^e z_{li} + \varphi_{li}^e \beta_{li}^e s_{li} & \geq (z_{li} + s_{li}) \pi_{li}^r, i \in \{2, 3, 4\}, l \in L \\
\alpha_{li}^e & \geq 0, i \in I, l \in L \\
\alpha_{li}^e & \geq 0, i \in I, l \in L \\
\beta_{li}^e & \geq 0, i \in I, l \in L \\
\beta_{li}^e & \geq 0, i \in I, l \in L \\
z_{li} & \in \{0,1\} and s_{li} \in \{0,1\}, l \in L, i \in I \\
y = \sum_{k=1}^K m_h x_h^k
\end{align*}
\]
Mathematical Model

\[ x \in \text{argmax}\{\sum_{h=1}^{H} \sum_{\kappa=1}^{K} \rho_h^\kappa x_h^\kappa\} \]

\[ \text{s.t.} \]

\[ \sum_{h=1}^{H} x_h^\kappa = D^k, \kappa \in K \]

\[ \sum_{h=1}^{H} \left( m_h \sum_{\kappa=1}^{K} x_h^\kappa \right) \leq r_{li} p_{li} \]

\[ x_h^\kappa \geq 0, h \in H, \kappa \in K \]

\[ t_{li} = t_{li}^0, i \in I, l \in L \]

\[ w_{li} = w_{li}^0, i \in I, l \in L \]

- Max trip satisfaction
- Flow conservation
- Link capacity
- Variable constraints
- Static travel time
- Static waiting time

Two classes of traffic demand: Business (B) and non-business (NB)

Linear utility function used to measure the preference of travelers to a certain intermodal path

\[ \rho_h^\kappa = a^{ck} C_h + a^{wk} W_h + a^{tk} T_h + a^{rk} R_h, \ h \in H, \kappa \in K \]

Constant link travel time and waiting time, do not factor traffic congestion directly
Solution Methodology

- **Model Computational Complexity**
  - Bi-level model, NP hard
  - First level, nonlinear mixed integer program
  - Second level, linear program

- **Solution Method**
  - Substituting the second level by its KKT conditions
  - Bi-level program => one level nonlinear program (Mathematical Program with Complementarity Constraints, MPCC))
  - Branch and Bound algorithms to address integer variables
A Small Case Study

- Study intercity trip from Lafayette to Washington D.C. with the given OD traffic demand equal to 150.
- Investigate the system optimal traffic flow distributions considering energy consumption under different traffic demand compositions (business trips and non-business trips).
- Investigate the optimal traffic flow distributions considering system energy consumption under the various road traffic conditions.
• One OD: Lafayette to Washington D.C.
• Determined total traffic demand, 150
• Four traffic modes: private auto, transit, rail, and air
• Nine links, and twenty two intermodal paths differentiated by links and modes
• Cities: Lafayette, Indianapolis, Baltimore, Pittsburg, Dallas, and Washington D.C.
Without considering energy, intermodal paths including auto are used very often.

Considering energy, intermodal paths including transit and rail are highly recommended.
Energy Consumption

System energy consumption is significantly reduced by shifting travelers from the intermodal paths including Auto to the intermodal paths including transit and rail.
Reducing the system energy consumption leads to
- Transit systems bring down ticket price
- Rail and air may increase ticket prices
- Customers using low energy efficiency mode need to pay more
Preliminary Results

- Experiments: increase road traffic time to 1.25, 1.5, 1.75, and 2 times of the original value $t^0$
- Check the system optimal solution
  - 4 Paths are included
  - Paths 5 (1-2-6), Path 10 (1-3-7); Path 14 (1-4-8); Path 6 (1-2-6);
- Transit, Air, and Rail

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<tr>
<th>Path \ Ranking</th>
<th>Energy Computation</th>
<th>Travel Time</th>
<th>Fare</th>
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<tr>
<td>Path 5 (cheaper but not efficient)</td>
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<td>Path 6 (cheaper and efficient)</td>
<td>2</td>
<td>2→3</td>
<td>4</td>
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<td>Path 10 (expensive and efficient)</td>
<td>4</td>
<td>3→2</td>
<td>1</td>
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<tr>
<td>Path 14 (expensive and efficient)</td>
<td>3</td>
<td>4</td>
<td>1</td>
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</table>

Score 4: best one → 1: worst one

- Path 14 has the smallest travel time; Path 10 consumes the least fuel; Path 5 and Path 6 are relatively cheap; the trade-off exists between Path 5, 6, 10, and 14.
Preliminary Results

- As traffic becomes more congested, the advantage of path 14 in travel time becomes smaller; traffic demand shifts from path 14 (most energy efficient) to other paths such as path 6 (cheaper and relatively efficient).
- Need to consider traveler’s preference and multimodal network structures, even though energy consumption is the main concern.
Summary

- Build a rigorous mathematical model which provides technical support for system policy makers to reduce energy consumption in multimodal transportation systems in long-term.

- Case study indicates that system energy consumption can be significantly reduced by shifting traffic demand to the more energy efficient intermodal paths.

- It is possible that air, combined with other traffic modes such as transit and rail, results in energy efficient intermodal paths. The collaboration between different traffic modes will benefit energy consumption reduction.

- System policy affecting both demand and supply is needed to reduce energy consumption in multimodal transportation systems

- Systematically considering the mode energy efficiency, traveler preference, and network structure is needed to reduce energy consumption in multimodal transportation systems
Future Work

- The emission and energy consumption issues in metropolitan multimodal transportation systems, such as Chicago
- Traffic modes
  - Transit, private auto, metro, rail
  - Need data supports from the supply side
- Clarify the applicable policy options
  - Need the input from policy maker side
- Interaction between policy options taking and traffic supply
  - Need necessary data support
- Traffic demand
  - Traffic demand distribution
  - Traffic mode choice model
OTHER MAJOR INITIATIVE
IntelliDrive with Vehicle-Infrastructure (and Driver-Data) Integration

- Real-time Data Capture and Management
- Many Applications

Data-rich Environment

- Vehicle Status Data
- Infrastructure Status Data
- Weather Data
- Truck Data
- Location Data

Reduce Speed 35 MPH
Transit Signal Priority
Weather Application
Real-Time Travel Info
Signal Phase & Timing Adjusts Real-Time Conditions
Safety Alerts and Warnings

Source: USDOT
Routing Policy I (II): At each intersection \( n \), this policy helps drivers find a link \( a^* \) among all the available links so that the expected travel time (variance) from current link to destination is minimized.
**MAJOR INITIATIVE**

**IntelliDrive: Reliable Route Guidance Experiments**

- **Borman Sub-network as Test-bed**
  - Origin node (27), Destination node (19)
  - 29 nodes and 46 links
  - Running experiments in 30 days
  - Providing daily guidance for traveler to go through the O-D

- **Findings of Routing Policy I**
  - Employing the short-term arc travel time distribution, always leads to a path with a smaller average travel time than, applying long-term historical arc travel time distribution
  - With the same real-time information accuracy, routing policy I will result in a better path than pre-defined shortest path
  - With high real-time information accuracy, online routing following policy I will significantly improve the chance to find out the best path on the ground

- **Findings of Routing Policy II**
  - Paths under the guidance of Policy I and Policy II integrating short-term travel time distribution have less variance than the path using long-term historic travel time distribution
  - The path under the guidance of Policy II has less variance than the route under Policy I
  - Hence, the Routing Policy II can efficiently find the most reliable path en-route; in addition it benefits from the embedded information fusion model
Thank you!

Comments and Questions?
Preliminary Results

- Experiments: increase road traffic time to 1.25, 1.5, 1.75, and 2 times of the original value $t^0$
- Check the system optimal solution
- 4 Paths are included
- Paths 5 (1-2-6), 10 (1-3-7), and 14 (1-4-8): Transit, Air, and Transit
- Path 6 (1-2-6): Transit, Air, and Rail

Path 14 has the smallest travel time; Path 10 consumes the least fuel; Path 5 and Path 6 are relatively cheap; the trade-off exists between Path 5, 6, 10, and 14.
Mathematical Program with Complementarity Constraints (MPCC)

\[
\begin{align*}
\text{Min} & \quad \sum_l \sum_i r_{li} \delta_{li} \\
\text{s.t.} & \quad M^1 \\
0 & \leq z_{li} \leq 1, \ l \in L, \ i \in I \\
0 & \leq s_{li} \leq 1, \ l \in L, \ i \in I \\
\rho_h^\kappa - \lambda^\kappa - \sum_{l=1}^L \sum_{i=1}^I \mu_i^l m_{hi}^l + \gamma_h^\kappa & = 0, \ h \in H, \ k \in K \\
\sum_{h=1}^H x_h^\kappa & = D_k, \ k \in K \\
0 & \leq \gamma_h^\kappa \perp x_h^\kappa \geq 0, \ h \in H, \ k \in K \\
0 & \leq \mu_i^l \perp r_{lip_i} - \sum_{h=1}^H (m_{hi}^l \sum_{k=1}^K x_h^k) \geq 0, \ i \in I, \ l \in L 
\end{align*}
\]

The same as previous model

Linear relaxation

KKT conditions
Future Work

- Perform more comprehensive case study over a large network
- Test the impact of gasoline price on the system energy consumption
- Test the interactions between different modes including network structure changes

The end
Thank you!
## Input Data Based on Survey (1/2)

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Lagrangian, KKT Conditions

- **Lagrangian function**

\[
L(x, \lambda, \mu, \gamma) = \sum_{h=1}^{H} \sum_{\kappa=1}^{K} \rho^\kappa_h x^\kappa_h - \sum_{\kappa=1}^{K} \lambda^\kappa \left( \sum_{h=1}^{H} x^\kappa_h - D^\kappa \right) - \sum_{l=1}^{L} \sum_{i=1}^{I} \mu_{li} \left( \sum_{h=1}^{H} \left( m^l_{hi} \sum_{\kappa=1}^{K} x^\kappa_h \right) - r_{li} p_{li} \right) + \sum_{h=1}^{H} \sum_{\kappa=1}^{K} \gamma^\kappa_h x^\kappa_h
\]

- **KKT Conditions**

\[
\begin{align*}
\rho^\kappa_h - \lambda_k - \sum_{i=1}^{I} \sum_{i=1}^{J} \mu_{li} m^l_{hi} + \gamma^\kappa_h &= 0, \ h \in H, \kappa \in K \\
\sum_{h=1}^{H} \sum_{\kappa=1}^{K} x^\kappa_h &= D_k \\
0 &\leq \gamma^\kappa_h \perp x^\kappa_h \geq 0, \ h \in H, \kappa \in K \\
0 &\leq \mu_{li} \perp r_{li} p_{li} - \sum_{h=1}^{H} \left( m^l_{hi} \sum_{\kappa=1}^{K} x^\kappa_h \right) \geq 0, \ i \in I, l \in L
\end{align*}
\]
World Energy Production 2007/08
Methodology

**Variables**

- **Supplier side**
  - $c, r$
  - $\alpha^e, \alpha^e$
  - $\beta^e, \beta^e$

- **S-D:** $z, s$

- **Demand side**
  - $x, y$

**Parameters**

- **Policy maker side**
  - Allowance, tax impact $c^0$

- **Supplier side**
  - $r^0, c^0, t^0, w^0, p^0, \delta$
  - $[b^r, u^r], [b^c, u^c]$
  - $(\pi^r, \pi^c), (\varepsilon, \varepsilon)$

- **Demand side**
  - $(\theta, \vartheta), (\zeta, \eta)$

- **Main Idea**

  - **Policy Maker**
    - Make policy to minimize energy consumption

  - **Traffic Supplier**
    - Adjust fare and service frequency to guarantee profit for most modes

  - **S-D: Ridership Elasticity**

  - **Traffic Demand**
    - Maximize trip satisfaction
Branch and Bound Algorithm

Initial

\( l = 1 \)
\( i = 2 \)
\( LB \)

- Check new candidate nodes
  - \( l = l + 1 \)
  - \( i = i + 1 \)
  - \( z^*, s^* \)
  - LB

Update LB and candidate solution \((z^*, s^*)\) if F1, F2 or F3 provides integer solution

\[ z_{li} + s_{li} \leq 1, \ i = \{2, 3, 4\}, \ l = 1 \ldots L; \ z_{li} \in \{0, 1\}; \ s_{li} \in \{0, 1\}; \]
Transportation Dominates Total U.S. Petroleum Consumption

Share of U.S. Petroleum Use by Transportation Modes, 2009

- **Cars and Light Trucks**: 48%
- **Trucks**: 29%
- **Aviation**: 6%
- **Other modes**: 4%
- **Non-transport**: 13%

*Source: U.S. Dept. of Energy*

- **Car and Light Trucks** account for most of the share, then Truck and Aviation
Motivations

Oil provides 36% of energy sources in USA
Non-renewable energy source, limited storage on earth
Energy crisis has gained attention around the world
