EPA

Freight Demand Modeling and Logistics Planning for Assessment of Freight Systems’ Environmental Impacts

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Outline

1. Background

2. Inter-regional Freight Demand Modeling
   - Forecasting freight demand considering economic growth factors
   - Freight transportation mode choice and its environmental impacts
   - Freight shipment demand network assignment under congestion
     - Integrated decision-support software

3. Intra-regional Freight Demand Modeling
   - Logistics systems planning for regional freight delivery
   - Urban freight truck routing under stochastic congestion and emission considerations

4. Conclusions and Future Research Plan
Background

• Rapid globalization and ever-increasing demand for freight movements
• Emission problems from freight transportation
  – Most freight transportation modes are powered by diesel engines
  – Significant sources of national air pollutants (e.g., NO\textsubscript{X}, PM) and greenhouse gases (e.g., CO\textsubscript{2}) (ICF Consulting, 2005)

• Emissions from freight transportation activities
  – Climate change (on global scale)
  – Air quality and human health (in regional and urban areas)

• Freight delivery systems need to be thoroughly investigated to understand their impacts on environment
Emission projections today

**Input-output model**
- Economy-wide model
- Separate economic sectors
- Apply emission coefficient to activity in each sector
  
  (+): *response to economic environment*, e.g. fuel switching
  
  (-): Little “How-to”–engineering component

**Technology & infrastructure model**
- Situation-specific
- Data intensive, requiring fleet composition, traffic links, etc.
- Emissions from specific conditions & vehicle types
  
  (+): Realistic emissions that can be connected to policy decisions
  
  (-): Difficult to extrapolate to other situations

**Hybrid model**
- Activity and growth driven by input-output model
- Linked to technology choice using general theoretical principles
- Models (e.g. emission rates) constrained by observations whenever possible

...and tomorrow
Inter-regional freight

Global Economic Forecasts

Future Economic Scenarios

Employment, Population; Commodity Origin & Destination

Inter-regional Freight Flow

CO2 & Pollutants Emission Projections

Shift share & Input-Output Model

Freight Commodity Transportation Forecasting Model

Phoenix Model

S. Smith, PNNL

Urban Spatial Structure

B. Lee, S. Lee, Urban Planning

Freight Transportation System

Y. Ouyang, T. Hwang, Transportation (CEE)

Air Quality and Emission

T. Bond, L. Liu, F. Yan, Air Quality (CEE)

For heavy-duty trucks and rail
Intra-regional freight

Global Economic Forecasts

Future Economic Scenarios

Phoenix Model

Urban Spatial Structure

Urban development scenarios
(compact/polycentric/BAU)

Spatial autoregression model

Freight Transportation System

Delivery activity

Ring-sweep algorithm

Air Quality and Emission

CO2 & Pollutants Emission Projections

SPEWTrand Model

For medium duty trucks; not presented here

S. Smith, PNNL

B. Lee, S. Lee, Urban Planning

Y. Ouyang, T. Hwang, Transportation (CEE)

T. Bond, L. Liu, F. Yan, Air Quality (CEE)
Framework

Freight demand and logistics modeling:
Develop and integrate a set of U.S. freight transportation system models to capture interdependencies on future economic growth and urban spatial structure changes.

Scope
(i) Inter-regional freight flow; e.g., from Los Angeles to Chicago
(ii) Intra-regional freight flow; e.g., within Chicago metropolitan area
(iii) Point-to-point delivery routing

Various Economic Factors Projections
Input-Output Commodity Value Forecasts
Employment Distribution within Domestic Regions

Inter-regional Freight Flow
Trip Generation
Trip Distribution
Mode Split
Traffic Assignment

Intra-regional Freight Flow
Regional Level Truck Freight Delivery
Point-to-Point Truck Routing in Urban Freight Delivery

Long-haul Truck and Rail Emission
Short-haul Truck Emission

Air Quality and Climate Impacts in the U.S. Regions
Global Air Quality and Climate Impacts

Global Economic Forecasts Models
Urban Spatial Structure and Input-Output Models
Freight Transportation Systems Models
Air Quality and Climate Impacts Models

Employment Distribution within Domestic Regions

Scope

(i) Inter-regional freight flow; e.g., from Los Angeles to Chicago
(ii) Intra-regional freight flow; e.g., within Chicago metropolitan area
(iii) Point-to-point delivery routing
Inter-regional Freight Demand

Four-step freight commodity transportation demand forecasting model (NCHRP Report 606, 2008)

Economic growth factor forecast for each geographical region

- **Trip Generation**
  - Entering and exiting freight demand (attractions and productions) by zone

- **Trip Distribution**
  - Zonal O/D freight demand

- **Mode Split**
  - Zonal O/D freight demand by shipping mode

- **Traffic Assignment**
  - Traffic flow, average speed on each link

123 domestic Freight Analysis Zone (FAZ)

[Diagram showing geographical region and network connections]
Introduction

- Objective
  Forecast future freight demand that begins and ends in each FAZ, and distribute them on all O/D pairs

- Methodology: RAS algorithm (Stone, 1961; Stone and Brown, 1962)
  Basic Ideas
  - Forecast of economic growth factors are given for all FAZs
  - Current FAZ structure does not change (i.e., neither new zone will appear nor currently existing zone will disappear)
  - Distribution of future freight demand is proportional to that of base-year demand
For commodity type \( i \in \{1, 2, \ldots, N\} \),

- \( O \) = origin zone set, \( \{1, 2, \ldots, Z\} \)
- \( D \) = destination zone set, \( \{1, 2, \ldots, Z\} \)

- \( P_o^i \) = base-year total production of commodity \( i \) in an origin zone \( o \)
- \( A_d^i \) = base-year total attraction of commodity \( i \) in a destination zone \( d \)
- \( \alpha_o^{i,y} \) = growth rate of commodity \( i \) production in an origin zone \( o \) for future year \( y \)
- \( \beta_d^{i,y} \) = growth rate of commodity \( i \) attraction in a destination zone \( d \) for future year \( y \)
- \( D_{od}^i \) = freight volume of commodity \( i \) moving from origin zone \( o \) to destination zone \( d \)
### Freight Demand Generation/Distribution

**Step 0.** Generate base-year freight demand O/D matrix for commodity $i$:

Let $D_{od}^i$ be base-year commodity $i$ freight movement from origin $o$ to destination $d$.

<table>
<thead>
<tr>
<th>O</th>
<th>1</th>
<th>2</th>
<th>..</th>
<th>$d$</th>
<th>..</th>
<th>Z</th>
<th>Given Production</th>
<th>Future Production</th>
</tr>
</thead>
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</tbody>
</table>

**Step 1.** Estimate future production and future attraction for all FAZs:

Multiply each $P_o^i$, $\alpha_o^{i,y}$ by $\beta_d^{i,y}$.

Define $V_o^i = \alpha_o^{i,y} P_o^i \cdot W_d^i$ and $A_d^i$, $\forall o \in O, d \in D$.

![Diagram of freight demand generation/distribution](image-url)
Freight Demand
Generation/Distribution

Step 2. Since future input and output commodity growth are modeled separately,

Total future production summed across all origin zones
\[ \left( \sum_{o \in O} V_o^i \right) \neq \]

Total future attraction summed across all destination zones
\[ \left( \sum_{d \in D} W_d^i \right) \]

- Assume freight commodity productions are derived by attractions
- Multiply future productions of all origin zones by the same factor:
  \[ V_o^i \leftarrow V_o^i \left( \frac{\sum_{d \in D} W_d^i}{\sum_{o \in O} V_o^i} \right), \forall o \in O. \]
  - Then, \( \sum_{o \in O} V_o^i = \sum_{d \in D} W_d^i \)
**Freight Demand Generation/Distribution**

**Step 3. Apply RAS algorithm:**

Modify each entry \( (D_{od}^i) \) iteratively to match with the future production in each row and the future attraction in each column.

Define tolerance \( \varepsilon \ll 1 \), and let \( L \) = large positive integer and \( n = 1 \).

Define \( R_o^i = \frac{V_o^i}{\sum_{d \in D} D_{od}^i}, \forall o \in O \), and \( C_d^i = \frac{W_d^i}{\sum_{o \in O} D_{od}^i} \), \forall d \in D \).

While \( \{(n \leq L) \text{ and } (|R_o^i - 1| > \varepsilon \text{ for some } o \in O \text{ or } |C_d^i - 1| > \varepsilon \text{ for some } d \in D)\} \)

\[
\begin{align*}
\text{Set } & D_{od}^i \leftarrow R_o^i D_{od}^i, & \forall o \in O, d \in D, \\
\text{Update } & C_d^i \leftarrow \frac{W_d^i}{\sum_{o \in O} D_{od}^i}, & \forall d \in D, \\
\text{Set } & D_{od}^i \leftarrow C_d^i D_{od}^i, & \forall o \in O, d \in D, \\
\text{Update } & R_o^i \leftarrow \frac{V_o^i}{\sum_{d \in D} D_{od}^i}, & \forall o \in O, \\
\text{Update } & n \leftarrow n + 1,
\end{align*}
\]

<table>
<thead>
<tr>
<th>O</th>
<th>1</th>
<th>2</th>
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<th>d</th>
<th>.</th>
<th>Z</th>
<th>Given Production</th>
<th>Future Production</th>
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<td>W_d^i</td>
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</table>
Freight Transportation Mode Choice

- **Goal**
  Draw connections among various economic and engineering factors, freight transportation modal choice, and subsequently freight transportation emissions
  
  - Significant difference in emissions across modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>CO₂ Emission Factor (kgCO₂/ton-mile)</th>
<th>CH₄ Emission Factor (gCH₄/ton-mile)</th>
<th>N₂O Emission Factor (gN₂O/ton-mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Road Truck</td>
<td>0.2970</td>
<td>0.0035</td>
<td>0.0027</td>
</tr>
<tr>
<td>Rail</td>
<td>0.0252</td>
<td>0.0020</td>
<td>0.0006</td>
</tr>
<tr>
<td>Waterborne Craft</td>
<td>0.0480</td>
<td>0.0041</td>
<td>0.0014</td>
</tr>
<tr>
<td>Aircraft</td>
<td>1.5270</td>
<td>0.0417</td>
<td>0.0479</td>
</tr>
</tbody>
</table>

Source: EPA (2008)

Freight Transportation Mode Choice

- Focus on two dominating freight modes: Truck and Rail
- Macroscopic binomial logit market share model for mode choice
  - Dependent variable: Annual market % share of shipments between modes (between 0 and 1)
  - Explanatory variables for each commodity type:
    - Commodity value per ton ($/ton): $VALUE$
    - Avg. shipment distance for truck (mile): $DIST_T$
    - Avg. shipment distance for rail (mile): $DIST_R$
    - Crude oil price ($/barrel): $OILPRC$
  - Data: Observed modal split for each O/D pair
Mode Choice: 
Binomial Logit Market Share Model

Utility of truck for commodity $n$: $U^n_T = a_{1n} + b_{1n} \cdot VALUE + c_{1n} \cdot DIST_T + d_{1n} \cdot OILPRC,$
Utility of rail for commodity $n$: $U^n_R = a_{2n} + b_{2n} \cdot VALUE + c_{2n} \cdot DIST_R + d_{2n} \cdot OILPRC,$

Market share of truck for commodity $n$: $P^n_T = \frac{e^{U^n_T}}{e^{U^n_T} + e^{U^n_R}} = \frac{e^{U^n_T - U^n_R}}{e^{U^n_T - U^n_R} + 1},$

Market share of rail for commodity $n$: $P^n_R = \frac{e^{U^n_R}}{e^{U^n_T} + e^{U^n_R}} = \frac{1}{e^{U^n_T - U^n_R} + 1},$

$\ln \left( \frac{P^n_T}{1 - P^n_T} \right) = U^n_T - U^n_R$

$= (a_{1n} - a_{2n}) + (b_{1n} - b_{2n}) \cdot VALUE + (c_{1n}) \cdot DIST_T + (-c_{2n}) \cdot DIST_R + (d_{1n} - d_{2n}) \cdot OILPRC.$

- Generalized linear form with four explanatory variables
- Intercept and coefficients estimated via linear regression
Data Sources and Processing

• Freight Transportation Data
  – Freight Analysis Framework (FAF) database from the U.S. DOT
    Datasets Version 2 (FAF²) for year 2002 and version 3 (FAF³) for year 2007
  – Commodity Flow Survey (CFS) data from the U.S. Census Bureau
    Freight transportation activities in years 1993 and 1997
    Average shipment distances of truck and rail
  – West Texas Intermediate (WTI) crude oil price from Economagic.com
    o Merged into one useable database (69,477 observations)

• Divide the database into two sets for each commodity type
  i. Training set for estimation: 2/3 of the total observations
  ii. Test set for validation: 1/3 of the total observations

• Statistical software package, R (version 2.12.1)
Estimation Results and Goodness of Fit

<table>
<thead>
<tr>
<th></th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
<th>Type 5</th>
<th>Type 6</th>
<th>Type 7</th>
<th>Type 8</th>
<th>Type 9</th>
<th>Type 10</th>
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<tr>
<td>Intercept</td>
<td>1.989E+00</td>
<td>1.777E+00</td>
<td>3.800E+00</td>
<td>9.383E-01</td>
<td>1.390E+00</td>
<td>2.954E+00</td>
<td>3.014E+00</td>
<td>1.910E+00</td>
<td>1.702E+00</td>
<td>9.978E-01</td>
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<tr>
<td>z-statistic Intercept</td>
<td>12761.00</td>
<td>5868.29</td>
<td>28335.00</td>
<td>10357.00</td>
<td>15685.00</td>
<td>21139.20</td>
<td>4176.90</td>
<td>5472.90</td>
<td>811.40</td>
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<tr>
<td>Pr(&gt;</td>
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<tr>
<td>z-statistic Value per ton</td>
<td>2.428E-03</td>
<td>2.096E-03</td>
<td>1.059E-03</td>
<td>9.746E-03</td>
<td>6.210E-04</td>
<td>6.130E-04</td>
<td>4.850E-04</td>
<td>1.113E-04</td>
<td>7.085E-04</td>
<td>4.311E-03</td>
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<tr>
<td>Avg. truck distance</td>
<td>-1.532E-03</td>
<td>-1.766E-03</td>
<td>-1.190E-03</td>
<td>-1.663E-03</td>
<td>-1.531E-03</td>
<td>1.904E-04</td>
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<td>-4.025E-03</td>
<td>-1.901E-03</td>
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<td>z-statistic</td>
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<td>-2488.00</td>
<td>-3390.00</td>
<td>-2418.20</td>
<td>252.00</td>
<td>3714.60</td>
<td>2113.00</td>
<td>-1792.30</td>
<td>-472.10</td>
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<tr>
<td>Avg. rail distance</td>
<td>-1.123E-03</td>
<td>5.149E-06</td>
<td>-1.960E-03</td>
<td>-2.155E-03</td>
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<tr>
<td>WTI crude oil price</td>
<td>4.579E-03</td>
<td>-4.808E-03</td>
<td>-1.383E-02</td>
<td>-2.901E-02</td>
<td>-7.312E-03</td>
<td>-3.134E-03</td>
<td>-1.297E-03</td>
<td>1.011E-02</td>
<td>2.285E-02</td>
<td>3.305E-02</td>
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<td>z-statistic</td>
<td>1634.00</td>
<td>-965.59</td>
<td>-5993.00</td>
<td>-14669.00</td>
<td>-2758.90</td>
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<tr>
<td>(b) Number of data used</td>
<td>3,802</td>
<td>5,468</td>
<td>3,753</td>
<td>3,105</td>
<td>5,883</td>
<td>6,068</td>
<td>6,035</td>
<td>5,100</td>
<td>5,041</td>
<td>2,062</td>
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<td>(c) Pseudo McFadden</td>
<td>0.348</td>
<td>0.427</td>
<td>0.241</td>
<td>0.659</td>
<td>0.270</td>
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<td>0.203</td>
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<td>R-squared</td>
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<td>0.456</td>
<td>0.261</td>
<td>0.747</td>
<td>0.311</td>
<td>0.410</td>
<td>0.143</td>
<td>0.229</td>
<td>0.143</td>
<td>0.445</td>
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</tbody>
</table>
Estimation Results and Goodness of Fit

• All estimates are statistically significant (all \( p \)-values \( \leq 0.001 \))

• Interpretations and insights
  – Positive Intercept: Everything else being equal, truck is more likely to be chosen
  – Positive “Value per ton”: Truck tends to ship higher value goods than rail
  – Negative “Avg. truck distance”: As shipping distance increases, utility of truck decreases
  – Negative “Avg. rail distance”: As shipping distance increases, rail is preferred
  – Negative “WTI crude oil price”: As oil price increases, rail is preferred
Traffic Assignment

• Goal: Assign freight traffic onto modal networks for all shipment O/D pairs

• Route choice rule: User equilibrium (Wardrope, 1959; Sheffi, 1985)
  – Each motorist selects the shortest travel time route between O/D
  – All used routes connecting each O/D pair have the same cost/travel time which is less than or equal to the costs of unused routes

• Algorithm
  1. Convex combinations algorithm (Frank and Wolfe, 1956, coded in VC++)
  2. Input: graph representation of modal networks, demand for all O/D pairs
  3. Output file: assigned traffic flow, average speed on each link, link cost, etc.
Truck Traffic Assignment

• Model development
  – Standard network assignment problem under user equilibrium principle (Sheffi, 1985)
  – Bureau of Public Roads (BPR) link cost function (Bureau of Public Roads, 1970) modified to include background traffic volume

• Data for graph representation of freight truck network
  1) O/D nodes: 120 centroids of FAF³ regions boundary
     – Exclude Hawaii (2 zones) and Alaska (1 zone)
  2) U.S. road network: FAF³ network
     – Consider only major interstate highways
     – Background traffic (AADT) and link capacity in Year 2007

• Data for truck freight demand
  FAF³ truck shipment database (FHWA U.S. DOT, 2011)
  – Real truck freight demand data (in tonnage) in Year 2007
Truck Traffic Assignment: Data (2)

- Simplified U.S. major highway freight truck road network

1) 178 nodes
   - Centroids of domestic FAZs (120 nodes)
   - Major junctions in the interstate highway network (58 nodes)

2) 14,400 O/D pairs
   - Each centroid of 120 FAF³ zones is both origin and destination of freight demand

3) 588 links
   - Mostly major interstate highways
   - Some local roads: for FAF³ centroids located far from the major interstate highway network
Truck Traffic Assignment: Data (3)

- Parameters
  - Average truckload (tons per truck) = 16 (FHWA U.S. DOT, 2007; EPA and NHTSA, 2011)
  - Passenger-car equivalents (assuming rolling terrain) = 2.5 (HCM, 2000)
  - Hours of operation of the freight truck delivery system = 24×365
  - Truck free flow speed (mph) = 65 (Bai et al., 2011)
  - Background traffic = AADT/(2 × 24)
  - BPR link cost function modified to include background traffic volume

\[ t(\omega) = t_f \left[ 1 + \alpha \left( \frac{\omega + b}{C} \right)^\beta \right] \]

where \( t_f \) = link free flow travel time (hr), \( \omega \) = assigned traffic volume (# of veh/hr), \( b \) = background traffic volume (# of veh/hr), \( C \) = link capacity (# of veh/hr), \( \alpha = 0.15 \), and \( \beta = 4 \)
Truck Traffic Assignment Results

- Total Cost = \( \sum \) (Link Travel Time \( \times \) Assigned Link Flow) = \( \sum_{a \in A} t_a(x_a) x_a = 699,827.88 \) (veh-hr/hour)
- Convergence is reached within a tolerance of 0.0001% after 12 iterations (0.640 sec CPU time)
- Output: link and node number, link distance, total and assigned traffic volume, link cost (link travel time), average link speed at equilibrium

* Unit of assigned flow:
  # of vehicles (passenger cars) per hour
Model Validation

- Freight traffic distribution (annual tonnage) on the U.S. highway (red), rail (brown), and inland waterways (blue) networks in Year 2007 (FHWA U.S. DOT, 2011)
Model Validation

- Truck traffic distribution on the U.S. highway network

Trend consistent in a high level:
Washington, Oregon, California, Florida, the Midwest states near Chicago, and northeastern regions

Less emphasized in our result:
Some main highway links that connect Southern California, Arizona, and Oklahoma
Rail Traffic Assignment

• Rail network operates very differently from highway network
  - Link traffic flow in opposite directions shares the same track infrastructure
  - Assign bi-directional traffic flow on one shared undirected link (i.e., undirected graph)
• Railroad-specific link cost function (Krueger 1999; Lai and Barkan, 2009)
  – For undirected railroad link $e \in E$

$$
    t_e(\omega_e) = T_e + \frac{\alpha_e d_e}{100} e^{\beta_e \omega_e}, \forall e \in E,
$$

where,  

- $T_e$ = link free flow travel time (hour)
- $d_e$ = link length (mile)
- $\omega_e$ = the total rail link flow (# of trains/day)
- $\alpha_e, \beta_e$ = parameters uniquely determined by rail operating conditions

Rail Traffic Assignment: Methodology

- Equivalent directed graph representation of the undirected rail network
  Each undirected link is replaced by two separate directed links in opposite directions

- Railroad link cost function for the directed graph

\[ t_{ij}(x_{ij} + x_{ji}) = T_{ij} + \frac{\alpha_{ij} d_{ij}}{100} e^{\beta_{ij}(x_{ij} + x_{ji})}, \forall (i, j) \in A \]

  Link travel times on both directed links (from node \( i \) to \( j \) and from node \( j \) to \( i \)) are identical

- Modify conventional convex combinations algorithm
  - Consider traffic volume in both directions whenever link cost is updated
Rail Traffic Assignment: Data (1)

• Data for graph representation of rail network
  1) O/D nodes: 120 centroids of FAF³ regions boundary
     – Exclude Hawaii (2 zones) and Alaska (1 zone)
  2) U.S. rail network: Rail network GIS data (ATLAS, 2011)
     – Select rail network main lines on which Class I railroads (AMTK, BNSF, CSXT, KCS, NS, UP, CN, CP in the database) operate
     – Incorporated double track information obtained from Richards and Cobb (2010)

• Data for rail freight demand
  – Converted the freight shipment demand in tonnage into equivalent numbers of trainloads based on the types of commodities (AAR, 2007; Cambridge Systematics, Inc., 2007)

• Parameters: operation days per year = 365; free flow speed (mph) = 60 (Krueger, 1999)
Railroad Traffic Assignment: Data (2)

- Simplified U.S. rail network

1) 183 nodes
   - Centroids of domestic FAZs (120 nodes)
   - Major intersections in the selected rail network (63 nodes)

2) 40,909 O/D pairs
   - Consider both shipment O/D pairs and commodity types

3) 566 links
   - Mostly major railroad tracks on which Class I railroads operate
   - Some tracks on which other minor railroads operate: for FAF$^3$ centroids located far from the major rail network
Railroad Traffic Assignment: User Equilibrium Results

- Total Cost = \( \sum (\text{Link Travel Time} \times \text{Assigned Link Flow}) = \sum_{(i,j) \in A} t_{ij} (x_{ij} + x_{ji}) x_{ij} = 75,426 \) (train-hr/day)
- Convergence is reached within a tolerance of 0.001% after 2,569 iterations (25.559 sec CPU time)
- Output: link number, link origin and destination node, link distance, freight shipment volume (for each commodity type), link cost (link travel time), average link speed

* Unit of assigned flow: # of trains per day
Model Validation

- Rail traffic distribution on the U.S. rail network

Trend consistent at a high level:
Washington, California, Wyoming, Montana, the Midwest states near Chicago, northeastern regions, and some main links that connect Southern California, Texas, and Kansas

More emphasized in our result:
Idaho, Oregon, and southeastern regions
Software Development

- Integrated decision-support software for four-step inter-regional freight demand forecasting
- Visual Basic Applications (VBA) in Microsoft Excel platform

Overview of the software

Input

Main Program

Output

Included in one Excel file
Software Development

- Procedure of the program

Input

Main Program

Output

Four-step Inter-regional Freight Commodity Transportation Demand Forecasting Model

Future Year: 2010

Economic Growth and Environmental Policy Scenario:

1. High Business as usual

Uncheck if individual step needs to be run

Entire Model

Trip Generation → Trip Distribution → Modal Split → Network Assignment

Show input data sheets

*Note: This software will periodically provide an opportunity to abort the program. No response is needed if you want to keep the program running.*
Software Development

- Input worksheets
  - Each step in the four-step analysis requires different input worksheets to conduct the analysis
  - Total eighteen different input worksheets
    - Trip generation and Trip distribution
      - “Attraction_S1”, “Attraction_S2”, “Attraction_S3”, “Attraction_S4”, “Production_S1”, “Production_S2”, “Production_S3”, “Production_S4”, and “2007Demand”
    - Modal split
      - “TruckDist”, “RailDist”, and “ModalSplit”
    - Network assignment

Procedure of the program
- Input
- Main Program
- Output
Software Development

- **Procedure of the program**

  - **Input**
  - **Main Program**
  - **Output**

- **Output worksheets**
  Results from different steps will be recorded in seven different output worksheets
  - Trip generation
    - “Trip_Generation”
  - Trip distribution
    - “Trip_Distribution”
  - Modal split
    - “Modal_Split”
  - Truck freight demand network assignment
    - “TruckResult” and “TruckMap”
  - Rail freight demand network assignment
    - “RailResult” and “RailMap”
Software Development

Visualization of the final results

“TruckMap” worksheet

“RailMap” worksheet

• Help decision-makers explore atmospheric impacts of future freight shipment activities in various economic scenarios
Illustrative Examples of Model Application

Sample Questions:

• How would economic growth affect inter-regional freight transportation?
• How would fuel price affect freight modal choice?
• How could congestion in current transportation infrastructure restrict freight movements, and what are the impacts of capacity investments?
Future Freight Demand Forecast

• Forecast future freight demand distribution within the U.S. from 2010 to 2050 in five-year increments

• Four scenarios
  - Scenario 1 (S1): High GDP growth & Business as usual
  - Scenario 2 (S2): High GDP growth & Climate policy
  - Scenario 3 (S3): Low GDP growth & Business as usual
  - Scenario 4 (S4): Low GDP growth & Climate policy

• Data
  1. Base-year freight demand distribution matrix:
     Freight Analysis Framework data version 3 (FAF³) for Year 2007
        Origin, Destination, Commodity type, Freight demand (in tonnage)
  2. Future I/O commodity value growth estimates for all scenarios:
     Exogenously given from the input-out model (2005-2050 in five-year increments)
Future Freight Demand Forecast

- Freight demand forecasting results
  - Algorithm converged in a short time
  - Future freight demand is generated (360, 120-by-120 matrices)

<table>
<thead>
<tr>
<th>Year</th>
<th>Scenario 1: High GDP growth with business as usual (c) Total freight demand forecasted (thousand ton) (g) % change</th>
<th>Scenario 2: High GDP growth with climate policy (d) Total freight demand forecasted (thousand ton) (h) % change</th>
<th>Scenario 3: Low GDP growth with business as usual (e) Total freight demand forecasted (thousand ton) (i) % change</th>
<th>Scenario 4: Low GDP growth with climate policy (f) Total freight demand forecasted (thousand ton) (j) % change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>15,059,745</td>
<td>15,059,745</td>
<td>15,059,745</td>
<td>15,059,745</td>
</tr>
<tr>
<td>2010</td>
<td>15,703,789</td>
<td>15,648,288</td>
<td>15,528,787</td>
<td>15,494,244</td>
</tr>
<tr>
<td>2015</td>
<td>17,501,995</td>
<td>17,438,001</td>
<td>16,929,857</td>
<td>16,890,825</td>
</tr>
<tr>
<td>2020</td>
<td>19,431,308</td>
<td>18,780,540</td>
<td>18,355,956</td>
<td>17,742,894</td>
</tr>
<tr>
<td>2025</td>
<td>21,438,103</td>
<td>20,650,764</td>
<td>19,755,145</td>
<td>19,023,791</td>
</tr>
<tr>
<td>2030</td>
<td>23,693,953</td>
<td>22,780,286</td>
<td>21,271,576</td>
<td>20,435,507</td>
</tr>
<tr>
<td>2035</td>
<td>26,034,285</td>
<td>24,945,108</td>
<td>22,725,696</td>
<td>21,747,683</td>
</tr>
<tr>
<td>2040</td>
<td>28,697,929</td>
<td>27,356,813</td>
<td>24,523,312</td>
<td>23,339,737</td>
</tr>
<tr>
<td>2045</td>
<td>31,574,234</td>
<td>29,893,810</td>
<td>26,377,074</td>
<td>24,903,553</td>
</tr>
<tr>
<td>2050</td>
<td>34,673,664</td>
<td>32,621,827</td>
<td>28,351,364</td>
<td>26,573,564</td>
</tr>
</tbody>
</table>

- Suitable for long-term economic forecasts
  Global economic forecasts models: hard to capture unexpected short-term economic fluctuations (e.g., recession in 2007-2009)
Model Application - Emission Estimation

- Modal split and the following emission estimations for a range of WTI crude oil price
  - Select one arbitrary data record: Commodity type 5 (basic chemicals, chemical and pharmaceutical products) from Texas to Colorado

<table>
<thead>
<tr>
<th>Freight value per unit weight</th>
<th>Avg. truck distance</th>
<th>Avg. rail distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1,240.85/ton</td>
<td>1,005 miles</td>
<td>1,332 miles</td>
</tr>
</tbody>
</table>

Total annual freight shipment demand in data = 328,000 ton

- Forecast annual freight shipment split for different oil price range
- Estimate total emission and greenhouse gas inventory


<table>
<thead>
<tr>
<th></th>
<th>CO₂ emission factor (kgCO₂/ton-mile)</th>
<th>CH₄ emission factor (gCH₄/ton-mile)</th>
<th>N₂O emission factor (gN₂O/ton-mile)</th>
<th>PM₁₀ emission factor (gPM₁₀/ton-mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>0.2970</td>
<td>0.0035</td>
<td>0.0027</td>
<td>0.092</td>
</tr>
<tr>
<td>Rail</td>
<td>0.0252</td>
<td>0.0020</td>
<td>0.0006</td>
<td>0.013</td>
</tr>
</tbody>
</table>
## Model Application - Emission Estimation

<table>
<thead>
<tr>
<th>WTI crude oil price ($/barrel)</th>
<th>Truck share prediction (%)</th>
<th>Rail share prediction (%)</th>
<th>Truck CO₂ emission (ton)</th>
<th>Rail CO₂ emission (ton)</th>
<th>Total CO₂ emission (ton)</th>
<th>Truck CH₄ emission (kg)</th>
<th>Rail CH₄ emission (kg)</th>
<th>Total CH₄ emission (kg)</th>
<th>Truck N₂O emission (kg)</th>
<th>Rail N₂O emission (kg)</th>
<th>Total N₂O emission (kg)</th>
<th>Truck PM₁₀ emission (kg)</th>
<th>Rail PM₁₀ emission (kg)</th>
<th>Total PM₁₀ emission (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>66.8%</td>
<td>33.2%</td>
<td>65,412</td>
<td>3,654</td>
<td>69,066</td>
<td>771</td>
<td>290</td>
<td>1,061</td>
<td>595</td>
<td>87</td>
<td>682</td>
<td>20,262</td>
<td>1,885</td>
<td>22,147</td>
</tr>
<tr>
<td>60</td>
<td>63.5%</td>
<td>36.5%</td>
<td>62,163</td>
<td>4,019</td>
<td>66,182</td>
<td>733</td>
<td>319</td>
<td>1,052</td>
<td>565</td>
<td>96</td>
<td>661</td>
<td>19,256</td>
<td>2,073</td>
<td>21,329</td>
</tr>
<tr>
<td>80</td>
<td>60.0%</td>
<td>40.0%</td>
<td>58,784</td>
<td>4,399</td>
<td>63,183</td>
<td>693</td>
<td>349</td>
<td>1,042</td>
<td>534</td>
<td>105</td>
<td>639</td>
<td>18,209</td>
<td>2,269</td>
<td>20,479</td>
</tr>
<tr>
<td>100</td>
<td>56.5%</td>
<td>43.5%</td>
<td>55,304</td>
<td>4,791</td>
<td>60,094</td>
<td>652</td>
<td>380</td>
<td>1,032</td>
<td>503</td>
<td>114</td>
<td>617</td>
<td>17,131</td>
<td>2,471</td>
<td>19,602</td>
</tr>
<tr>
<td>120</td>
<td>52.9%</td>
<td>47.1%</td>
<td>51,758</td>
<td>5,189</td>
<td>56,947</td>
<td>610</td>
<td>412</td>
<td>1,022</td>
<td>471</td>
<td>124</td>
<td>594</td>
<td>16,033</td>
<td>2,677</td>
<td>18,710</td>
</tr>
<tr>
<td>140</td>
<td>49.2%</td>
<td>50.8%</td>
<td>48,181</td>
<td>5,591</td>
<td>53,773</td>
<td>568</td>
<td>444</td>
<td>1,012</td>
<td>438</td>
<td>133</td>
<td>571</td>
<td>14,925</td>
<td>2,885</td>
<td>17,809</td>
</tr>
<tr>
<td>160</td>
<td>45.6%</td>
<td>54.4%</td>
<td>44,613</td>
<td>5,993</td>
<td>50,606</td>
<td>526</td>
<td>476</td>
<td>1,001</td>
<td>406</td>
<td>143</td>
<td>548</td>
<td>13,820</td>
<td>3,091</td>
<td>16,911</td>
</tr>
<tr>
<td>180</td>
<td>42.0%</td>
<td>58.0%</td>
<td>41,091</td>
<td>6,389</td>
<td>47,480</td>
<td>484</td>
<td>507</td>
<td>991</td>
<td>374</td>
<td>152</td>
<td>526</td>
<td>12,729</td>
<td>3,296</td>
<td>16,024</td>
</tr>
<tr>
<td>200</td>
<td>38.5%</td>
<td>61.5%</td>
<td>37,651</td>
<td>6,776</td>
<td>44,426</td>
<td>444</td>
<td>538</td>
<td>981</td>
<td>342</td>
<td>161</td>
<td>504</td>
<td>11,663</td>
<td>3,495</td>
<td>15,158</td>
</tr>
<tr>
<td>220</td>
<td>35.1%</td>
<td>64.9%</td>
<td>34,324</td>
<td>7,150</td>
<td>41,474</td>
<td>404</td>
<td>567</td>
<td>972</td>
<td>312</td>
<td>170</td>
<td>482</td>
<td>10,632</td>
<td>3,688</td>
<td>14,321</td>
</tr>
<tr>
<td>240</td>
<td>31.8%</td>
<td>68.2%</td>
<td>31,140</td>
<td>7,508</td>
<td>38,648</td>
<td>367</td>
<td>596</td>
<td>963</td>
<td>283</td>
<td>179</td>
<td>462</td>
<td>9,646</td>
<td>3,873</td>
<td>13,519</td>
</tr>
<tr>
<td>260</td>
<td>28.7%</td>
<td>71.3%</td>
<td>28,120</td>
<td>7,848</td>
<td>35,968</td>
<td>331</td>
<td>623</td>
<td>954</td>
<td>256</td>
<td>187</td>
<td>442</td>
<td>8,711</td>
<td>4,048</td>
<td>12,759</td>
</tr>
<tr>
<td>280</td>
<td>25.8%</td>
<td>74.2%</td>
<td>25,282</td>
<td>8,167</td>
<td>33,449</td>
<td>298</td>
<td>648</td>
<td>946</td>
<td>230</td>
<td>194</td>
<td>424</td>
<td>7,832</td>
<td>4,213</td>
<td>12,044</td>
</tr>
<tr>
<td>300</td>
<td>23.1%</td>
<td>76.9%</td>
<td>22,638</td>
<td>8,464</td>
<td>31,102</td>
<td>267</td>
<td>672</td>
<td>939</td>
<td>206</td>
<td>202</td>
<td>407</td>
<td>7,012</td>
<td>4,366</td>
<td>11,379</td>
</tr>
</tbody>
</table>

- National emission estimation
  Aggregate emission calculations across all shipment O/D pairs and all commodity types
Rail Network Capacity Expansion and Its Effect on Network Assignment

- Rail freight demand: projected to increase 88% by Year 2035
  - Sever congestion is expected (Cambridge Systematics, Inc., 2007)
  - Infrastructure investment may be needed near potential chokepoints → Will affect future rail freight demand assignment patterns

- “Before and After” comparison for Year 2035
  - Action: on the most congested railroad links in 2035
  - Average link speed ≤ 10 mph
  - Single tracks will be expanded to full double tracks
Rail Network Capacity Expansion and Its Effect on Network Assignment

- Congestion prediction in Year 2035 without infrastructure investment

Our model

Cambridge Systematics, Inc. (2007)

- FAF3 zones
- 50 < Avg. speed
- 40 < Avg. speed ≤ 50
- 30 < Avg. speed ≤ 40
- 20 < Avg. speed ≤ 30
- 10 < Avg. speed ≤ 20
- 0 < Avg. speed ≤ 10

* Unit of Average speed: mph
Rail Network Capacity Expansion and Its Effect on Network Assignment

Congestion prediction from our model in 2035 after capacity expansion

<table>
<thead>
<tr>
<th>(a) Capacity expansion</th>
<th>Before</th>
<th>After</th>
<th>% reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b) Total cost (10^3 train-hr/day)</td>
<td>2,025</td>
<td>1,364</td>
<td>32.67</td>
</tr>
<tr>
<td>(c) Total ton-mile (10^3 ton-mile/day)</td>
<td>10,496,597</td>
<td>10,411,213</td>
<td>0.81</td>
</tr>
</tbody>
</table>

- Decrease in total ton-miles
  - Less detour toward shipment destinations
  - Improvements in rail freight delivery efficiency

* Unit of Average speed: mph
Framework

Freight demand and logistics modeling:
Develop and integrate a set of U.S. freight transportation system models to capture interdependencies on future economic growth and urban spatial structure changes

Scope
(i) Inter-regional freight flow; e.g., from Los Angeles to Chicago
(ii) Intra-regional freight flow; e.g., within Chicago metropolitan area
(iii) Point-to-point delivery routing
Introduction

• Bulk of freight arriving at the destinations (i.e., terminals) in each FAZ
  - Broken for delivery to distributed individual customers
  - Also, freight needs to be collected from a large number of supply points to the set of origins (i.e., terminals) in each FAZ

• Freight delivery activities within large urban areas are critical issues
  - Emissions from freight shipments comprise a large share of toxic air pollutants in most metropolitan areas worldwide (OECD, 2003)
  - Residents in metropolitan areas are more likely to be affected by the air pollution problems than those in rural areas

• Need to investigate freight shipment modeling and logistics planning at the intra-regional level
Introduction

• Logistics systems model for freight distribution within an FAZ
  – Vehicles need to serve spatially distributed customer demand which might be large scale (Large-scale Vehicle Routing Problem)
  – Estimate network delivery efficiency

• Methodology: Continuum Approximation (Newell and Daganzo, 1986a)
  (i) Assume continuous customer demand density that may vary slowly over space
  (ii) Suitable for large-scale estimation (asymptotic approximation)

• Objective: Estimate near-optimum total delivery distance

  Total travel distance within a delivery region
  = Total line-haul distance + Total local travel distance

(Ouyang, 2007)
Within FAZ Delivery Procedure

• Application of the ring-sweep algorithm to estimate regional freight delivery

• Assumptions
  – Freight demand in each census tract is concentrated at the centroid of the census tract
  – Freight demand will be assigned to the nearest terminal (if multiple terminals)
  – Freight is delivered by identical short-haul trucks with constant low speed (e.g. 30 mph)
  – Euclidean metric roadway network

• Objective: Estimate the total transportation cost (i.e., total travel distance)
Within FAZ Delivery

- Total delivery cost to serve freight demand within an FAZ
  = Total line-haul distance \((L_1)\) + Total local travel distance \((L_2)\)

- “distribution” and “collection”

(1) Total line-haul distance

\[
d_i = \text{distance from the terminal to the centroid of the census tract } i
\]

\[
E_{ij} = \text{number of employees in an industry type } j \text{ in the census tract } i
\]

\[
I = \text{total number of census tracts}
\]

\[
J = \text{total number of industry types considered}
\]

\[
C = \text{truck capacity (in tonnage)}
\]

\[
D = \text{total freight demand in a given FAZ (tons per day)}
\]

Total line-haul distance \((L_1)\) = \[
\frac{2D \sum_{i=1}^I \sum_{j=1}^J E_{ij} d_i}{C \sum_{i=1}^I \sum_{j=1}^J E_{ij}}
\]
Within FAZ Delivery

(2) Total local travel distance

\[ N = \text{total number of demand points in a given FAZ} = \sum_{i=1}^{I} N_i \]

where \( N_i = \text{total number of demand points in each census tract} \)

\[ i = \sum_{j=1}^{J} \frac{E_{ij}}{a_j} \]

\( a_j = \text{average number of employees per firm in an industry type } j \)
- represents how many employees are served on average by one truck visit
- may vary across industries

\[ \delta = \text{uniformly distributed demand point density in a given FAZ} \]

where \( A = \text{area of an FAZ} \)

Total local travel distance \( (L_2) = \frac{0.57N}{\sqrt{\delta}} \)
Application

• Estimate regional freight delivery cost and the related emissions (CO₂, NOₓ, PM, and VOC) in 36 FAZs that cover 27 major Metropolitan Statistical Areas (MSAs) from 2010 to 2050
• Data
  (i) Forecast of employment distributions (from urban spatial structure model): wholesale trade, retail trade, and manufacturing industries
  (ii) Future truck and rail freight demand for each FAZ (from four-step inter-regional freight demand model)
• Three urban development scenarios
  (i) Scenario 1 “Business as usual”: current urban sprawl continues in the U.S.
  (ii) Scenario 2 “Polycentric development”: CBD (current trend), sub-centers (high-growth)
  (iii) Scenario 3 “Compact development”: both CBD and sub-centers (high-growth)
• Inter-regional freight demand scenario: high GDP growth under business as usual
• Freight collection and distribution deliveries from truck and railroad terminals are modeled separately
• Commodities are delivered separately considering different industry types
• Light and medium trucks: capacity = 4 tons (FHWA U.S. DOT, 2007; Davis et al., 2012), avg. speed = 30 mph
Application

- Regional freight delivery from truck terminals

A number of truck terminals are located near the junctions of major highways

1. Commodities related to the wholesale and retail trade industries for terminal $k$

$$L_{f1}^k = \frac{2\alpha_1(D_w + D_R)\sum_{i=1}^{I_k} \sum_{j=1}^{2} E_{ij} d_{ki}}{C\sum_{i=1}^{I} \sum_{j=1}^{2} E_{ij}}, \quad L_{f2}^k = \frac{0.57 N_f^k}{\sqrt{\delta_f^k}}, \text{ where } N_f^k = \frac{\alpha_1}{a_1} \sum_{i=1}^{I_k} \sum_{j=1}^{2} E_{ij} \quad \text{and} \quad \delta_f^k = \frac{N_f^k}{A_k}$$

2. Commodities related to the manufacturing industry for terminal $k$

$$L_{p1}^k = \frac{2\alpha_2 D_M \sum_{i=1}^{I_k} E_{i3} d_{ki}}{C\sum_{i=1}^{I} E_{i3}}, \quad L_{p2}^k = \frac{0.57 N_p^k}{\sqrt{\delta_p^k}}, \text{ where } N_p^k = \frac{\alpha_2}{a_2} \sum_{i=1}^{I_k} E_{i3} \quad \text{and} \quad \delta_p^k = \frac{N_p^k}{A_k}$$

3. Total freight delivery cost in the FAZ summed across all truck terminals $k \in K$

$$G_T = \sum_{k=1}^{K} \left( L_{f1}^k + L_{f2}^k + L_{p1}^k + L_{p2}^k \right)$$
Application

• Regional freight delivery from railroad terminals
  Several railroad terminals are located near the intersections of major railroad links
  1. Commodities for direct shipments from railroad terminals
     - Trucks are not involved in freight delivery
  2. Commodities for short-haul truck delivery from railroad terminals
     (1) Commodities related to the wholesale and retail trade industries for terminal $q$
        $$L_{s1}^q = \frac{2\beta_1 (D_W + D_R) \sum_{i=1}^{I_q} \sum_{j=1}^{2} E_{ij} q_i}{C \sum_{i=1}^{I} \sum_{j=1}^{2} E_{ij}}, \quad L_{s2}^q = \frac{0.57 N_s^q}{\sqrt{\delta_s^q}},$$
        where $N_s^q = \frac{\beta_1 \sum_{i=1}^{I_q} \sum_{j=1}^{2} E_{ij}}{a_1}$ and $\delta_s^q = \frac{N_s^q}{A_q}$

     (2) Commodities related to the manufacturing industry for terminal $q$
        $$L_{m1}^q = \frac{2\beta_2 D_M \sum_{i=1}^{I_q} E_{i3} q_i}{C \sum_{i=1}^{I} E_{i3}}, \quad L_{m2}^q = \frac{0.57 N_m^q}{\sqrt{\delta_m^q}},$$
        where $N_m^q = \frac{\beta_2 \sum_{i=1}^{I_q} E_{i3}}{a_2}$ and $\delta_m^q = \frac{N_m^q}{A_h}$

  3. Total freight delivery cost in the FAZ summed across all railroad terminals $q \in Q$
     $$G_R = \sum_{q=1}^{Q} (L_{s1}^q + L_{s2}^q + L_{m1}^q + L_{m2}^q)$$
## Case Study

### Scenarios

1. Business as usual
2. Polycentric development
3. Compact development

<table>
<thead>
<tr>
<th>MSA</th>
<th># of FAZ</th>
<th>Scenario</th>
<th>CO₂ (10³ kg per day)</th>
<th>NOₓ (kg per day)</th>
<th>PM (kg per day)</th>
<th>VOC (kg per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2010</td>
<td>2030</td>
<td>2020</td>
<td>2040</td>
<td>2050</td>
</tr>
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<td>Los Angeles</td>
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<td>3,413.69</td>
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<td>4,479.54</td>
<td>14.91</td>
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<td>2</td>
<td>3,316.92</td>
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<td>3,284.42</td>
<td>3.89</td>
<td>3,898.15</td>
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<td>San Francisco</td>
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<td>1</td>
<td>1,660.95</td>
<td>4.30</td>
<td>2,028.74</td>
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<td>1,600.03</td>
<td>0.47</td>
<td>1,919.17</td>
<td>0.84</td>
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<tr>
<td></td>
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<td>3</td>
<td>1,592.55</td>
<td>1,903.15</td>
<td>2,275.03</td>
<td>2,718.09</td>
</tr>
<tr>
<td>Chicago</td>
<td>2</td>
<td>1</td>
<td>5,715.29</td>
<td>6.01</td>
<td>7,188.84</td>
<td>15.31</td>
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<td></td>
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<td>2</td>
<td>5,415.29</td>
<td>0.44</td>
<td>6,344.03</td>
<td>1.76</td>
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<tr>
<td></td>
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<td>3</td>
<td>5,391.50</td>
<td>6,234.48</td>
<td>7,478.88</td>
<td>8,887.85</td>
</tr>
<tr>
<td>New York</td>
<td>3</td>
<td>1</td>
<td>5,614.27</td>
<td>4.07</td>
<td>7,512.56</td>
<td>17.00</td>
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<td>2</td>
<td>5,423.98</td>
<td>0.55</td>
<td>6,556.63</td>
<td>2.11</td>
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<tr>
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<td></td>
<td>3</td>
<td>5,394.54</td>
<td>6,420.85</td>
<td>7,920.22</td>
<td>9,642.45</td>
</tr>
</tbody>
</table>

*Emission factors (TRL, 1999)*
Framework

Freight demand and logistics modeling:
Develop and integrate a set of U.S. freight transportation system models to capture interdependencies on future economic growth and urban spatial structure changes

Scope
(i) Inter-regional freight flow; e.g., from Los Angeles to Chicago
(ii) Intra-regional freight flow; e.g., within Chicago metropolitan area
(iii) Point-to-point delivery routing
Introduction

• Improvements in fleet operations from trucking service sector
  – Reduction in vehicle emissions
  – Huge benefits (urban air quality, human exposure)

• Roadway congestion in large urban areas is stochastic
  – Real time information technology
    Avoid heavy congestion by dynamically choosing the minimum expected cost path
  – Shortest path problem in a stochastic network setting (Miller-Hooks and Mahmassani, 2000; Waller and Ziliaskopoulos, 2002)
    Cost component: travel delay (focus on minimizing the expected total travel time)
Introduction

• Traffic congestion in large urban areas
  – Responsible for air pollution and related human health problems (Copeland, 2011)
• Trucking freight delivery contribute to the largest share of air pollutants in metropolitan areas (ICF Consulting, 2005)
  – Environmental cost caused by truck activities (CO₂, VOC, NOₓ, and PM)
  – Penalties for late or early truck arrival at destination (ensure delivery punctuality)
• “Total” cost = ∑ [ Total delivery time + Emissions + Penalty ]
• Minimum expected travel time solution (classical shortest path approach)
  – Does not necessarily guarantee the minimum expected “total” cost solution
Model Formulation

• Consider urban roadway networks
  Represented by a graph $D(V, A)$ where $V =$ node set and $A =$ directed link set
• From origin to destination, truck driver needs to decide the next link whenever he/she arrives at each node to minimize the expected total cost
• Assumptions
  (i) Truck speed on each link is stochastic (uniquely determined by stochastic congestion state on the link)
  (ii) Truck speed on each link follows a certain probability distribution
    - Fixed throughout the period of routing study (e.g., morning rush hour)
    - Not necessarily identical across the links
  (iii) Consider only major arterial roads or freeways to represent urban network links
    - Queue formed on a link does not spill over into immediate downstream links
    - Congestion states are independent across the links
### Model Formulation

**Origin** $g \in V$, **destination** $s \in V$  

$d_{ij} =$ length of link $(i, j) \in A$ (mile)  

$U_{ij} =$ stochastic truck speed (mph) on link $(i, j) \in A$  

$W(\cdot) =$ emission rate (g/veh-mile), function of the truck speed $U_{ij}$  

$x_{ij} =$ assignment of vehicle on link $(i, j) \in A$

<table>
<thead>
<tr>
<th><strong>Total travel time</strong></th>
<th><strong>Emissions</strong></th>
<th><strong>Penalty</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize $E \left[ \alpha \sum_{(i,j) \in A} \frac{d_{ij}}{U_{ij}} x_{ij} + \beta \sum_{(i,j) \in A} d_{ij} x_{ij} W(U_{ij}) + P \left( \sum_{(i,j) \in A} \frac{d_{ij}}{U_{ij}} x_{ij} \right) \right]$</td>
<td>Minimizes expected total travel cost</td>
<td></td>
</tr>
</tbody>
</table>

subject to \[\sum_{\{j(i,j) \in A\}} x_{ij} - \sum_{\{j(j,i) \in A\}} x_{ji} = \begin{cases} 1, & \text{if } i = g, \\ -1, & \text{if } i = s, \\ 0, & \text{otherwise,} \end{cases} \]

$x_{ij} \in \{0,1\}, \quad \forall (i, j) \in A.$

$\alpha ($$/hr), \beta ($$/gram) =$ parameters to convert units  

$P(\cdot) =$ penalty ($) for late or early arrival, function of the total travel time ($T$)  

$E =$ scheduled travel time (hr), shippers’ preference on the total delivery time (given)  

If $T = E$, no penalty; otherwise, assign penalty
Solution Approaches:
(1) Dynamic Programming

- Stage: each node $i \in V$ in a given network
- State: truck arrival time $m \in [0, \infty)$ at each stage $i \in V$
- Decision: choice from a finite set of decisions on the next link to move onto $\{(i, j) \mid (i, j) \in A\}$
- Truck speed: positive, continuous random variable which follows a certain probability density function
- Algorithm can be written into a recursive Bellman equation with backward induction
- Optimal solution
  Minimum expected total cost of the freight truck from its origin
Solution Approaches:
(2) Deterministic Shortest Path Heuristic

- In many real roadway networks, truck drivers need to select the next travel link in real time (i.e., within several seconds)
- Heuristic to find
  - Feasible solution in a very short computation time even for very large networks
  - Upper bound to the optimum solution
- Shortest path from origin to destination is obtained using the expected link cost considering only link travel time and the related emissions
- Once truck reaches the destination, penalty cost is added
Numerical Examples

- Tested on four examples: small networks and large-scale urban transportation networks

5-node and 13-link network (Powell, 2011)

15-node and 25-link network (Papadimitriou and Steiglitz, 1998)

24-node and 76-link Sioux Falls network (Bar-Gera, 2009)

416-node and 914-link Anaheim network (Bar-Gera, 2009)
Numerical Examples

- Assign a high penalty for late but a low penalty for early arrival
  \[ P(T) = \begin{cases} 
  100(T - E), & \text{if } T \geq E, \\
  -10(T - E), & \text{otherwise.}
  \end{cases} \]
  where, \( T \) = total travel time (hr), \( E \) = scheduled travel time (hr)

- Truck emission rate functions (g/veh-mile) for CO\(_2\), VOC, NO\(_X\), PM (TRL, 1999)

- Parameters that convert weight of emissions and time into monetary values
  280 ($/tonCO\(_2\)), 200 ($/tonVOC), 200 ($/tonNO\(_X\)), 300 ($/tonPM\(_{10}\)) (Muller and Mendelsohn, 2007; Winebrake et al., 2008), 20 ($/hr) (Bai et al., 2011)

- Truck speed on each link follows a randomly generated log-normal distribution
  mean = uniform [20, 60] (mph), s.d. = uniform [10, 15] (mph)
## Numerical Examples: Computational Results

<table>
<thead>
<tr>
<th>(a) Network</th>
<th>(b) Algorithm</th>
<th>(c) Min. expected total cost ($)</th>
<th>(d) Gap (%)</th>
<th>(e) Solution time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-node and 7-link network</td>
<td>Shortest path heuristic</td>
<td>33.33</td>
<td>2.54</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>Dynamic programming</td>
<td>32.51</td>
<td>-</td>
<td>0.218</td>
</tr>
<tr>
<td></td>
<td>($D = 0.025$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-node and 25-link network</td>
<td>Shortest path heuristic</td>
<td>20.49</td>
<td>2.61</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>Dynamic programming</td>
<td>19.97</td>
<td>-</td>
<td>0.725</td>
</tr>
<tr>
<td></td>
<td>($D = 0.030$)</td>
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<tr>
<td>24-node and 76-link Sioux Falls network</td>
<td>Shortest path heuristic</td>
<td>49.55</td>
<td>2.82</td>
<td>0.011</td>
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<tr>
<td></td>
<td>Dynamic programming</td>
<td>48.19</td>
<td>-</td>
<td>160.052</td>
</tr>
<tr>
<td></td>
<td>($D = 0.050$)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>416-node and 914-link Anaheim network</td>
<td>Shortest path heuristic</td>
<td>132.60</td>
<td>21.02</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>Dynamic programming</td>
<td>109.57</td>
<td>-</td>
<td>8.741.145</td>
</tr>
<tr>
<td></td>
<td>($D = 0.040$)</td>
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</tbody>
</table>
## Numerical Examples: Computational Results

- **Benchmark routing** = Ignoring emission cost in selecting the route
- **Proposed routing** = Considering emission cost in selecting the route
- **Cost difference** = Cost from the benchmark routing - Cost from the proposed routing

<table>
<thead>
<tr>
<th>(a) Network</th>
<th>(b) Scenario</th>
<th>(c) Min. expected total cost ($)</th>
<th>(d) Travel time ($)</th>
<th>(e) Emissions ($)</th>
<th>(f) Penalty ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-node and 7-link network</td>
<td>Benchmark design</td>
<td>35.45</td>
<td>13.88</td>
<td>13.76</td>
<td>7.80</td>
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<td></td>
<td>Proposed approach</td>
<td>32.51</td>
<td>14.39</td>
<td>10.81</td>
<td>7.30</td>
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<tr>
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<td>Cost difference</td>
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<td>-0.51</td>
<td>2.95</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.29%</td>
<td>-3.67%</td>
<td>21.42%</td>
<td>6.41%</td>
</tr>
<tr>
<td>15-node and 25-link network</td>
<td>Benchmark design</td>
<td>21.22</td>
<td>6.35</td>
<td>5.90</td>
<td>8.96</td>
</tr>
<tr>
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<td>Proposed approach</td>
<td>19.97</td>
<td>6.73</td>
<td>4.46</td>
<td>8.78</td>
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<tr>
<td></td>
<td>Cost difference</td>
<td>1.25</td>
<td>-0.38</td>
<td>1.44</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
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<td>5.87%</td>
<td>-5.97%</td>
<td>24.38%</td>
<td>2.08%</td>
</tr>
<tr>
<td>24-node and 76-link Sioux Falls network</td>
<td>Benchmark design</td>
<td>52.75</td>
<td>24.57</td>
<td>15.57</td>
<td>12.61</td>
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<td>48.19</td>
<td>14.52</td>
<td>9.22</td>
<td>24.45</td>
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<td>Cost difference</td>
<td>4.56</td>
<td>10.05</td>
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<td>8.64%</td>
<td>40.90%</td>
<td>40.82%</td>
<td>-93.93%</td>
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<td>416-node and 914-link Anaheim network</td>
<td>Benchmark design</td>
<td>114.38</td>
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<td>47.00</td>
<td>0.39</td>
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<td>67.29</td>
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<td>4.21%</td>
<td>-0.44%</td>
<td>11.04%</td>
<td>-21.76%</td>
</tr>
</tbody>
</table>
SPEW-Trend fleet model

Represent how emissions are affected by technology change and modal choice

- Input-output models; ANY driver of activity
- Vehicle Growth
- Vehicles in use
  - Normal vehicles built to different Tier levels
  - Transition rate
  - Superemitters
- Retirement rate
- Retired vehicles
Climate policy (carbon tax) causes modal shift to railway—*BUT not “enough”* (Commodity-limited)
Fuel use projection

MDH fuel consumption trend

- Baseline
- Potential
- Previous
- GCAM (input-output)

(*) regression!

No congestion (by tonne-km only)
With projected eff. improvement*
With congestion
GCAM (input-output)
Emission projection – air pollutants
(congestion case)
Conclusions

- Environmental problems from freight shipment activities
  - Climate change (on global scale)
  - Air quality and human health (in regional and urban areas)
- Choice of freight mode and routing them between/within geographical regions significantly affect regional and urban air quality
- Freight demand models are developed to reflect dependences on future economic growth and urban spatial changes
- Scope of the freight transportation
  - Inter-regional freight flow: Four-step freight demand forecasting model
  - Intra-regional freight flow: Various network optimization models and solution approaches
Contributions

• In this interdisciplinary project, we
  – Develop a comprehensive freight shipment modeling framework ranging from initial collecting systems, to freight movements and routing at the national scale, and then to final distributing systems
  – Provide deeper understanding of the interdependencies and connections among multiple traditionally separated research fields
  – Aid decision-makers in evaluating freight handling decisions that contribute to reducing adverse impacts on air quality and climate change
  – Facilitate decision-making processes in the freight industries or the government agencies by providing an integrated decision-support software
  – Extend and apply to other studies such as transportation network capacity expansion and maintenance as well as traffic safety prediction
  – Enhance human health and social welfare
Future Research

(1) Trip generation and trip distribution
   • “Distribution of future freight demand is proportional to that of the base-year freight demand” can be relaxed
     → Gravity model for freight demand distribution
   • Once newer version of FAF database becomes available
     → More recent base-year to improve forecast accuracy

(2) Modal split
   • Update the models using additional/newer version freight demand data
     → Estimation of precise environmental impacts of freight transportation systems
Future Research

(3) Network assignment
   • Impacts of infrastructure investment in the rail network on modal split
     → Enhanced level of service and its effect on future rail freight demand (i.e.,
       against other modes in a competitive freight shipment market)

(4) Stochastic urban freight truck routing problem
   • Apply time-dependent stochastic congestion state on each link
     → Link travel time and following emissions will be affected by stochastic
       truck speed as well as truck arrival time at the link origin node
   • Include local and collector roads in the urban transportation networks
     → Truck speed on downstream and upstream links may be correlated
   • Apply environmental impacts from transportation activities to other stochastic
     network optimization problems
Thank you!

Any questions?
Background

• Freight Analysis Zone (FAZ)
  – Defined in Freight Analysis Framework to represent the U.S. geographical regions with regard to freight activities
  – Composed of 123 domestic regions in total
    • 74 metropolitan areas
    • 33 regions representing the remaining parts of the states that these 74 metropolitan areas belong to
    • 16 remaining regions, each of which represents an entire state

• Map of domestic FAZs in Freight Analysis Framework version 3
## 10 Commodity Types

<table>
<thead>
<tr>
<th>Commodity type</th>
<th>Commodity description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture products and fish</td>
<td></td>
</tr>
<tr>
<td>Grain, alcohol, and tobacco products</td>
<td></td>
</tr>
<tr>
<td>Stones, nonmetallic minerals, and metallic ores</td>
<td></td>
</tr>
<tr>
<td>Coal and petroleum products</td>
<td></td>
</tr>
<tr>
<td>Basic chemicals, chemical and pharmaceutical products</td>
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</tr>
<tr>
<td>Logs, wood products, and textile and leather</td>
<td></td>
</tr>
<tr>
<td>Base metal and machinery</td>
<td></td>
</tr>
<tr>
<td>Electronic, motorized vehicles, and precision instruments</td>
<td></td>
</tr>
<tr>
<td>Furniture, mixed freight, and miscellaneous manufactured products</td>
<td></td>
</tr>
<tr>
<td>Commodity unknown</td>
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</tr>
</tbody>
</table>