EPA

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

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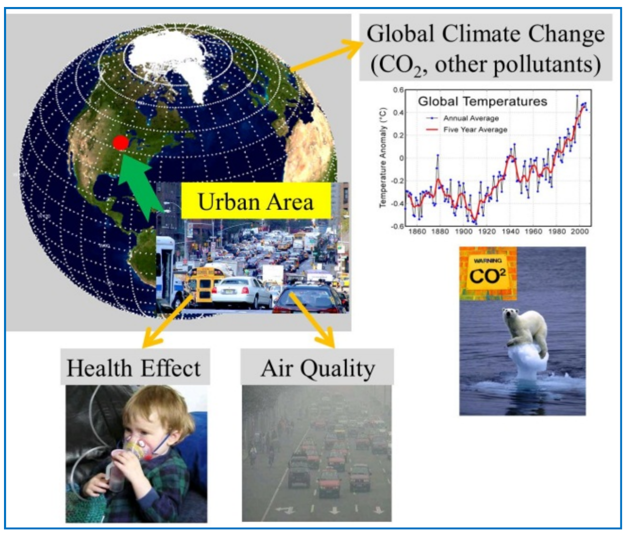
Outline

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_X, PM) and greenhouse gases (e.g., CO_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

…and tomorrow

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

Inter-regional freight

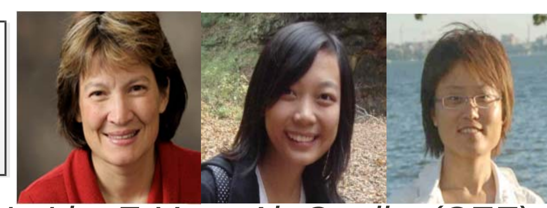
For heavy-duty trucks and rail

Global Economic Forecasts	Future Economic Scenarios	← Phoenix Model
Urban Spatial Structure	Employment, Population; Commodity Origin & Destination	← Shift share & Input-Output Model
Freight Transportation System	Inter-regional Freight Flow	← Freight Commodity Transportation Forecasting Model
Air Quality and Emission	CO2 & Pollutants Emission Projections	← SPEWTrend Model

S. Smith, PNNL

B. Lee, S. Lee, Urban Planning

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



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

Intra-regional freight

For medium duty trucks;
not presented here

Level	Scenario / output	Model
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	SPEWTrend Model

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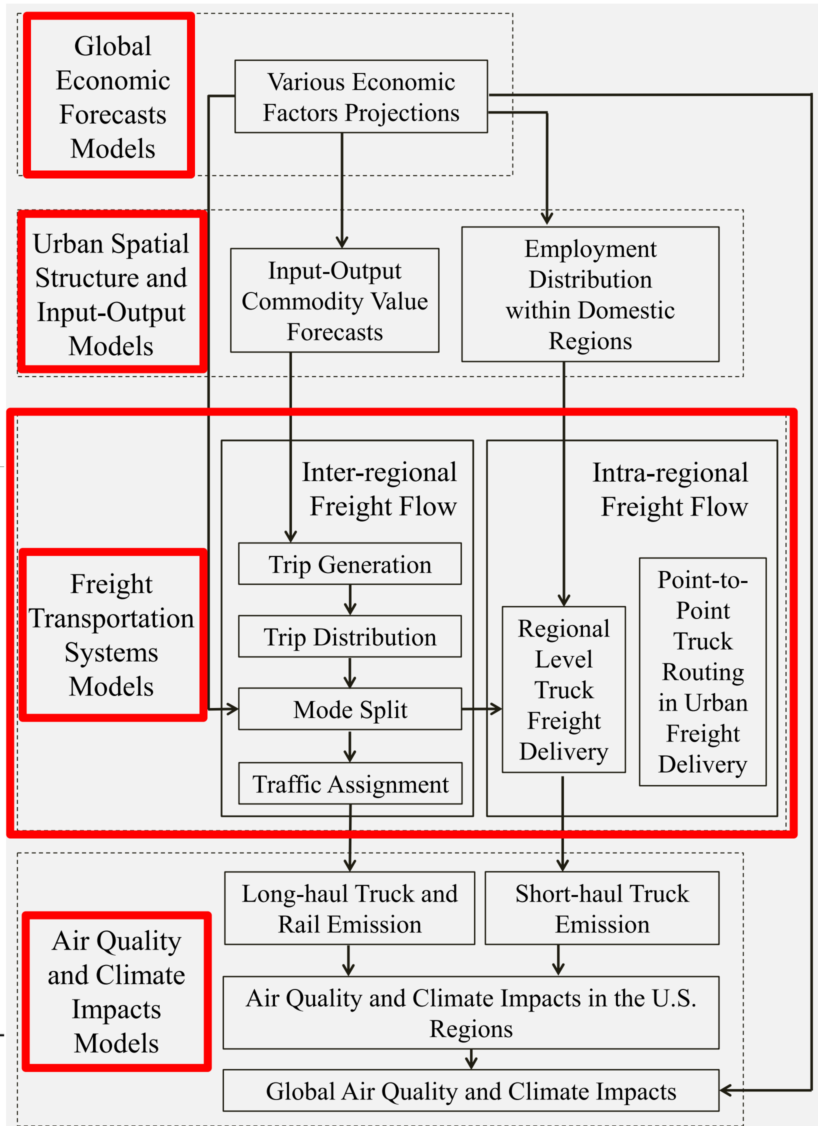
Framework



Freight demand and logistics modeling:

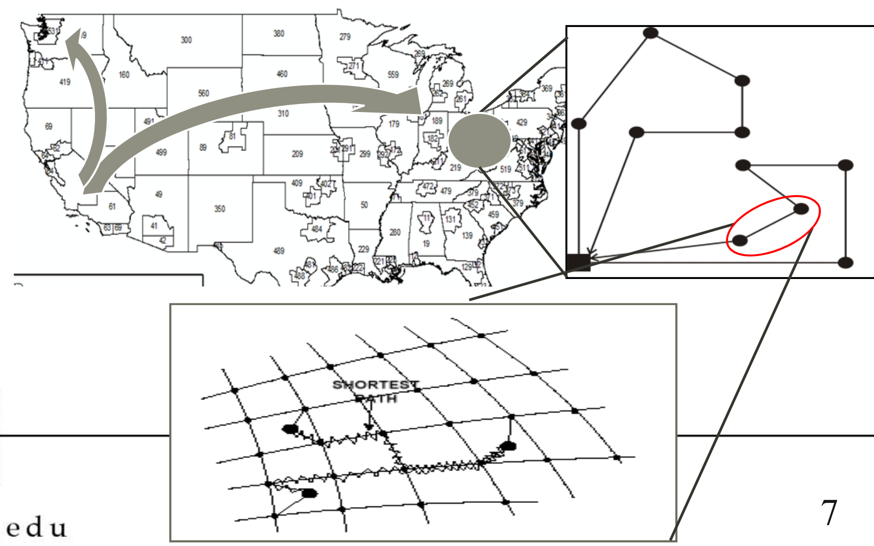
Develop and integrate a set of U.S. freight transportation system models to capture interdependencies on future economic growth and urban spatial structure changes

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



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

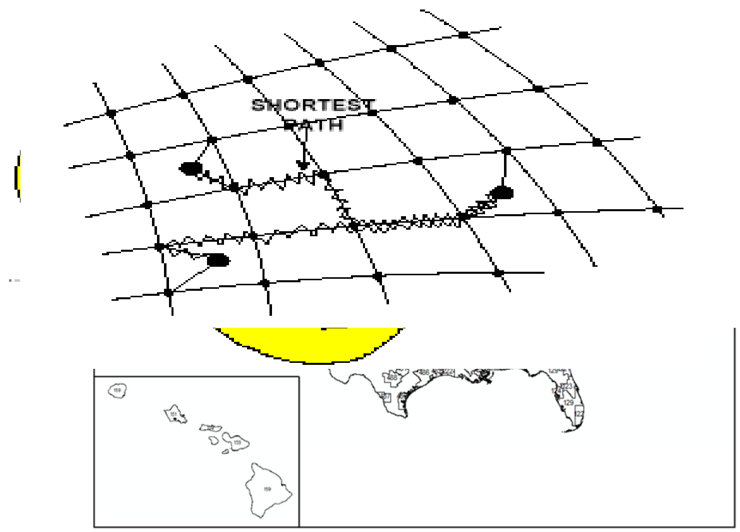
Zonal O/D freight demand by shipping mode

↓

Traffic Assignment

↓

Traffic flow, average speed on each link



123 domestic Freight Analysis Zone (FAZ)

Introduction

Trip Generation → Trip Distribution → Mode Split → Traffic Assignment

- 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

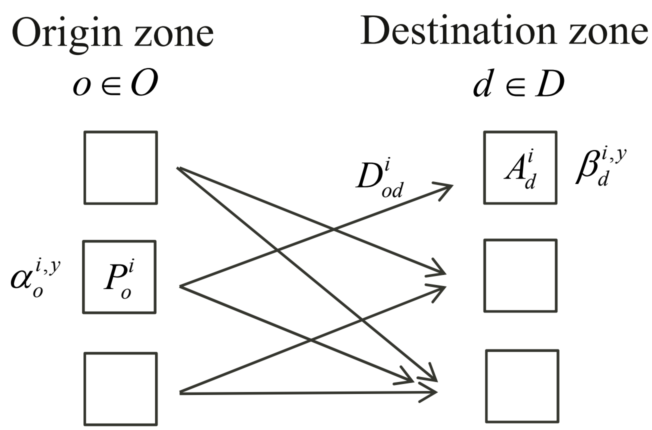
  – Forecast of economic growth factors are given for all FAZs

  – 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

Freight Demand Generation/Distribution

- Structure of base-year freight demand distribution data



For commodity type $i \in \{1, 2, \dots, N\}$,

O = origin zone set, $\{1, 2, \dots, Z\}$

D = destination zone set, $\{1, 2, \dots, Z\}$

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*

D / O	1	2	..	***d***	..	Z	Given Production	Future Production
1				.				
2				.				
:				:				
o	.	.	..	D_{od}^i	..	.	P_o^i	
:				:				
Z				.				
Given Attraction				A_d^i				
Future Attraction								

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

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

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

							P_o^i	V_o^i
				A_d^i				
				W_d^i				

Freight Demand Generation/Distribution

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

Total future production summed across all origin zones $\left(\sum_{\forall o \in O} V_o^i\right)$ $\neq$ Total future attraction summed across all destination zones $\left(\sum_{\forall d \in D} W_d^i\right)$

- Assume freight commodity productions are derived by attractions
- Multiply future productions of all origin zones by the same factor:

Update $V_o^i \leftarrow V_o^i \cdot \left(\dfrac{\sum_{\forall d \in D} W_d^i}{\sum_{\forall o \in O} V_o^i} \right), \forall o \in O.$

- Then, $\sum_{\forall o \in O} V_o^i = \sum_{\forall d \in D} W_d^i$

O \ D	1	2	..	***d***	..	Z	Given Production	Future Production
1								
2								
:								
o				D_{od}^i			P_o^i	V_o^i
:								
Z								
Given Attraction				A_d^i				
Future Attraction				W_d^i				

Freight Demand Generation/Distribution

Step 3. Apply RAS algorithm:

Modify each entry $\left(D^i_{od}\right)$ iteratively to match with the future production in each row and the future attraction in each column

D / O	1	2	..	*d*	..	Z	Given Production	Future Production
1								
2								
:								
o				D^i_{od}			P^i_o	V^i_o
:								
Z								
Given Attraction				A^i_d				
Future Attraction				W^i_d				

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

Define $R^i_o = \dfrac{V^i_o}{\sum_{d \in D} D^i_{od}}, \forall o \in O$, and $C^i_d = \dfrac{W^i_d}{\sum_{o \in O} D^i_{od}}, \forall d \in D$.

While $\{(n \le L)$ and $(\left|R^i_o - 1\right| > \varepsilon$ for some $o \in O$ or $\left|C^i_d - 1\right| > \varepsilon$ for some $d \in D)\}$

{

Set $D^i_{od} \leftarrow R^i_o D^i_{od}, \forall o \in O, d \in D,$

Update $C^i_d \leftarrow \dfrac{W^i_d}{\sum_{o \in O} D^i_{od}}, \forall d \in D,$

Set $D^i_{od} \leftarrow C^i_d D^i_{od}, \forall o \in O, d \in D,$

Update $R^i_o \leftarrow \dfrac{V^i_o}{\sum_{d \in D} D^i_{od}}, \forall o \in O,$

Update $n \leftarrow n + 1,$

}

Freight Transportation Mode Choice

Trip Generation → Trip Distribution → **Mode Split** → Traffic Assignment

- Goal

  Draw connections among various economic and engineering factors, freight transportation modal choice, and subsequently freight transportation emissions

  – Significant difference in emissions across modes

	CO_2 Emission Factor ($kgCO_2$/ton-mile)	CH_4 Emission Factor (gCH_4/ton-mile)	N_2O Emission Factor (gN_2O/ton-mile)
On-Road Truck	0.2970	0.0035	0.0027
Rail	0.0252	0.0020	0.0006
Waterborne Craft	0.0480	0.0041	0.0014
Aircraft	1.5270	0.0417	0.0479

Source: EPA (2008)

Ref: Hwang, T.S. and Ouyang, Y. (2014) "Freight shipment modal split and its environmental impacts: An exploratory study." *Journal of the Air & Waste Management Association*, 64(1): 2-12.

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 commidity n: $U_T^n = a_{1n} + b_{1n} \cdot VALUE + c_{1n} \cdot DIST_T + d_{1n} \cdot OILPRC,$

Utility of rail for commidity n: $U_R^n = a_{2n} + b_{2n} \cdot VALUE + c_{2n} \cdot DIST_R + d_{2n} \cdot OILPRC,$

Market share of truck for commidity n: $P_T^n = \dfrac{e^{U_T^n}}{e^{U_T^n} + e^{U_R^n}} = \dfrac{e^{U_T^n - U_R^n}}{e^{U_T^n - U_R^n} + 1},$

Market share of rail for commidity n: $P_R^n = \dfrac{e^{U_R^n}}{e^{U_T^n} + e^{U_R^n}} = \dfrac{1}{e^{U_T^n - U_R^n} + 1},$

$$\ln\left(\frac{P_T^n}{1 - P_T^n}\right) = U_T^n - U_R^n$$

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

- 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 (FAF^2) for year 2002 and version 3 (FAF^3) 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

			Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10
(a) Estimation results	Intercept	Estimate	1.989E+00	1.777E+00	3.800E+00	9.383E-01	1.390E+00	2.954E+00	3.014E+00	1.910E+00	1.702E+00	9.978E-01
		z-statistic	12761.00	5868.29	28335.00	10357.00	8350.80	15685.00	21139.20	4176.90	5472.90	811.40
		Pr(>|z|)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Value per ton	Estimate	2.428E-03	2.096E-03	1.059E-03	9.746E-03	6.210E-04	6.130E-04	4.850E-04	1.113E-04	7.085E-04	4.311E-03
		z-statistic	8593.00	7124.43	1211.00	25389.00	7289.40	5238.40	4593.40	1948.40	3655.00	1545.80
		Pr(>|z|)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Avg. truck distance	Estimate	-1.532E-03	-1.766E-03	-1.190E-03	-1.663E-03	-1.531E-03	1.904E-04	-3.142E-03	-4.025E-03	-1.901E-03	-2.042E-03
		z-statistic	-2796.00	-1680.74	-2488.00	-3390.00	-2418.20	252.00	-3714.60	-2113.00	-1792.30	-472.10
		Pr(>|z|)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Avg. rail distance	Estimate	-1.123E-03	5.149E-06	-1.960E-03	-2.155E-03	2.780E-04	-2.026E-03	1.225E-03	2.580E-03	2.232E-04	-1.599E-03
		z-statistic	-2258.00	5.30	-4958.00	-5019.00	485.40	-2912.50	1613.70	1494.90	234.50	-138.70
		Pr(>|z|)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	WTI crude oil price	Estimate	4.579E-03	-4.808E-03	-1.383E-02	-2.901E-02	-7.312E-03	-3.134E-03	-1.297E-03	1.011E-02	2.285E-02	3.305E-02
		z-statistic	1634.00	-965.59	-5993.00	-14669.00	-2758.90	-818.30	-389.90	963.90	4948.40	432.10
		Pr(>|z|)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
(b) Number of data used			3,802	5,468	3,753	3,105	5,883	6,068	6,035	5,100	5,041	2,062
(c) Pseudo R-squared	McFadden		0.348	0.427	0.241	0.659	0.270	0.381	0.133	0.203	0.134	0.438
	Nagelkerke		0.391	0.456	0.261	0.747	0.311	0.410	0.143	0.229	0.143	0.445

Estimation Results and Goodness of Fit

- All estimates are statistically significant (all p-values ≤ 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

Trip Generation → Trip Distribution → Mode Split → **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.

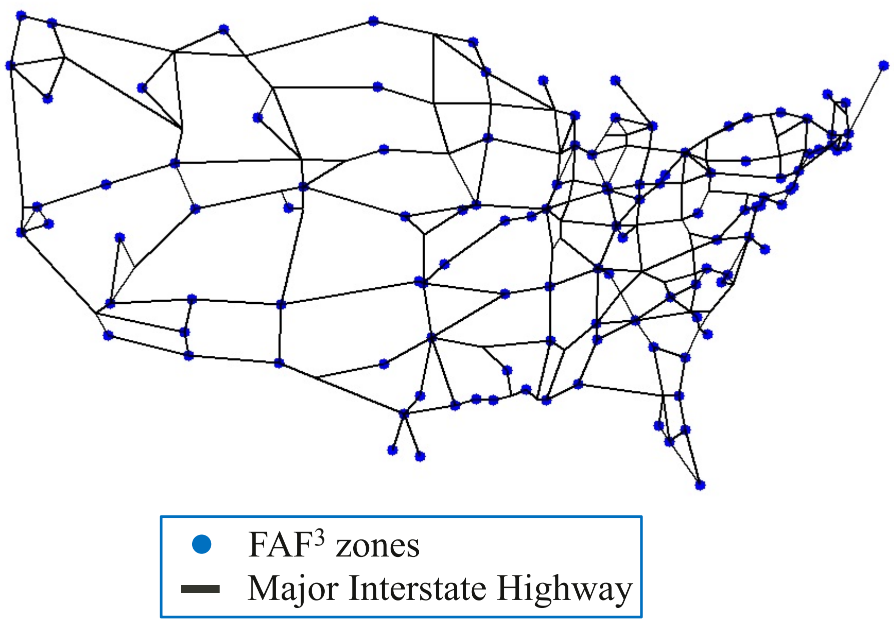
Truck Traffic Assignment

- 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 FAF^3 regions boundary
     - Exclude Hawaii (2 zones) and Alaska (1 zone)
  2) U.S. road network: FAF^3 network
     - Consider only major interstate highways
     - Background traffic (AADT) and link capacity in Year 2007
- Data for truck freight demand

  FAF^3 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 FAF^3 zones is both origin and destination of freight demand
3) 588 links
   - Mostly major interstate highways
   - Some local roads: for FAF^3 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

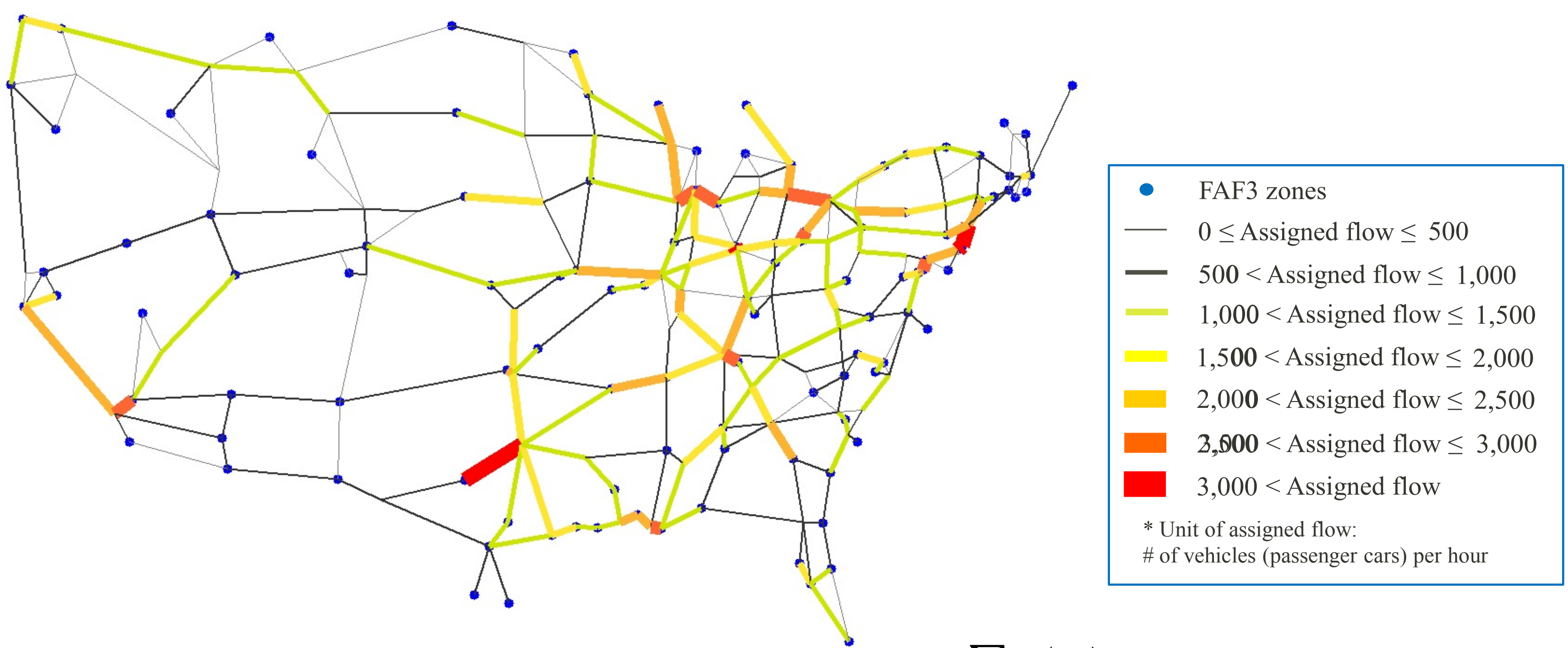
$$t(\omega) = t_f \left[1 + \alpha \left(\frac{\omega + b}{C} \right)^{\beta} \right]$$

where t_f = link free flow travel time (hr), ω = assigned traffic volume $(\#\text{of veh/hr})$,

b = background traffic volume $(\#\text{of veh/hr})$, C = link capacity $(\#\text{of veh/hr})$,

$\alpha = 0.15$, and $\beta = 4$

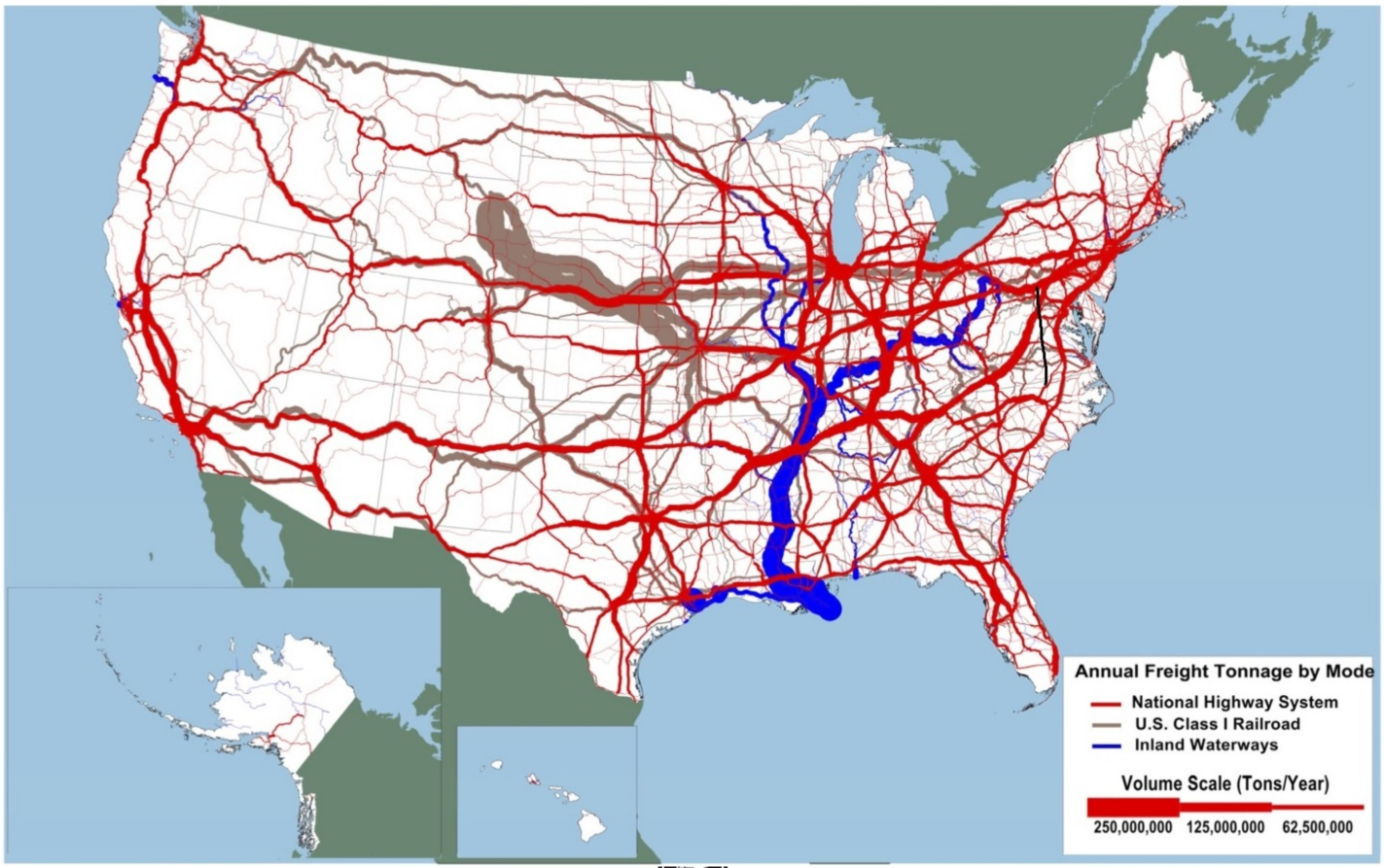
Truck Traffic Assignment Results



- Total Cost = ∑ (Link Travel Time × 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

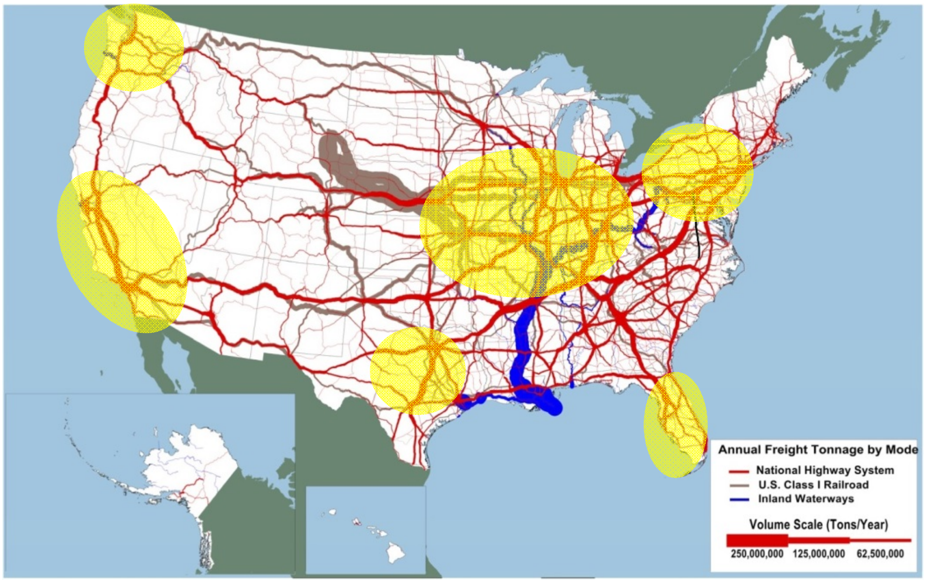
Model Validation

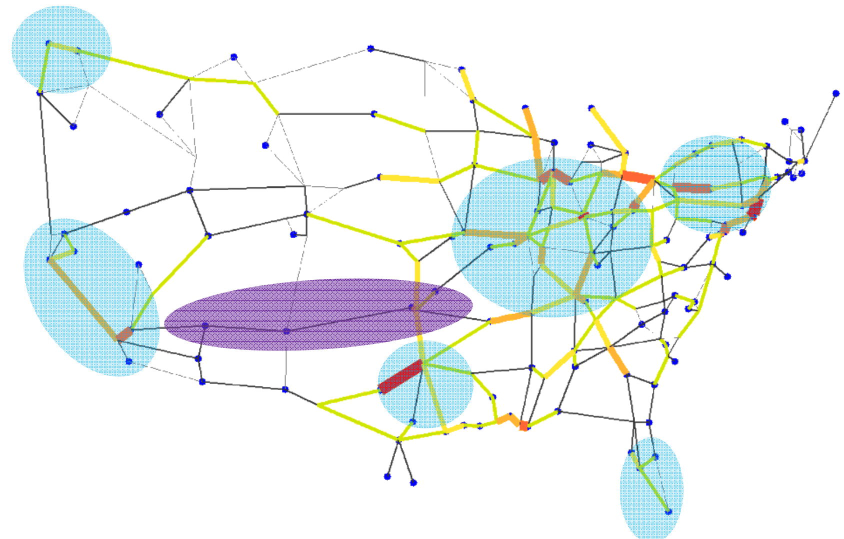
- Freight traffic distribution (annual tonnage) on the U.S. highway (red), rail (brown), and inland waterways (blue) networks in Year 2007 (FHWA U.S. DOT, 2011)



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)

ω_e = the total rail link flow (# of trains/day)

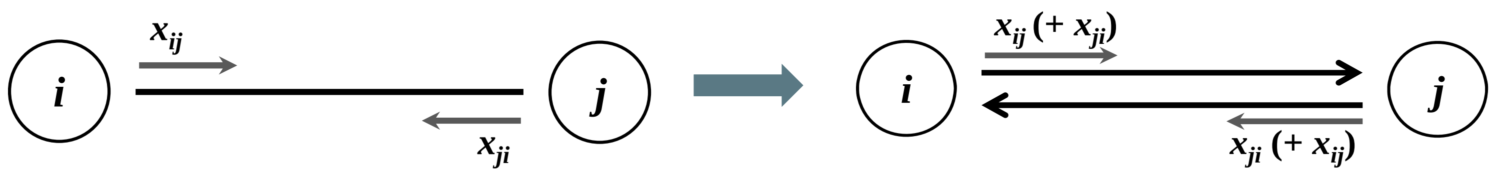
α_e, β_e = parameters uniquely determined by rail operating conditions

Ref: Hwang, T.S. and Ouyang, Y. "Assignment of freight shipment demand in congested rail networks." *Transportation Research Record*. In press.

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

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

  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

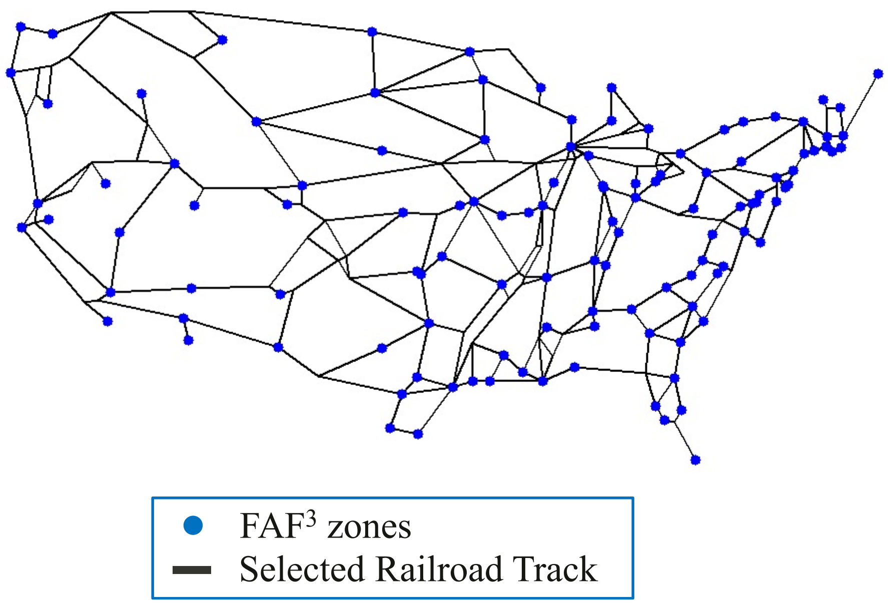
Rail Traffic Assignment: Data (1)

- Data for graph representation of rail network
  1) O/D nodes: 120 centroids of FAF^3 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
  - FAF^3 rail shipment database (FHWA U.S. DOT, 2011): freight demand in 2007
  - 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)

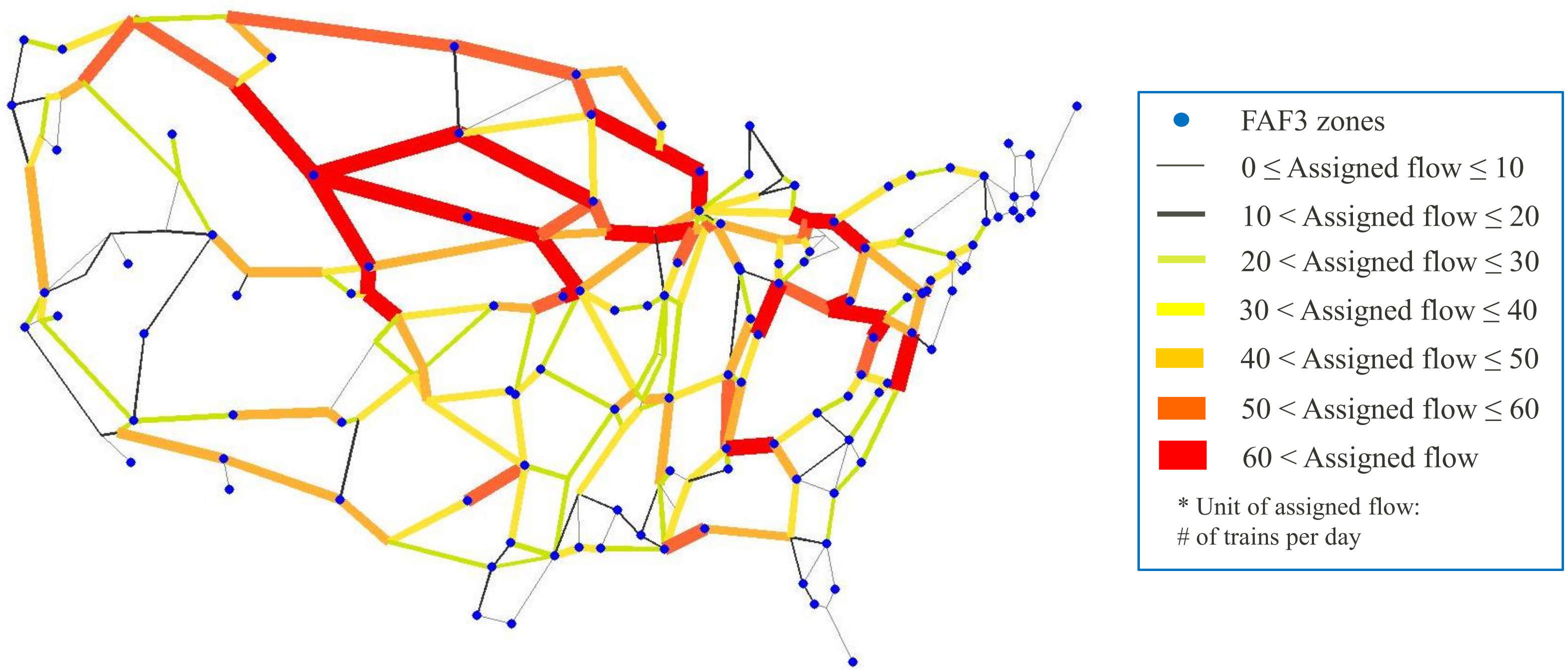
Railroad Traffic Assignment: Data (2)

- 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 FAF³ centroids located far from the major rail network

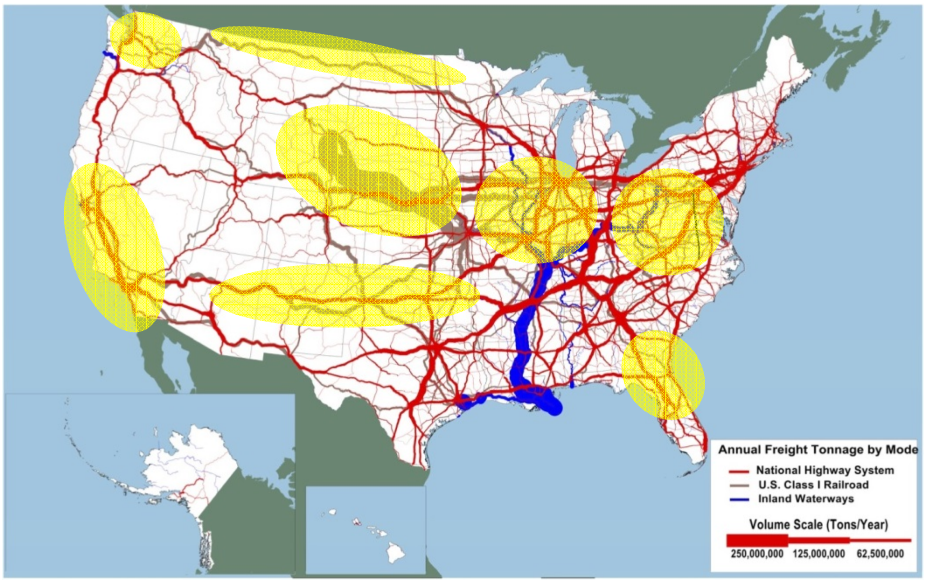
Railroad Traffic Assignment: User Equilibrium Results

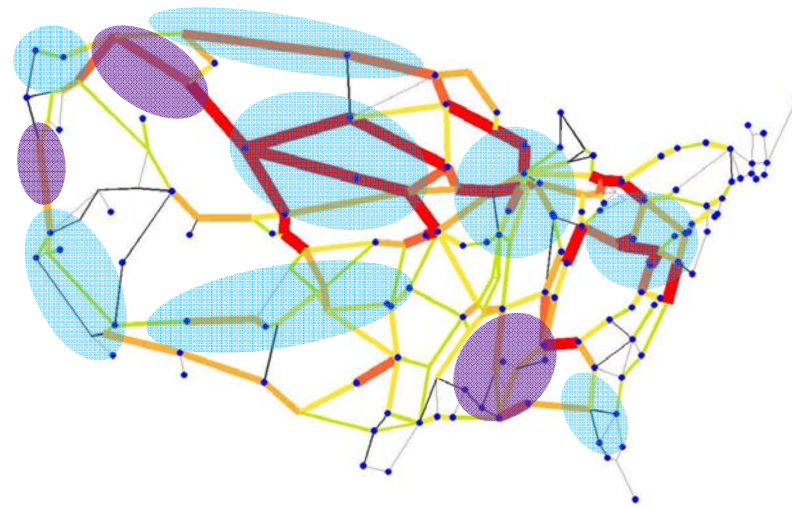


- Total Cost = ∑ (Link Travel Time × Assigned Link Flow) = $\sum_{(i,j)\in A} t_{ij}\left(x_{ij}+x_{ji}\right)x_{ij}$ = 75,426 (train-hr/day)
- Convergence is reached within a tolerance of 0.001% after 2,569 iterations (25.559 sec CPU time)
- Output: link number, link origin and destination node, link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

Model Validation

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





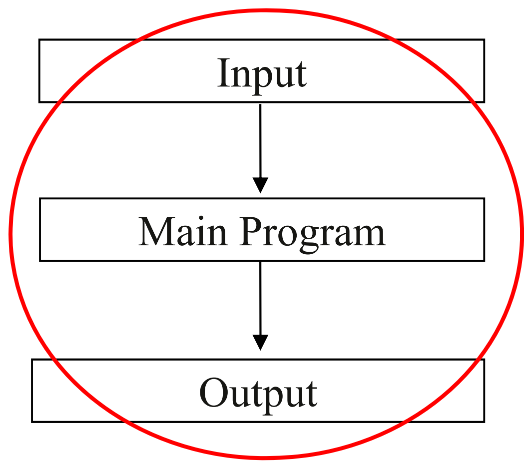
Trend consistent at a high level:
Washington, California, Wyoming, Montana, the Midwest states near Chicago, northeastern regions, and some main links that connect Southern California, Texas, and Kansas

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

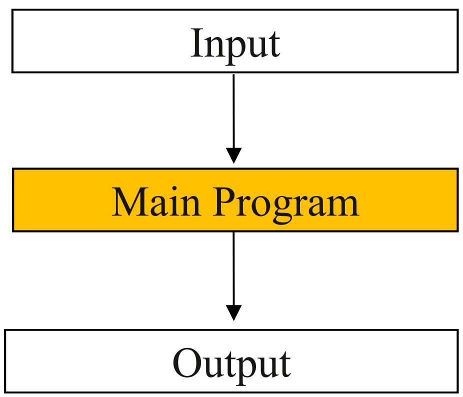
Overview of the software

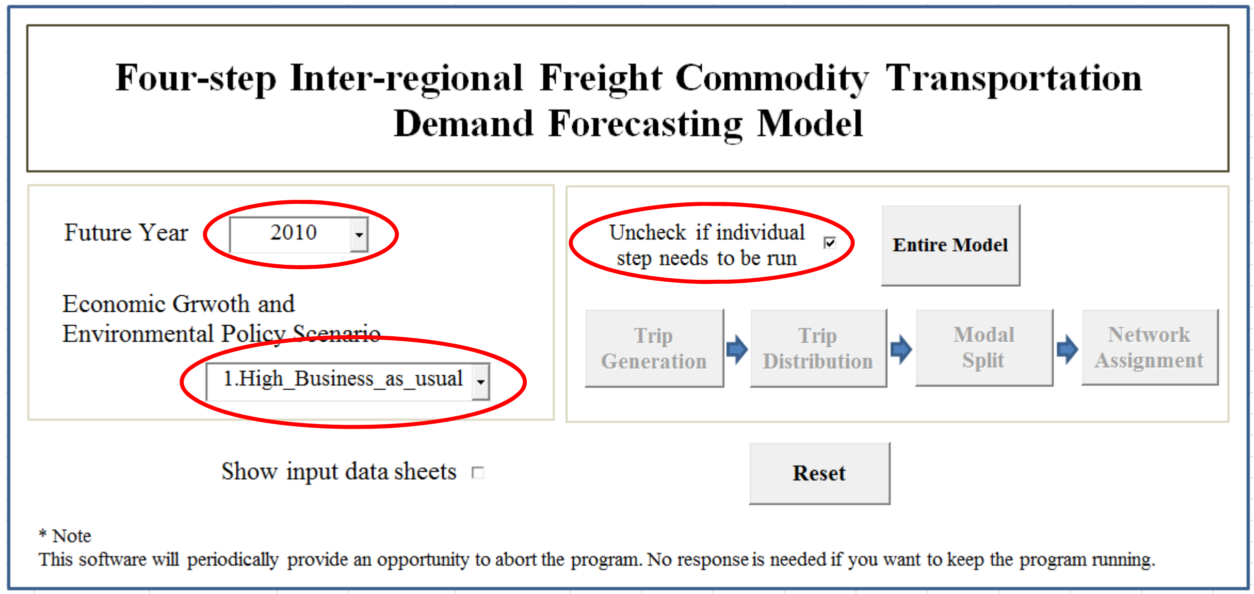


Included in one Excel file

Software Development

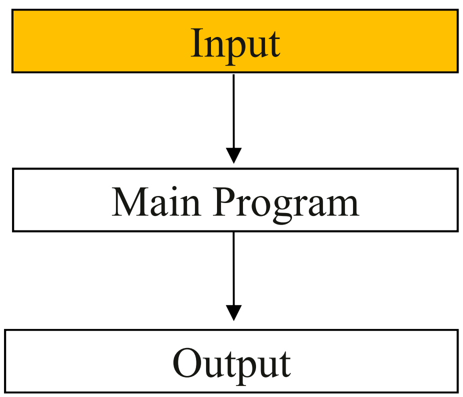
- Procedure of the program





Software Development

- Procedure of the program



- 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

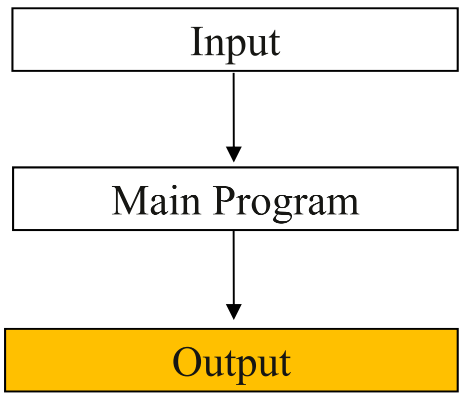
    “TruckDist”, “RailDist”, and “ModalSplit”

    Network assignment

    “TruckDemand”, “RailDemand”, “TruckNetwork”, “RailNetwork”, “TruckNode”, and “RailNode”

Software Development

- Procedure of the program



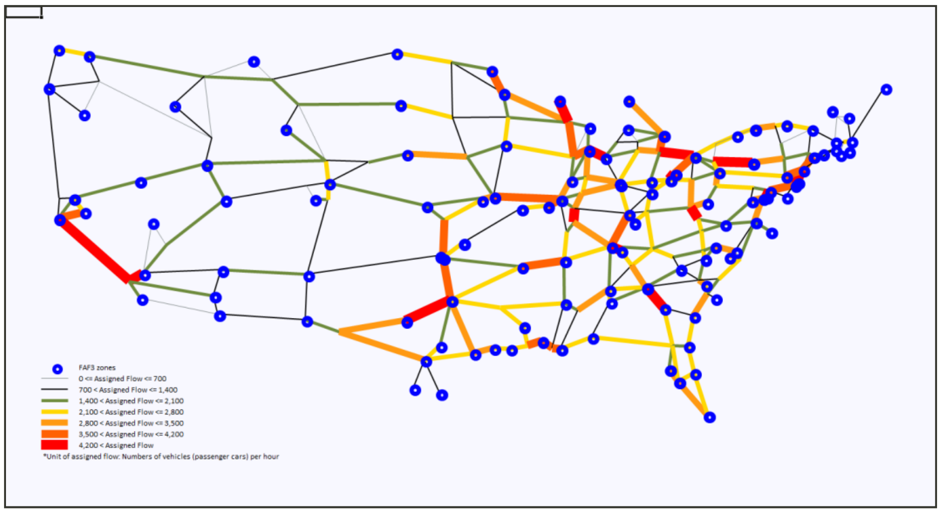
- Output worksheets

  Results from different steps will be recorded in seven different output worksheets

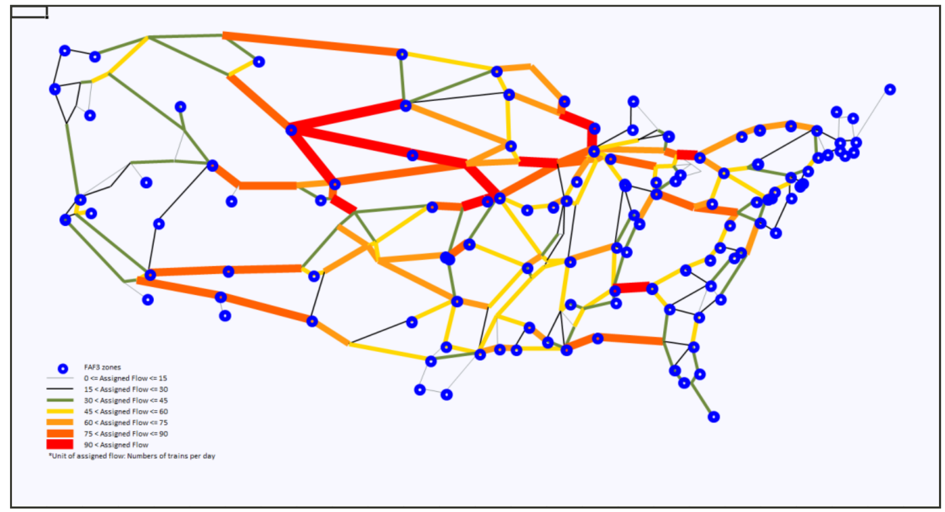
  - Trip generation
    "Trip_Generation"
  - Trip distribution
    "Trip_Distribution"
  - Modal split
    "Modal_Split"
  - Truck freight demand network assignment
    "TruckResult" and "TruckMap"
  - Rail freight demand network assignment
    "RailResult" and "RailMap"

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 (FAF^3) 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)

(a) Scenario	Scenario 1: High GDP growth with business as usual		Scenario 2: High GDP growth with climate policy		Scenario 3: Low GDP growth with business as usual		Scenario 4: Low GDP growth with climate policy	
(b) Year	(c) Total freight demand forecasted (thousand ton)	(g) % change	(d) Total freight demand forecasted (thousand ton)	(h) % change	(e) Total freight demand forecasted (thousand ton)	(i) % change	(f) Total freight demand forecasted (thousand ton)	(j) % change
2007	15,059,745	0.00	15,059,745	0.00	15,059,745	0.00	15,059,745	0.00
2010	15,703,789	4.28	15,648,288	3.91	15,528,787	3.11	15,494,244	2.89
2015	17,501,995	16.22	17,438,001	15.79	16,929,857	12.42	16,890,825	12.16
2020	19,431,308	29.03	18,780,540	24.71	18,355,956	21.89	17,742,894	17.82
2025	21,438,103	42.35	20,650,764	37.13	19,755,145	31.18	19,023,791	26.32
2030	23,693,953	57.33	22,780,286	51.27	21,271,576	41.25	20,435,507	35.70
2035	26,034,285	72.87	24,945,108	65.64	22,725,696	50.90	21,747,683	44.41
2040	28,697,929	90.56	27,356,813	81.66	24,523,312	62.84	23,339,737	54.98
2045	31,574,234	109.66	29,893,810	98.50	26,377,074	75.15	24,903,553	65.37
2050	34,673,664	130.24	32,621,827	116.62	28,351,364	88.26	26,573,564	76.45

- 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

Freight value per unit weight	Avg. truck distance	Avg. rail distance
$1,240.85/ton	1,005 miles	1,332 miles

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

Emission factors adopted from EPA (2008) and NRDC (2012)

	CO_2 emission factor ($kgCO_2$/ton-mile)	CH_4 emission factor (gCH_4/ton-mile)	N_2O emission factor (gN_2O/ton-mile)	PM_{10} emission factor (gPM_{10}/ton-mile)
Truck	0.2970	0.0035	0.0027	0.092
Rail	0.0252	0.0020	0.0006	0.013

Model Application - Emission Estimation

(a) WTI crude oil price ($/barrel)	(b) Truck share prediction (%)	(c) Rail share prediction (%)	(d) Truck CO_2 emission (ton)	(e) Rail CO_2 emission (ton)	(f) Total CO_2 emission (ton)	(g) Truck CH_4 emission (kg)	(h) Rail CH_4 emission (kg)	(i) Total CH_4 emission (kg)	(j) Truck N_2O emission (kg)	(k) Rail N_2O emission (kg)	(l) Total N_2O emission (kg)	(m) Truck PM_{10} emission (kg)	(n) Rail PM_{10} emission (kg)	(o) Total PM_{10} emission (kg)
40	66.8%	33.2%	65,412	3,654	69,066	771	290	1,061	595	87	682	20,262	1,885	22,147
60	63.5%	36.5%	62,163	4,019	66,182	733	319	1,052	565	96	661	19,256	2,073	21,329
80	60.0%	40.0%	58,784	4,399	63,183	693	349	1,042	534	105	639	18,209	2,269	20,479
100	56.5%	43.5%	55,304	4,791	60,094	652	380	1,032	503	114	617	17,131	2,471	19,602
120	52.9%	47.1%	51,758	5,189	56,947	610	412	1,022	471	124	594	16,033	2,677	18,710
140	49.2%	50.8%	48,181	5,591	53,773	568	444	1,012	438	133	571	14,925	2,885	17,809
160	45.6%	54.4%	44,613	5,993	50,606	526	476	1,001	406	143	548	13,820	3,091	16,911
180	42.0%	58.0%	41,091	6,389	47,480	484	507	991	374	152	526	12,729	3,296	16,024
200	38.5%	61.5%	37,651	6,776	44,426	444	538	981	342	161	504	11,663	3,495	15,158
220	35.1%	64.9%	34,324	7,150	41,474	404	567	972	312	170	482	10,632	3,688	14,321
240	31.8%	68.2%	31,140	7,508	38,648	367	596	963	283	179	462	9,646	3,873	13,519
260	28.7%	71.3%	28,120	7,848	35,968	331	623	954	256	187	442	8,711	4,048	12,759
280	25.8%	74.2%	25,282	8,167	33,449	298	648	946	230	194	424	7,832	4,213	12,044
300	23.1%	76.9%	22,638	8,464	31,102	267	672	939	206	202	407	7,012	4,366	11,379

- 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

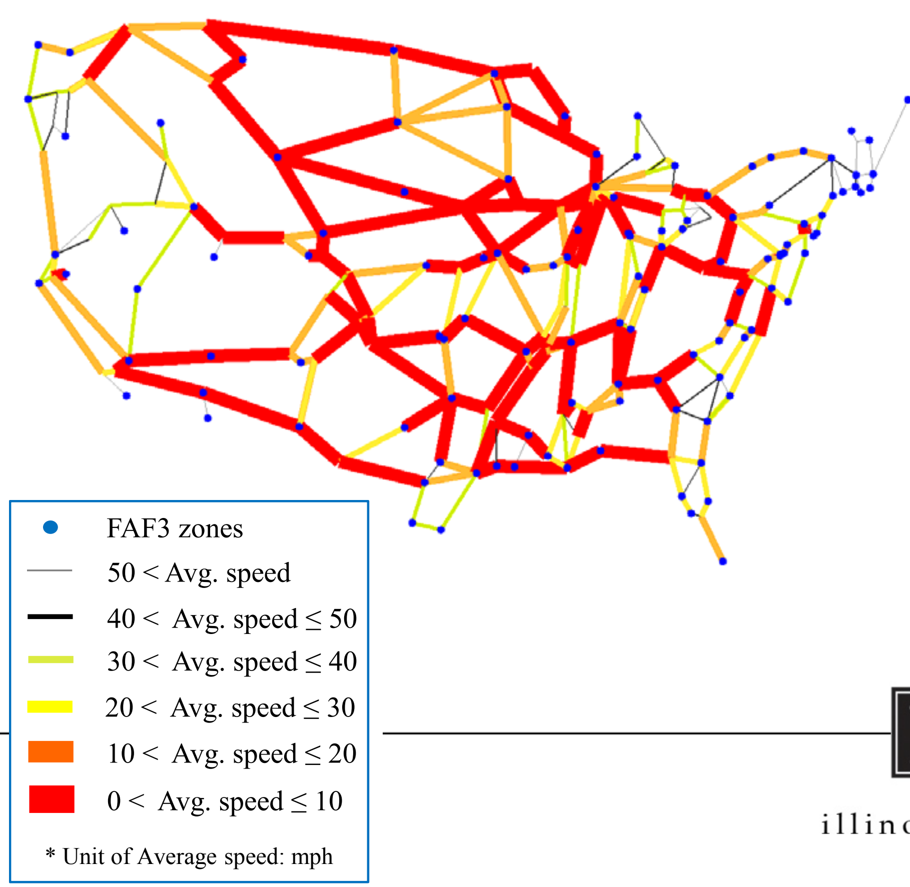
- Rail freight demand: projected to increase 88% by Year 2035
  - Sever congestion is expected (Cambridge Systematics, Inc., 2007)
  - Infrastructure investment may be needed near potential chokepoints
    → Will affect future rail freight demand assignment patterns

- "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

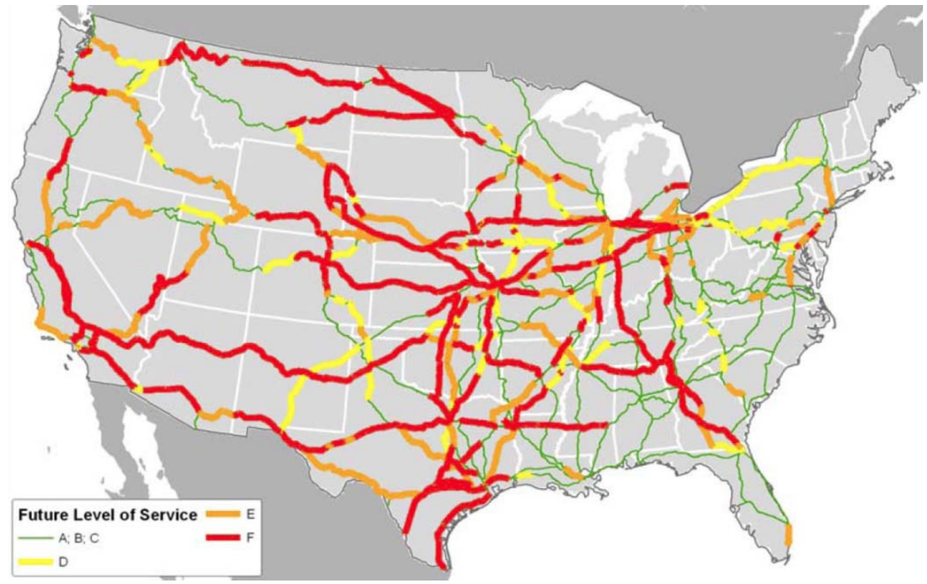
Rail Network Capacity Expansion and Its Effect on Network Assignment

- Congestion prediction in Year 2035 without infrastructure investment

Our model

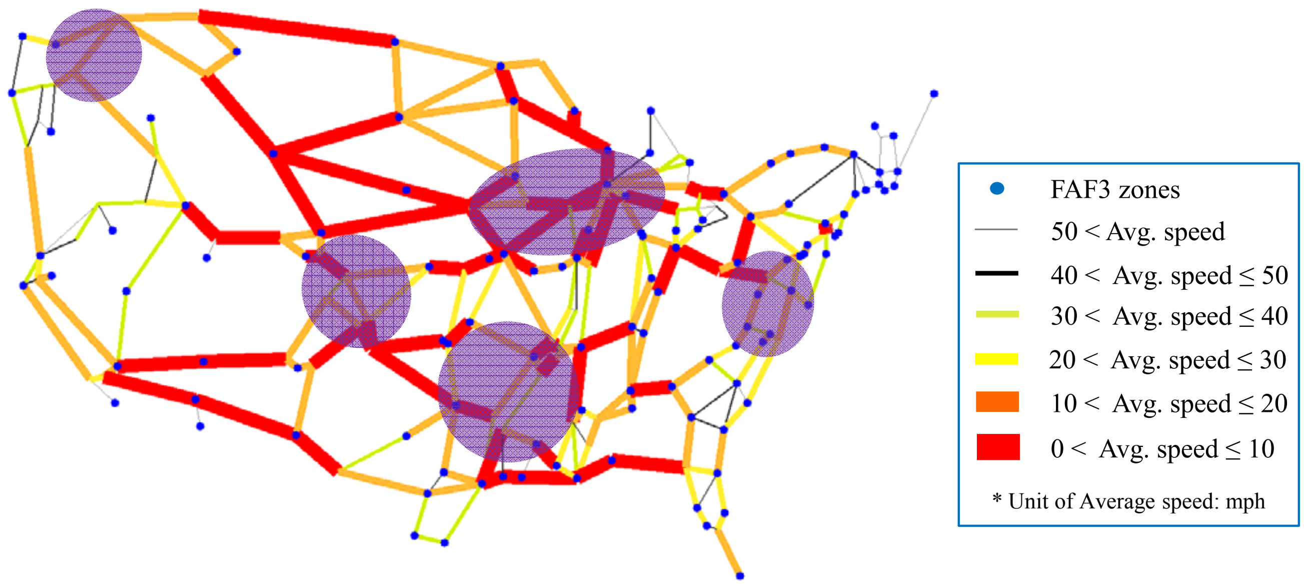


Cambridge Systematics, Inc. (2007)



Rail Network Capacity Expansion and Its Effect on Network Assignment

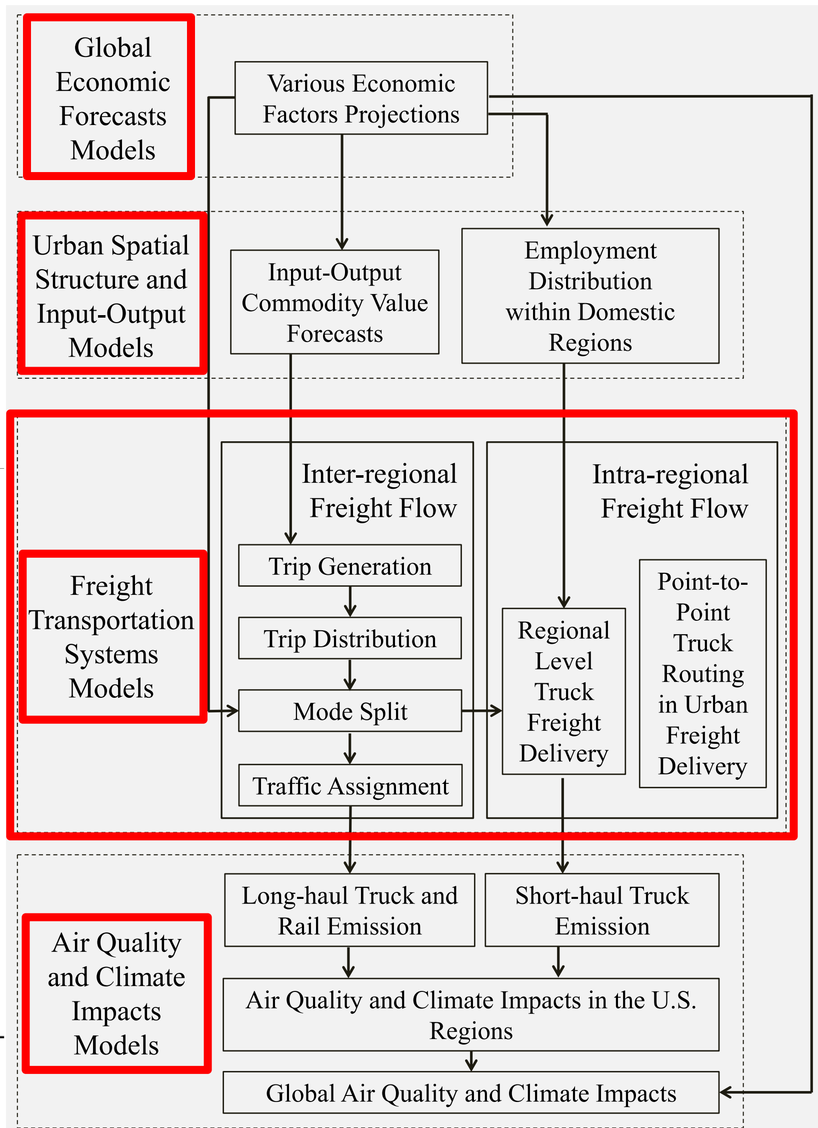
Congestion prediction from our model in 2035 after capacity expansion



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

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

Framework



Freight demand and logistics modeling:

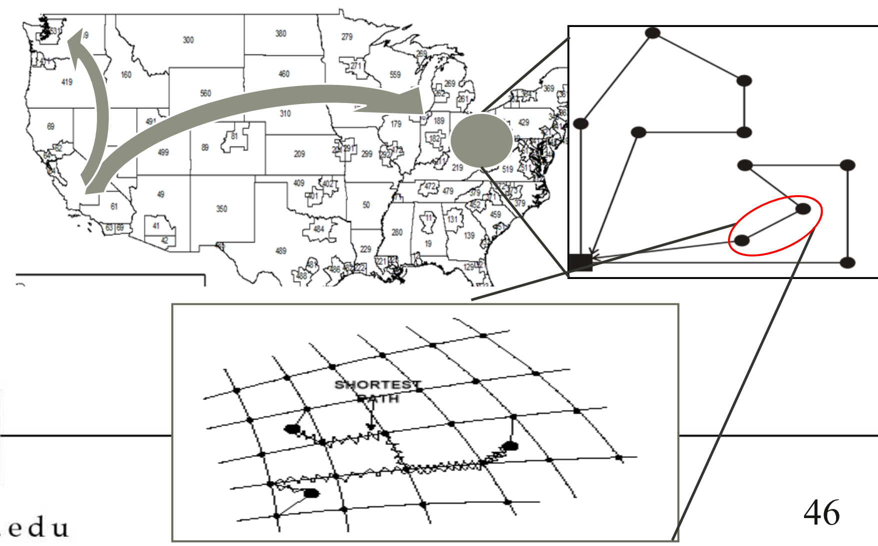
Develop and integrate a set of U.S. freight transportation system models to capture interdependencies on future economic growth and urban spatial structure changes

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

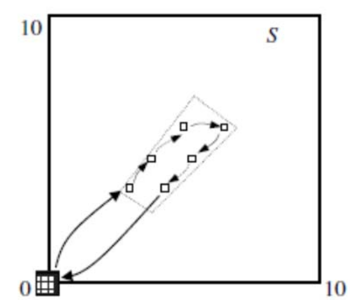
- Freight delivery activities within large urban areas are critical issues
  - Emissions from freight shipments comprise a large share of toxic air pollutants in most metropolitan areas worldwide (OECD, 2003)
  - Residents in metropolitan areas are more likely to be affected by the air pollution problems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

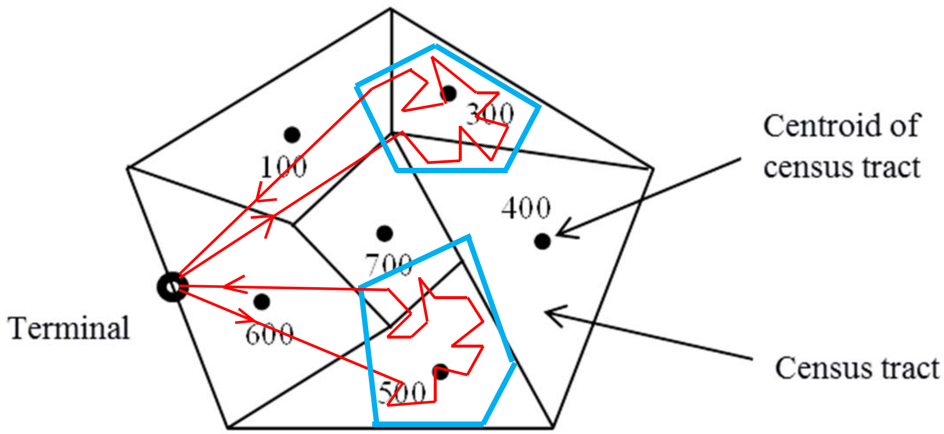
Total travel distance within a delivery region
= Total line-haul distance + Total local travel distance



Possible zoning and delivery plan example (Ouyang, 2007)

Within FAZ Delivery Procedure

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



Each FAZ is composed of a set of mutually disjointed census tracts

Freight delivery region (i.e., FAZ)

- 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 = distance from the terminal to the centroid of the census tract i

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

I = total number of census tracts

J = total number of industry types considered

C = truck capacity (in tonnage)

D = total freight demand in a given FAZ (tons per day)

$$\text{Total line-haul distance } (L_1) = \frac{2D\sum_{i=1}^{I}\sum_{j=1}^{J}E_{ij}d_i}{C\sum_{i=1}^{I}\sum_{j=1}^{J}E_{ij}}$$

Within FAZ Delivery

(2) Total local travel distance

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

where N_i = total number of demand points in each census tract i = $\sum_{j=1}^{J} \frac{E_{ij}}{a_j}$

a_j = 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

δ = uniformly distributed demand point density in a given FAZ $= \frac{N}{A}$

where A = 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 (CO_2, NO_X, 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

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

2. Commodities related to the manufacturing industry for terminal k

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

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

$$L_{s1}^{q} = \frac{2\beta_1 \left(D_W + D_R\right) \sum_{i=1}^{I_q} \sum_{j=1}^{2} E_{ij} d_{qi}}{C \sum_{i=1}^{I} \sum_{j=1}^{2} E_{ij}}, \quad L_{s2}^{q} = \frac{0.57 N_s^q}{\sqrt{\delta_s^q}}, \text{ where } N_s^q = \frac{\beta_1}{a_1} \sum_{i=1}^{I_q} \sum_{j=1}^{2} E_{ij} \text{ and } \delta_s^q = \frac{N_s^q}{A_q}$$

     (2) Commodities related to the manufacturing industry for terminal q

$$L_{m1}^{q} = \frac{2\beta_2 D_M \sum_{i=1}^{I_q} E_{i3} d_{qi}}{C \sum_{i=1}^{I} E_{i3}}, \quad L_{m2}^{q} = \frac{0.57 N_m^q}{\sqrt{\delta_m^q}}, \text{ where } N_m^q = \frac{\beta_2}{a_2} \sum_{i=1}^{I_q} E_{i3} \text{ and } \delta_m^q = \frac{N_m^q}{A_h}.$$

  3. Total freight delivery cost in the FAZ summed across all railroad terminals $q \in Q$

$$G_R = \sum_{q=1}^{Q} \left(L_{s1}^{q} + L_{s2}^{q} + L_{m1}^{h} + L_{m2}^{h} \right)$$

Case Study

Scenarios

1: Business as usual

2: Polycentric development

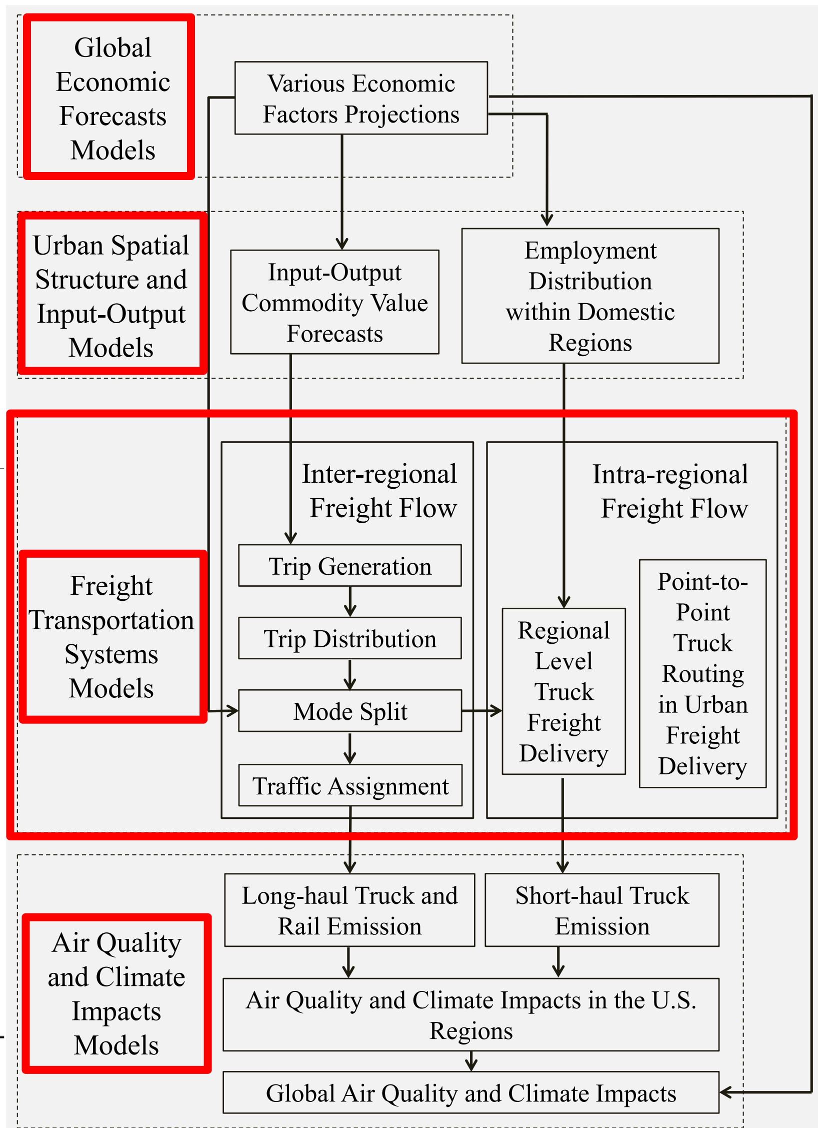
3: Compact development

MSA	# of FAZ	Scenario	Freight shipment (10^3 ton-mile) 2010	%	2020	%	2030	%	2040	%	2050	%
Los Angeles	1	1	3,413.69	3.94	4,479.54	14.91	5,524.88	16.35	6,728.67	18.01	8,084.86	19.71
		2	3,316.92	0.99	4,059.94	4.15	4,966.48	4.59	5,992.86	5.11	7,134.10	5.63
		3	3,284.42		3,898.15		4,748.61		5,701.67		6,753.96	
San Francisco	1	1	1,660.95	4.30	2,028.74	6.60	2,439.05	7.21	2,935.13	7.98	3,498.18	8.80
		2	1,600.03	0.47	1,919.17	0.84	2,294.17	0.84	2,741.66	0.87	3,243.02	0.86
		3	1,592.55		1,903.15		2,275.03		2,718.09		3,215.27	
Chicago	2	1	5,715.29	6.01	7,188.84	15.31	8,745.84	16.94	10,522.35	18.39	12,516.04	19.49
		2	5,415.29	0.44	6,344.03	1.76	7,633.72	2.07	9,096.19	2.34	10,737.94	2.52
		3	5,391.50		6,234.48		7,478.88		8,887.85		10,474.23	
New York	3	1	5,614.27	4.07	7,512.56	17.00	9,454.67	19.37	11,694.80	21.28	14,301.23	22.59
		2	5,423.98	0.55	6,556.63	2.11	8,100.81	2.28	9,865.76	2.32	11,926.56	2.24
		3	5,394.54		6,420.85		7,920.22		9,642.45		11,665.64	

MSA	Scenario	CO_2 (10^3 kg per day)			NO_X (kg per day)			PM (kg per day)			VOC (kg per day)		
		2010	2030	2050	2010	2030	2050	2010	2030	2050	2010	2030	2050
Los Angeles	1	1,223.98	1,980.95	2,898.84	13,467.99	21,797.22	31,897.06	1,321.77	2,139.21	3,130.42	4,189.74	6,780.87	9,922.81
	2	1,189.28	1,780.74	2,557.94	13,086.17	19,594.16	28,146.03	1,284.30	1,923.00	2,762.29	4,070.96	6,095.52	8,755.91
	3	1,177.63	1,702.62	2,421.64	12,957.95	18,734.62	26,646.30	1,271.71	1,838.64	2,615.10	4,031.07	5,828.13	8,289.36
San Francisco	1	595.53	874.52	1,254.28	6,552.91	9,622.73	13,801.30	643.11	944.39	1,354.48	2,038.53	2,993.52	4,293.43
	2	573.69	822.58	1,162.79	6,312.57	9,051.17	12,794.61	619.52	888.29	1,255.68	1,963.77	2,815.71	3,980.26
	3	571.01	815.72	1,152.84	6,283.05	8,975.64	12,685.17	616.63	880.88	1,244.94	1,954.58	2,792.22	3,946.21
Chicago	1	2,049.22	3,135.83	4,487.64	22,548.43	34,504.80	49,379.31	2,212.93	3,386.35	4,846.15	7,014.56	10,734.05	15,361.34
	2	1,941.66	2,737.08	3,850.10	21,364.85	30,117.17	42,364.23	2,096.78	2,955.74	4,157.68	6,646.36	9,369.11	13,179.03
	3	1,933.13	2,681.56	3,755.55	21,270.98	29,506.29	41,323.81	2,087.56	2,895.79	4,055.58	6,617.16	9,179.07	12,855.36
New York	1	2,013.00	3,389.98	5,127.72	22,149.88	37,301.34	56,422.39	2,173.82	3,660.81	5,537.37	6,890.58	11,604.02	17,552.36
	2	1,944.77	2,904.56	4,276.28	21,399.13	31,960.00	47,053.65	2,100.14	3,136.60	4,617.91	6,657.02	9,942.39	14,637.85
	3	1,934.22	2,839.80	4,182.73	21,282.97	31,247.50	46,024.25	2,088.74	3,066.67	4,516.88	6,620.89	9,720.74	14,317.62

*Emission factors (TRL, 1999)

Framework



Freight demand and logistics modeling:

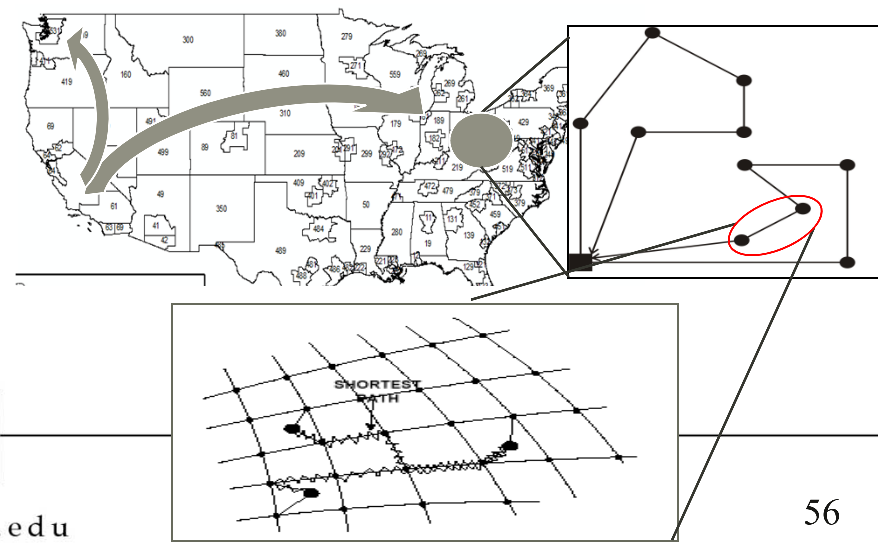
Develop and integrate a set of U.S. freight transportation system models to capture interdependencies on future economic growth and urban spatial structure changes

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



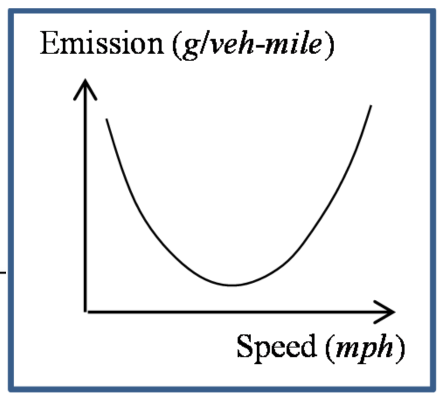
Introduction

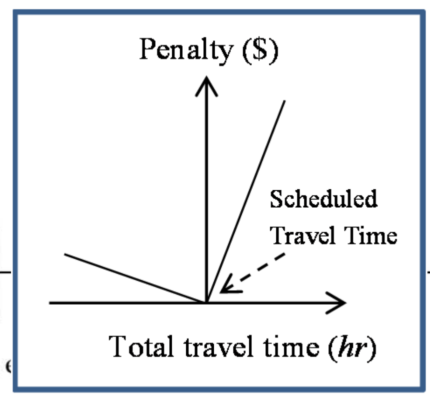
- Improvements in fleet operations from trucking service sector
  - Reduction in vehicle emissions
  - Huge benefits (urban air quality, human exposure)

- 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 (CO_2, VOC, NO_X, 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 $(i, j) \in A$

Total travel time **Emissions** **Penalty**

Minimize $\mathrm{E}\left[\alpha \sum_{(i,j)\in A} \frac{d_{ij}}{U_{ij}} x_{ij} + \beta \sum_{(i,j)\in A} d_{ij} x_{ij} W\left(U_{ij}\right) + P\left(\sum_{(i,j)\in A} \frac{d_{ij}}{U_{ij}} x_{ij}\right)\right],$ ➡ Minimizes expected total travel cost

subject to $\sum_{\{j|(i,j)\in A\}} x_{ij} - \sum_{\{j|(j,i)\in A\}} x_{ji} = \begin{cases} 1, & \text{if } i = g, \\ -1, & \text{if } i = s, \\ 0, & \text{otherwise,} \end{cases}$ ➡ Flow conservations at all network nodes

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

α (\$/hr), β (\$/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

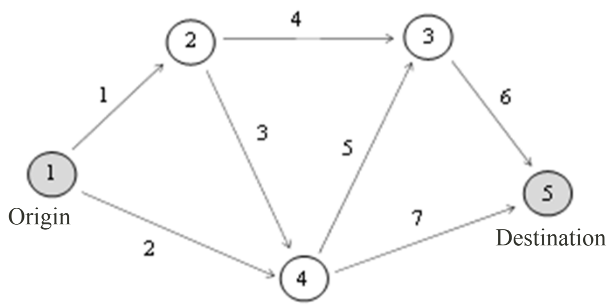
- Stage: each node $i \in V$ in a given network
- State: truck arrival time $m \in [0, \infty)$ at each stage $i \in V$
- Decision: choice from a finite set of decisions on the next link to move onto $\{(i,j) \mid (i,j) \in A\}$
- Truck speed: positive, continuous random variable which follows a certain 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

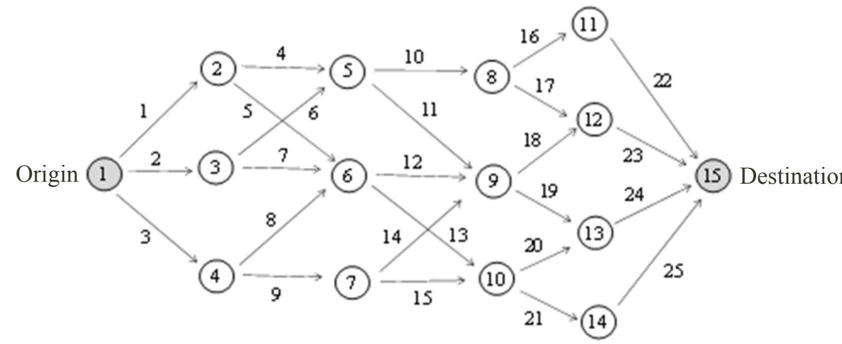
- In many real roadway networks, truck drivers need to select the next travel link in real time (i.e., within several seconds)
- Heuristic to find
  - Feasible solution in a very short computation time even for very large networks
  - Upper bound to the optimum solution
- Shortest path from origin to 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

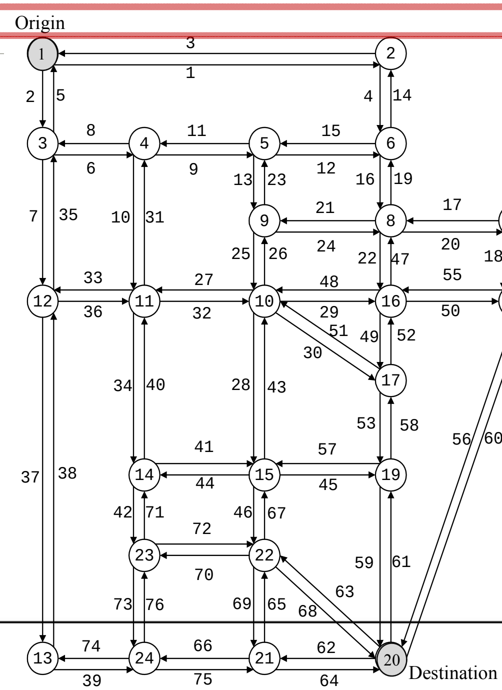
- Tested on four examples: small networks and large-scale urban transportation networks



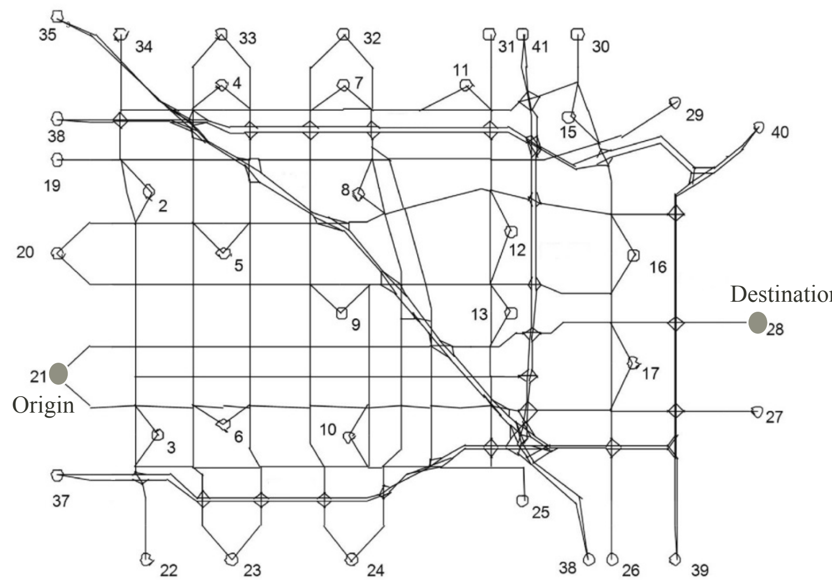
5-node and 13-link network (Powell, 2011)



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

(a) Network	(b) Algorithm	(c) Min. expected total cost ($)	(d) Gap (%)	(e) Solution time (sec)
5-node and 7-link network	Shortest path heuristic	33.33	2.54	0.008
	Dynamic programming (D = 0.025)	32.51	-	0.218
15-node and 25-link network	Shortest path heuristic	20.49	2.61	0.009
	Dynamic programming (D = 0.030)	19.97	-	0.725
24-node and 76-link Sioux Falls network	Shortest path heuristic	49.55	2.82	0.011
	Dynamic programming (D = 0.050)	48.19	-	160.052
416-node and 914-link Anaheim network	Shortest path heuristic	132.60	21.02	0.071
	Dynamic programming (D = 0.040)	109.57	-	8,741.145

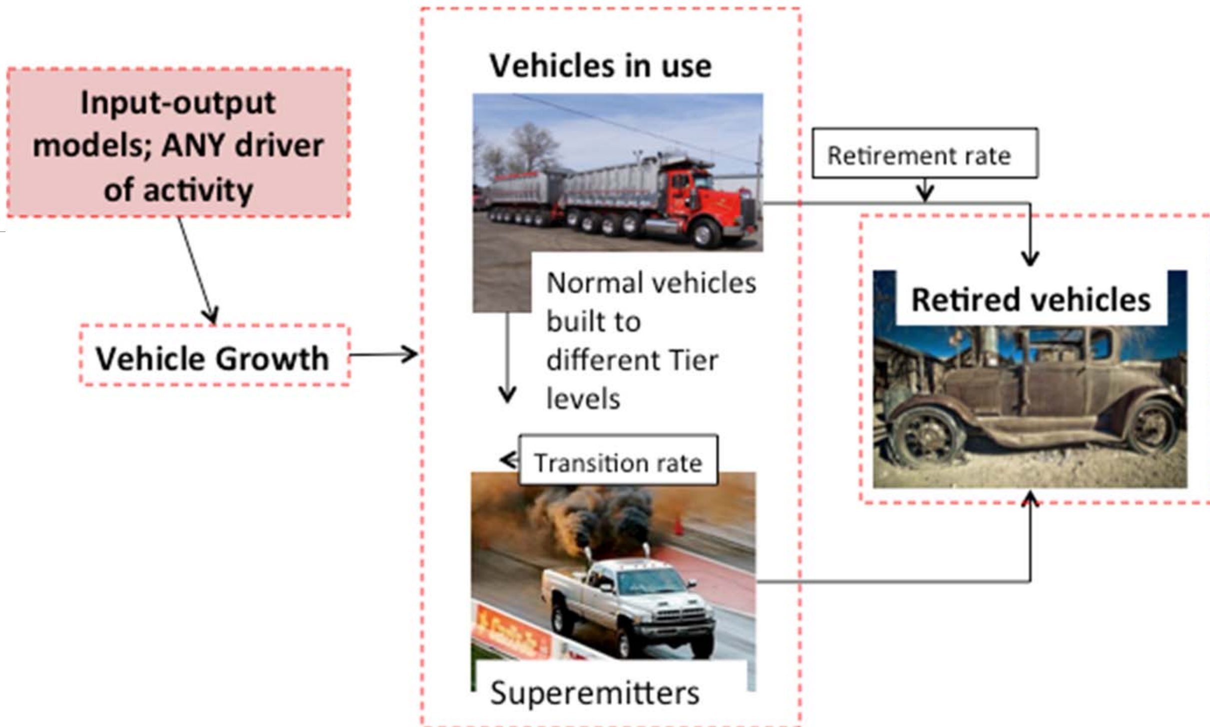
Numerical Examples: Computational Results

- 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

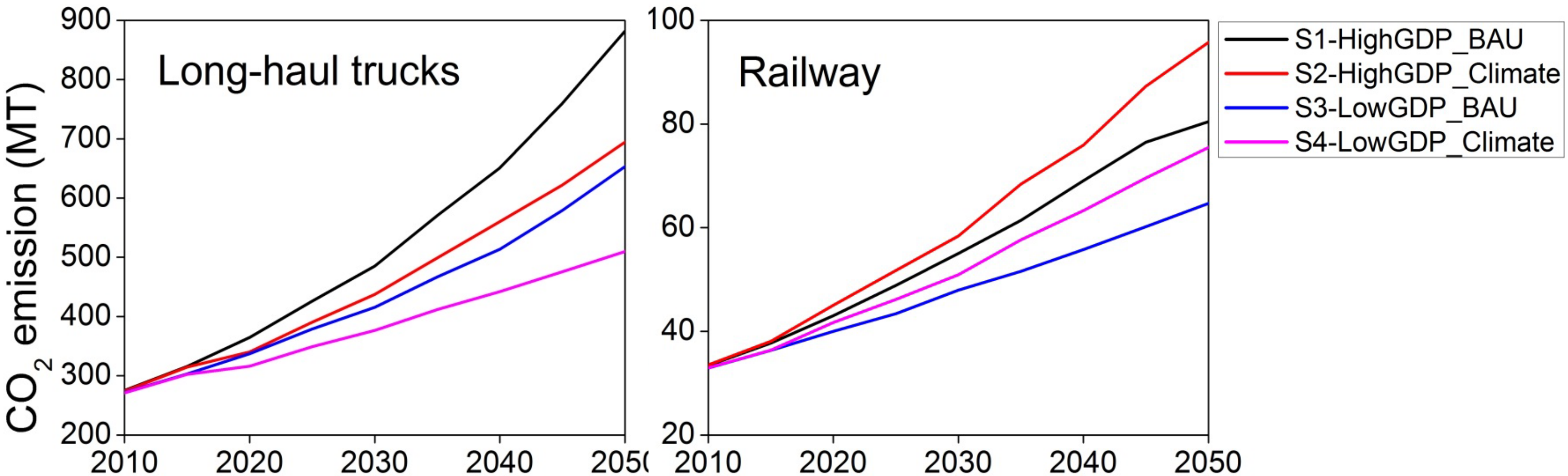
(a) Network	(b) Scenario	(c) Min. expected total cost ($)	(d) Travel time ($)	(e) Emissions ($)	(f) Penalty ($)
5-node and 7-link network	Benchmark design	35.45	13.88	13.76	7.80
	Proposed approach	32.51	14.39	10.81	7.30
	Cost difference	2.94	-0.51	2.95	0.50
		8.29%	-3.67%	21.42%	6.41%
15-node and 25-link network	Benchmark design	21.22	6.35	5.90	8.96
	Proposed approach	19.97	6.73	4.46	8.78
	Cost difference	1.25	-0.38	1.44	0.19
		5.87%	-5.97%	24.38%	2.08%
24-node and 76-link Sioux Falls network	Benchmark design	52.75	24.57	15.57	12.61
	Proposed approach	48.19	14.52	9.22	24.45
	Cost difference	4.56	10.05	6.36	-11.84
		8.64%	40.90%	40.82%	-93.93%
416-node and 914-link Anaheim network	Benchmark design	114.38	67.00	47.00	0.39
	Proposed approach	109.57	67.29	41.81	0.47
	Cost difference	4.81	-0.29	5.19	-0.08
		4.21%	-0.44%	11.04%	-21.76%

SPEW-Trend fleet model

Represent how emissions are affected by technology change and modal choice

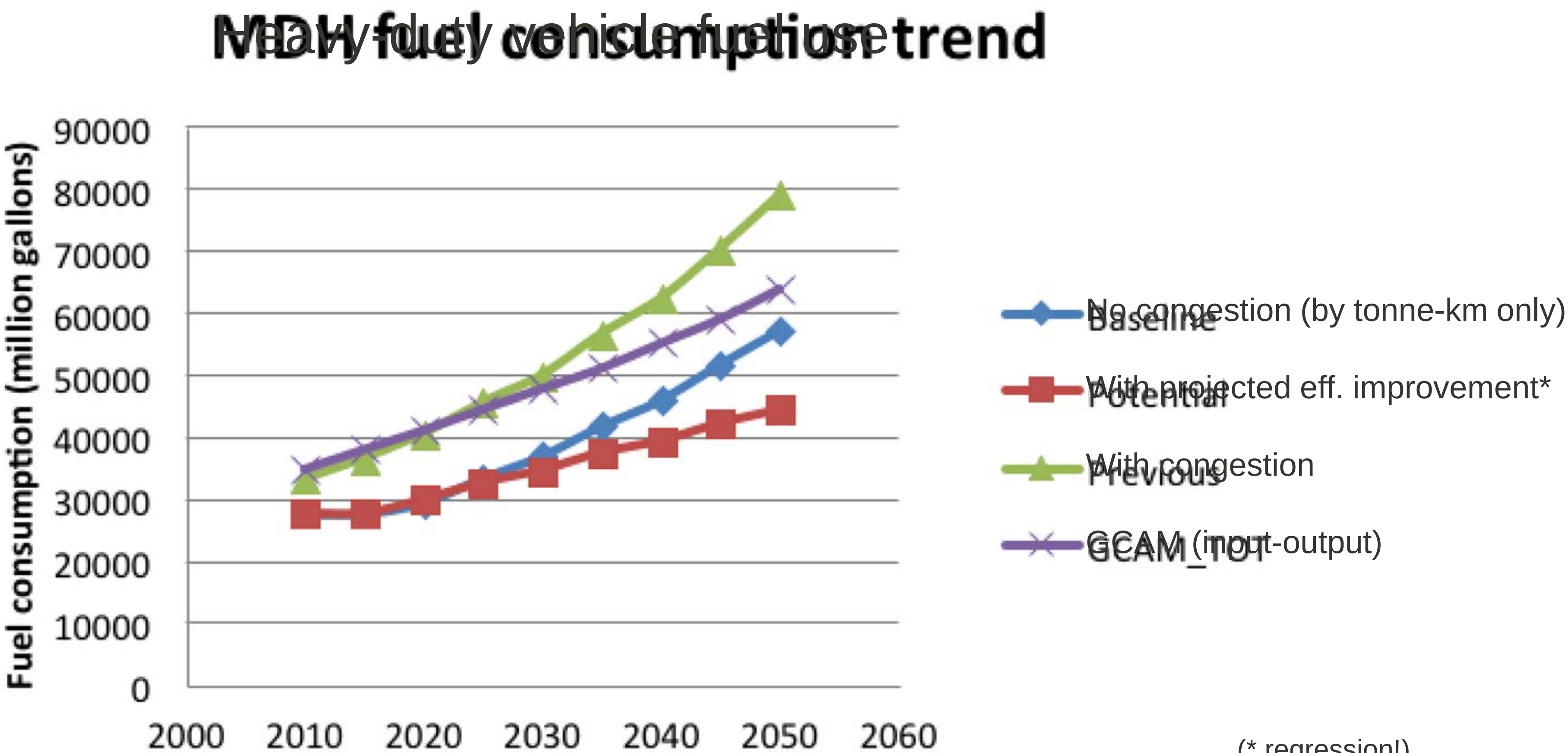


CO_2 emission projection



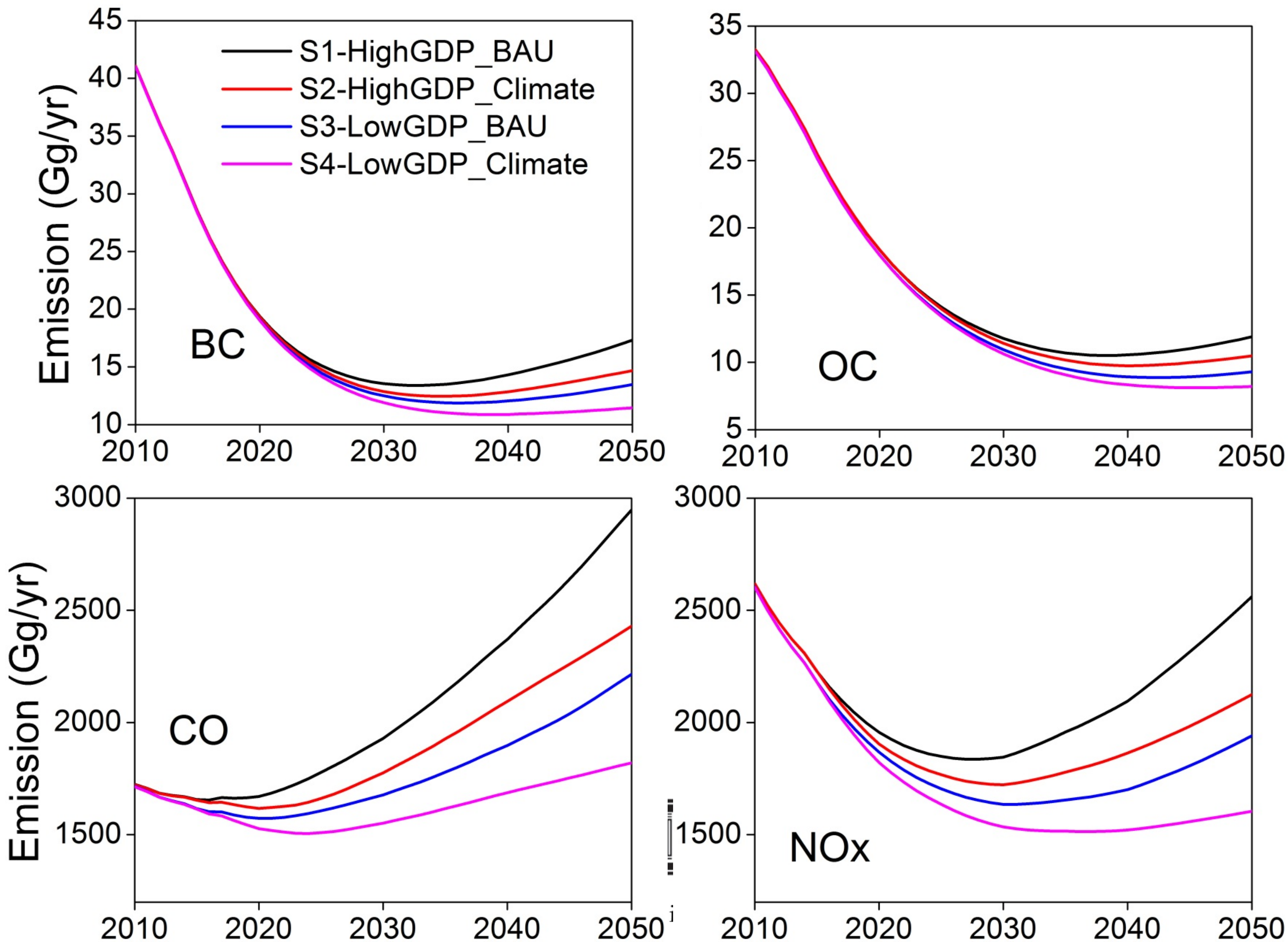
*Climate policy (carbon tax) causes modal shift to **railway– BUT not "enough" (Commodity-limited)***

Fuel use projection



(* regression!)

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

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