Global-to-Urban Models for Minimizing Air Quality and Climate Impacts of Freight Choice

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Adaptation for Future Air Quality Analysis and Decision Support Tools in Light of Global Change Impacts and Mitigation

EPA – RTP, 8 November 2010

How will freight activity (movement of goods) affect atmospheric environmental impacts?

Long-term climate (GHG emissions)

Short-term climate (short-lived climate forcers)

Long-range transport of air pollution

Background air quality

Urban air quality

Population exposure

Original design

Dimensions of change

	Global	Regional	Urban
Service activity	SGM/ MiniCAM		
Efficiency (fuel consumed per activity)	(assumed by SGM)	Freight mode (discrete choice and network loading)	Network model
Emission (emission per fuel or per activity)	SPEW-Trend	SPEW-Trend with new technologies	
Spatial Distribution	SPEW By region with surrogates	Distribution by origin-destination matrix	Urban spatial form

by commodity

by activity

by population/ jobs

Color legend

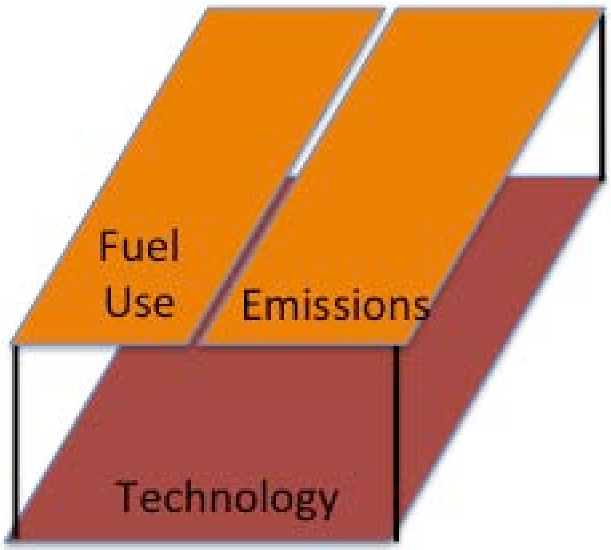
- Bond (technology & emissions)
- Ouyang (transportation logistics)
- Barkan (railroad operations)
- Lee (urban planning)
- Smith (economic scenarios)

Downscaling

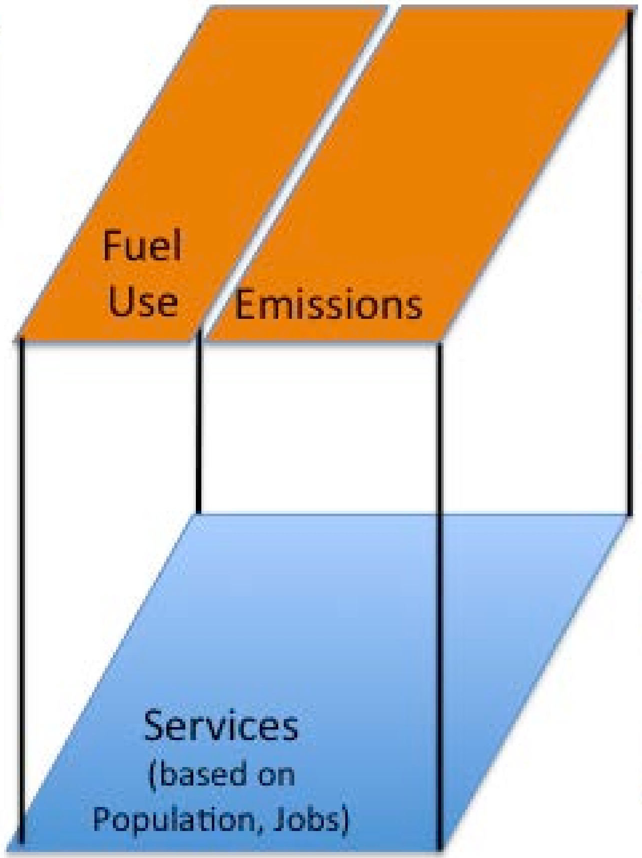
Upscaling

enhanced under this project

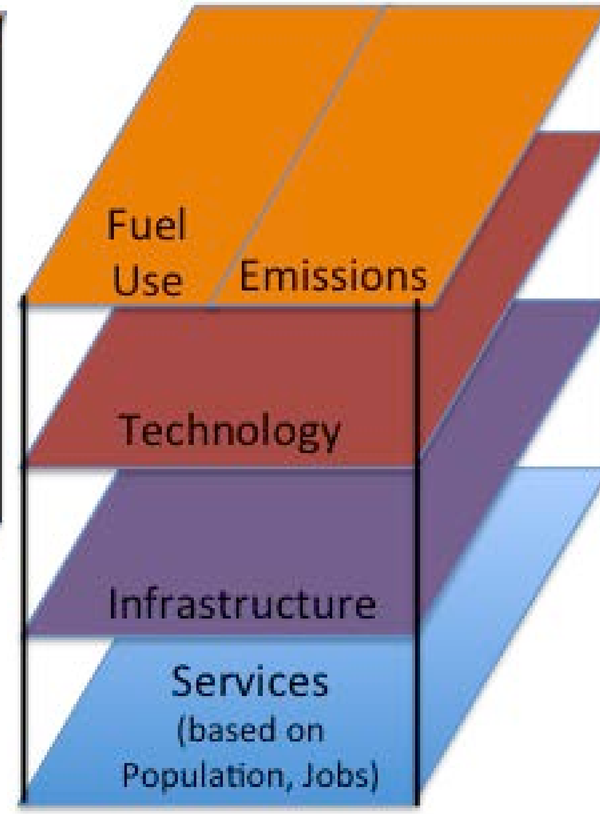
Change in large-scale emission projections



Atmospheric
Chemistry



Macroeconomic



Hybrid
Just-enough detail

Scales and analysis units

GLOBAL

By world region

Inputs from macroeconomic models (PHOENIX)

Increase in commodities

REGIONAL

Within USA

By Freight Analysis Zone (FAZ)

Interregional flows, including ports

Deliveries

URBAN

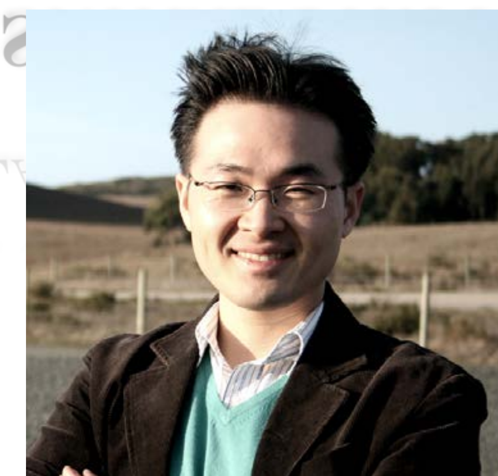
Within each FAZ

By Census Tract

Bumsoo Lee & student Sungwon Lee

Urban Planning Dept

1. Urban Spatial Structure
2. U.S. Future Employment Distribution



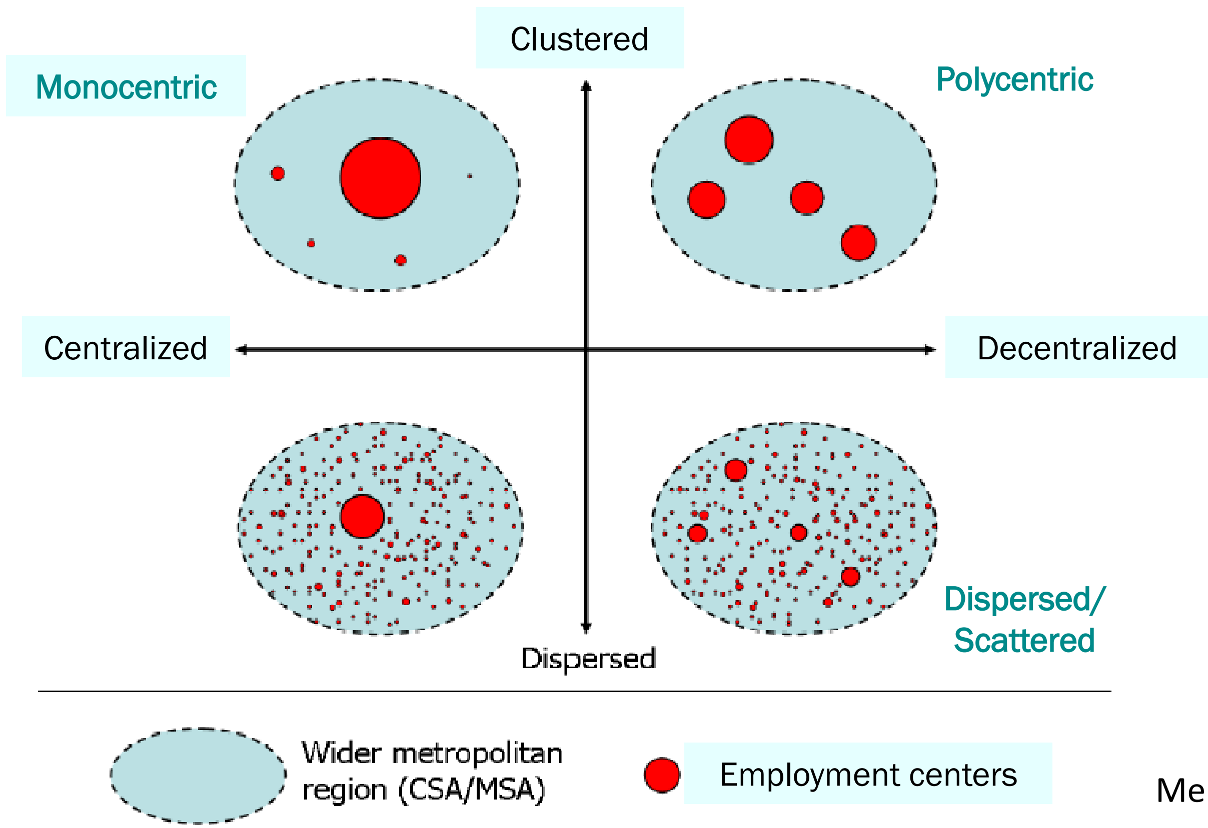
1. Urban spatial structure

GOAL: Represent future distribution of jobs within major metropolitan areas

- Affects intra urban freight transportation → *within-region* freight activity
- Affects distribution of emissions & exposure
- Affects ability of railroad planning to alter efficiency

Two dimensions of urban spatial structure

- Centralized vs. Decentralized: how concentrated jobs are near the Central Business District
- Clustered vs. Dispersed : how disproportionately jobs are clustered in a few locations



Modified from Meijers & Burger (2009)

Urban density gradients: Approach

Spatial autoregression models of employment and population density gradients of central business district (CBD) and subcenters

$$\Delta Y = \alpha + \rho W \Delta Y + \beta_1 DCBD + \beta_2 DSUB^{-1/2} + \beta_3 DINCH^{-1/2} + \varepsilon$$

ΔY: natural log of gross employment (population) density
W: spatial contiguity weight matrix
DCBD: distance from the CBD
DSUB: distance from the nearest subcenter
DINCH: distance from the nearest highway interchange
α,β1,β2,β3 = coefficients

Urban density gradients: Approach

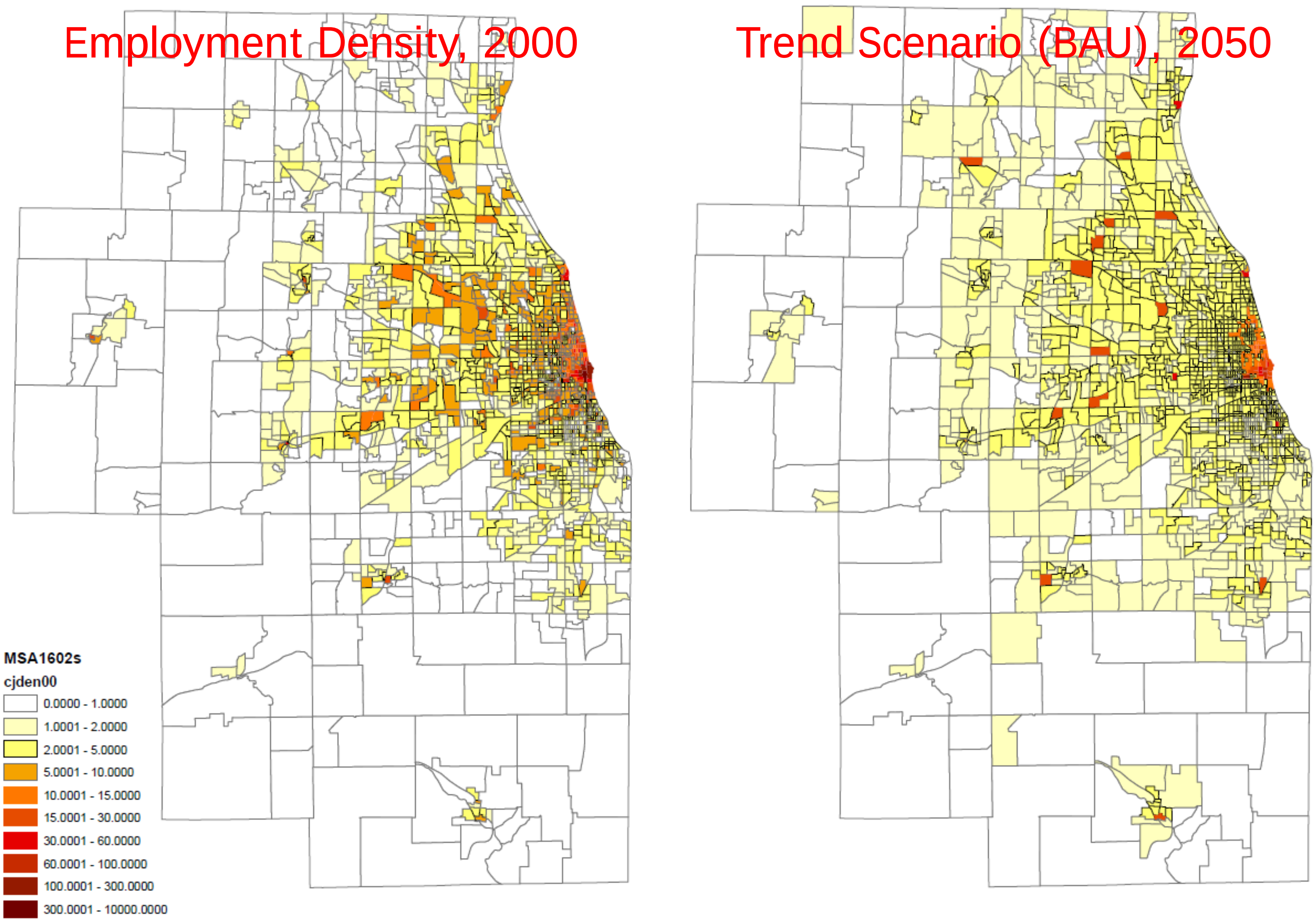
Spatial autoregression models of employment and population density gradients of central business district (CBD) and subcenters

Year	Distance from CBD (β)	Distance from Subcenter (γ)
1990	-0.072	0.145
2000	-0.039	0.120
Change	0.034	-0.027
MSAs with increased density gradients of CBDs or Subcenters	8 MSAs: Tulsa, Albuquerque, Scranton, Tucson, Raleigh, Grand Rapids, Greenville, Allentown	14 MSAs: Fort Wayne, Tulsa, Rochester, Memphis, Hartford, Las Vegas, Toledo, Colorado Springs, Bakersfield, Little Rock, Grand Rapids, Greensboro, Youngstown, Sacramento

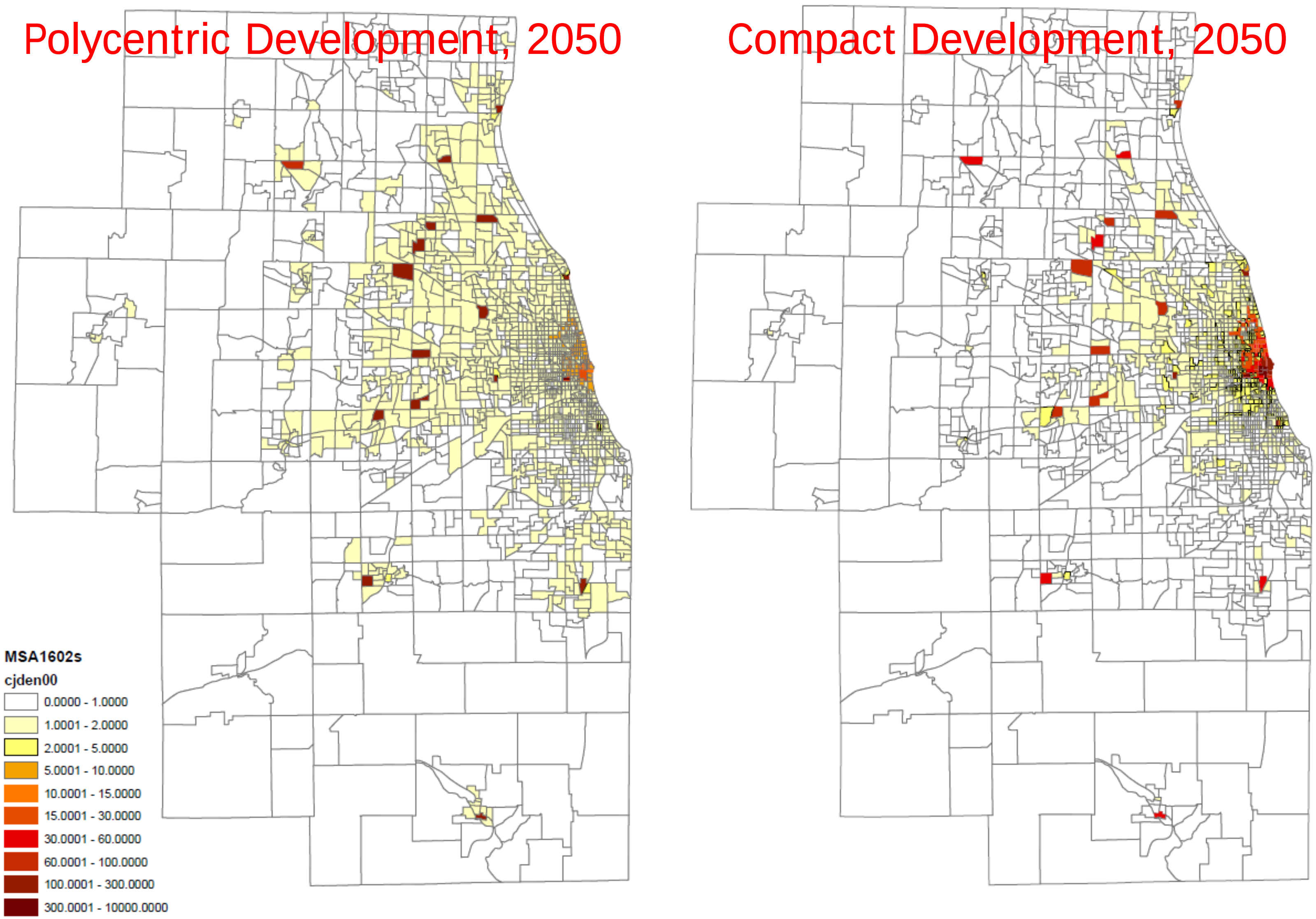
Urban form scenarios

1. Business as usual (BAU)
   - Trend decentralization and dispersion (Mean parameters)
2. Polycentric development scenario
   - Trend decentralization but significant subcentering
3. Compact development scenario
   - Recentralization and significant subcentering

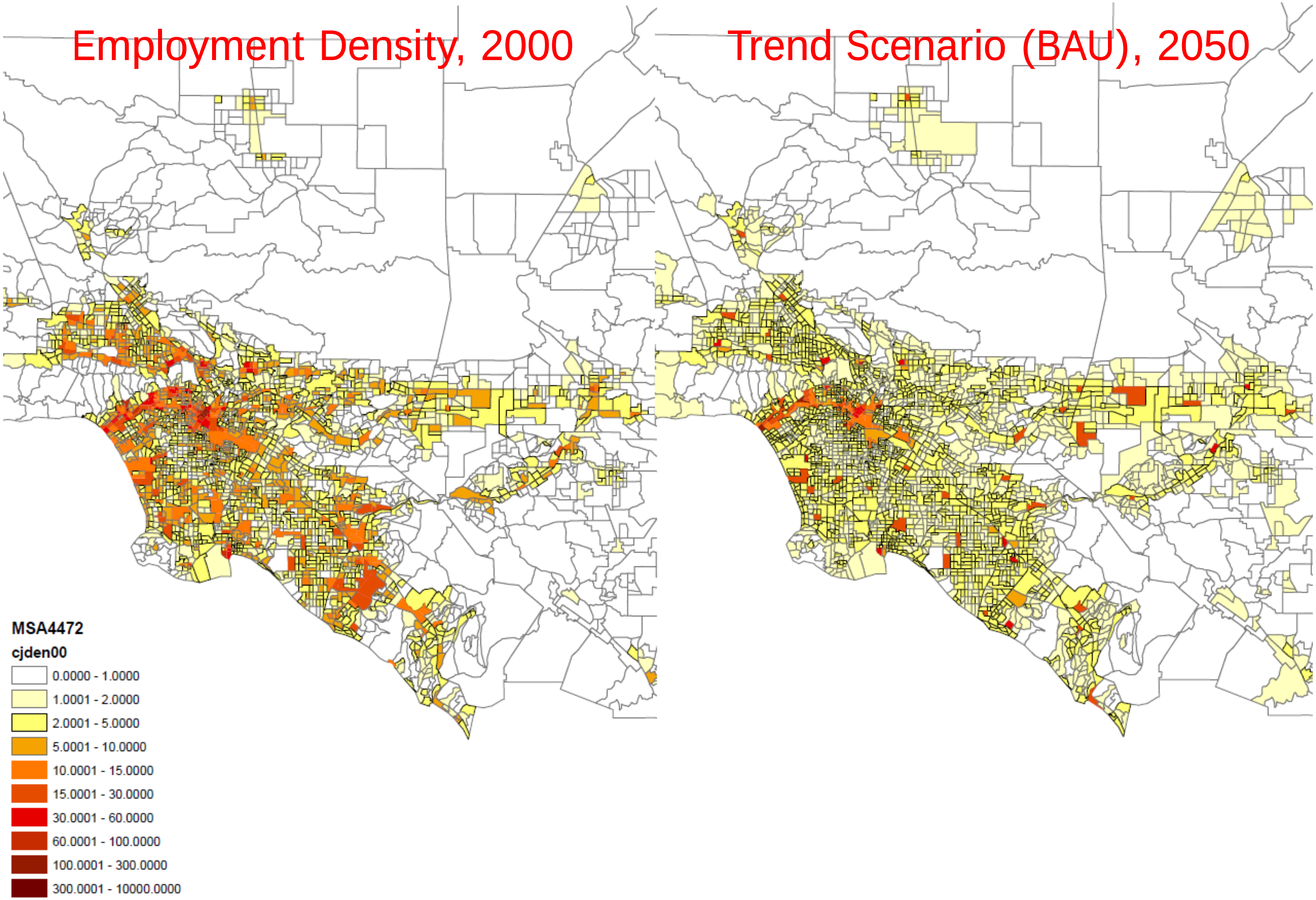
Employment Density Projections: Chicago, IL FAZ



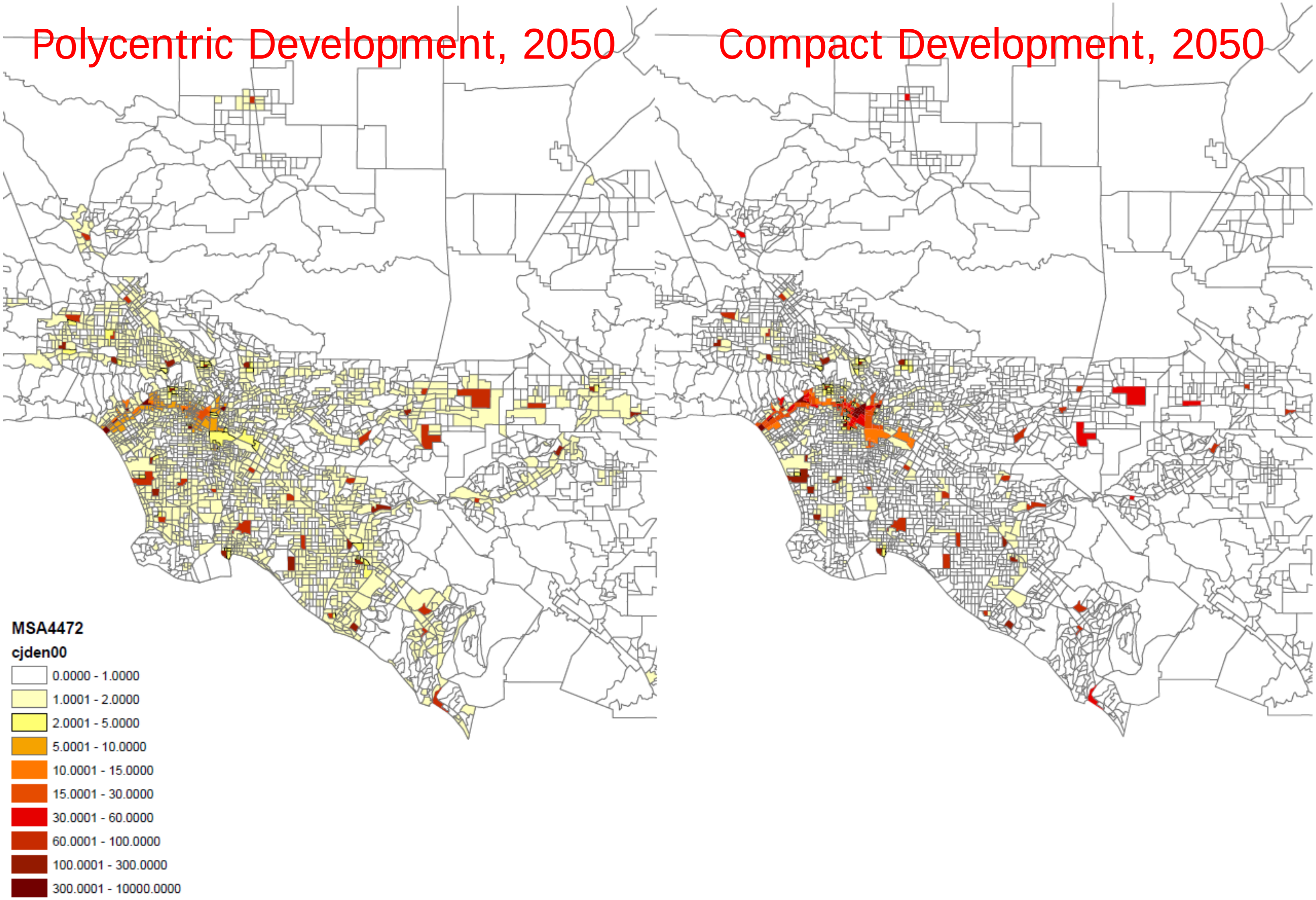
Employment Density Projections: Chicago, IL FAZ



Employment Density Projections: Los Angeles, CA FAZ



Employment Density Projections: Los Angeles, CA FAZ



2. Future employment distribution by FAZ

- Input data
  - U.S. population, GDP (by sector), and labor cost projections from a global CGE model (The Phoenix Model at Battelle PNNL)
  - County level population projection from EPA (the Integrated Climate and Land Use Change Scenarios, ICLUS)
  - County level 1998-2009 employment by industry from the County Business Patterns data by the US Census Bureau
- Methods
  - A standard **Shift-Share model** extrapolating the regional shift component
  - Control employment/population ratio based on the national trend
  - Multi-step top down allocation approach: US Total (1) → Census Division (9) → State (49) → FAZ (120)

Shift-Share Model

$$(\Delta E_{ir}) = E_{ir}^{t} - E_{ir}^{t-1} = NS_{ir}^{t} + IM_{ir}^{t} + RS_{ir}^{t}$$

t: time, i: industry, r: region

- Shift-share model: Decomposes regional employment growth
  1) National Share (NS) Component
     - Share of regional growth due to national grow

$$NS_{ir}^{t} = E_{ir}^{t-1}\left(\frac{E_{us}^{t}}{E_{us}^{t-1}} - 1\right)$$

  2) Industry Mix (IM) Component
     - The impacts of the region's mix of industries

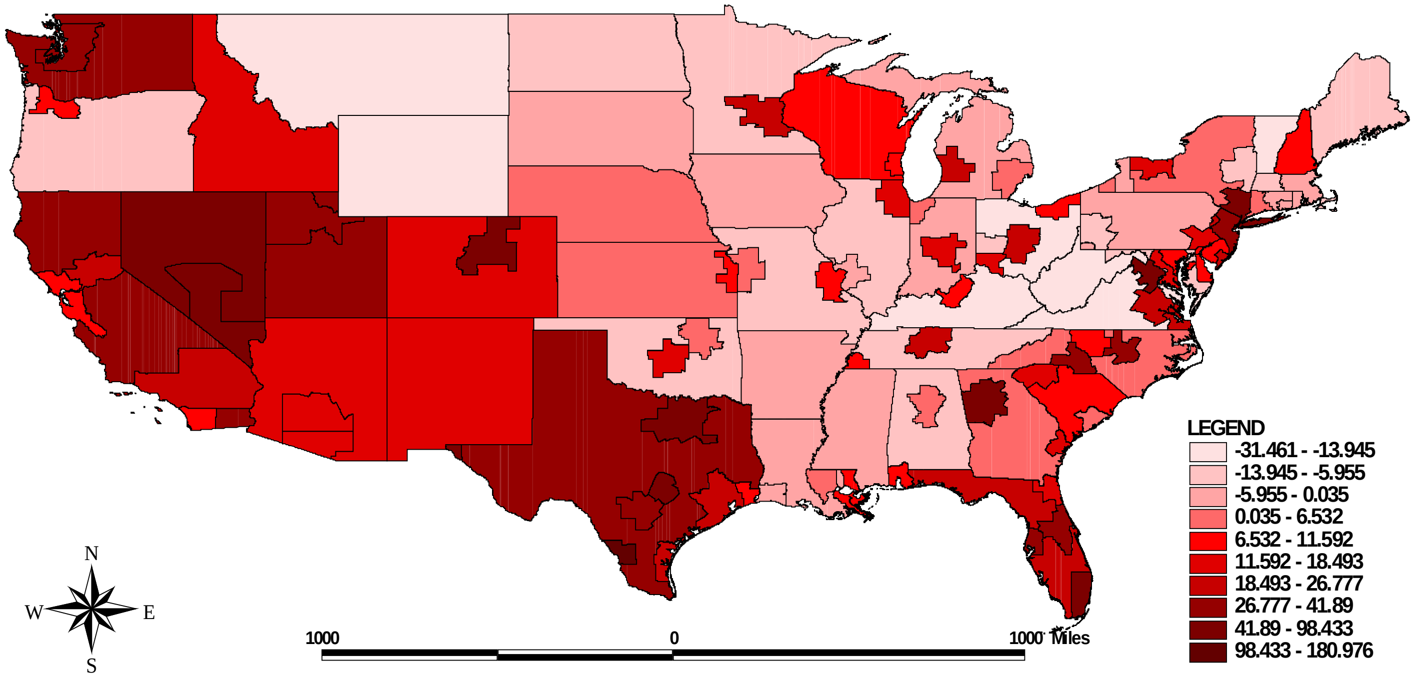
$$IM_{ir}^{t} = E_{ir}^{t-1}\left(\frac{E_{ius}^{t}}{E_{ius}^{t-1}} - \frac{E_{us}^{t}}{E_{us}^{t-1}}\right)$$

  3) Regional Shift (RS) Component
     - Created jobs as a result of regional competitiv

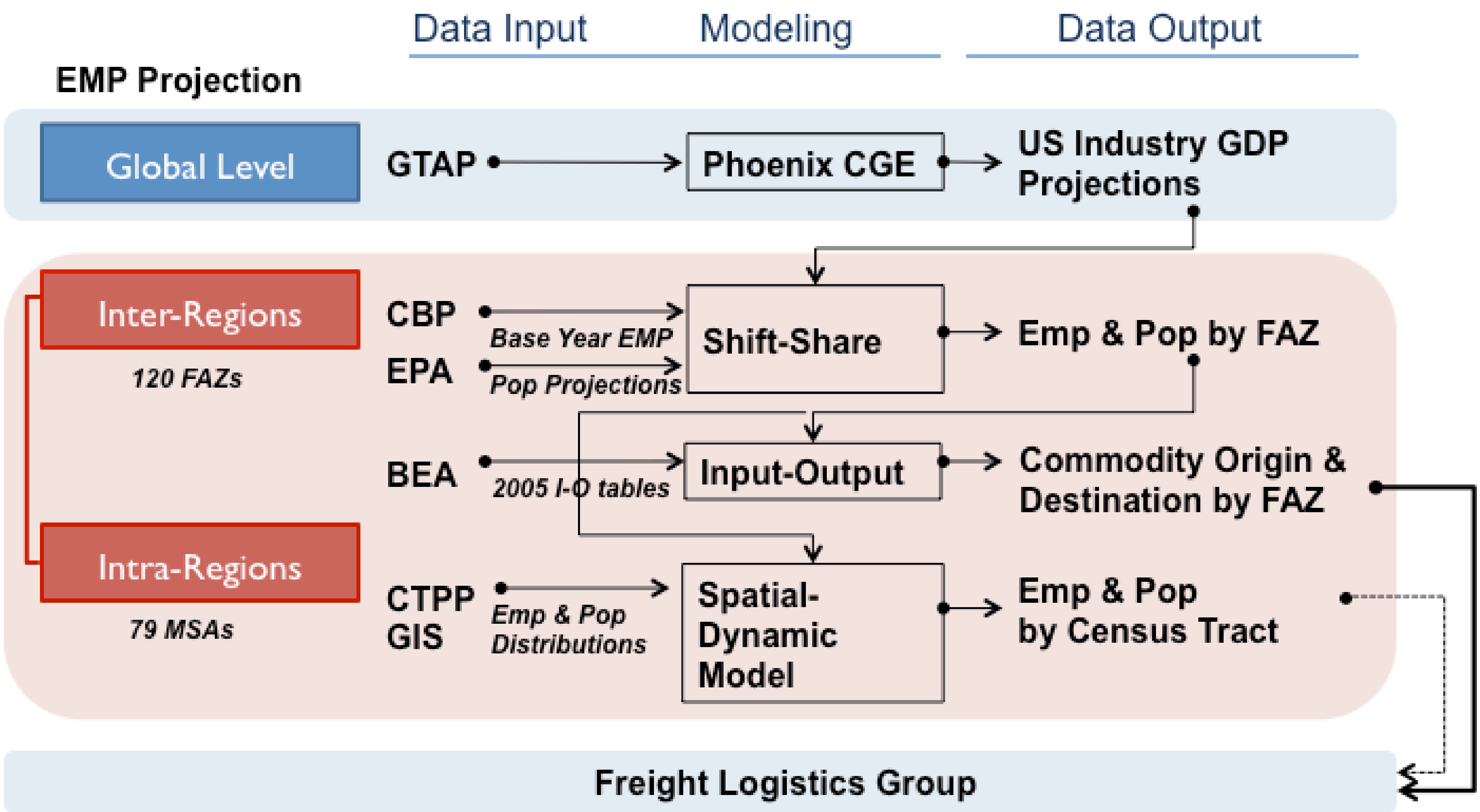
$$RS_{ir}^{t} = E_{ir}^{t-1}\left(\frac{E_{ir}^{t}}{E_{ir}^{t-1}} - \frac{E_{ius}^{t}}{E_{ius}^{t-1}}\right)$$

- FAZ employment growth projection
  - **NS** and **IM** for future periods come from a national level projection by industry (the Phoenix model)
  - Extrapolate the five-year mean **RS** for 1998-2009 into the future

Percent change in total employment



2. US future employment distribution



Yanfeng Ouyang & student Taesung Hwang

Civil Engineering – Transportation

3. Distribution of Freight via Rail and Truck
4. Delivery within Freight Zone

Freight and delivery logistics

- GOAL: Given future economy, represent freight movements between & within freight zones
  - Affected by: Strength of economy, commodities used
  - Affected by: Infrastructure capacity
  - Affected by: Fuel price & shipping time
  - Affects: interregional freight choice → national freight activity → total emissions
  - Affects: local distribution of emissions & exposure

3. Freight distribution between FAZs

- Four-Step Freight Commodity Transportation Forecasting Model
  - Closely resembles the four-step urban travel demand model for passengers.
  - Fewer standardized techniques exist for forecasting movement of 'freight' (Jiang et al., 1999; NCHRP Report 606, 2008).

Trip Generation	→	Trip Distribution	→	Mode Split	→	Traffic Assignment
From global macroeconomic model		*Scaled from present-day origin-destination matrix*		*Refined from existing work*		*Produced by network optimization model*

Trip generation and distribution

Challenge: develop a new origin-destination matrix

O \ D	1	2	..	d	..	Z	Given Production	Future Production
1								
2								
:								
o				D^i_{od}			P^i_o	FP^i_o
:								
Z								
Given Attraction				A^i_d				
Future Attraction				FA^i_d				

For each commodity:

1. Current attraction (based on employment) and production
2. Growth in production & attraction in each location
   - downscaled from macroeconomic model
3. Iterative algorithm converges rapidly

Mode choice: Binomial logit market share

Utility of truck (T) for commodity n: $U_T^n = a_{1n} + b_{1n} \cdot VALUE + c_{1n} \cdot DIST_T + d_{1n} \cdot OILPRC$

Utility of rail (R) for commodity n: $U_R^n = a_{2n} + b_{2n} \cdot VALUE + c_{2n} \cdot DIST_R + d_{2n} \cdot OILPRC$

Market share of truck (T) for commodity n: $P_n(T) = \dfrac{e^{U_T^n}}{e^{U_T^n} + e^{U_R^n}} = \dfrac{1}{1 + e^{U_R^n - U_T^n}} = \dfrac{e^{U_T^n - U_R^n}}{e^{U_T^n - U_R^n} + 1}$

Market share of rail (R) for commodity n: $P_n(R) = 1 - P_n(T) = \dfrac{1}{e^{U_T^n - U_R^n} + 1}$

Production of a single usable data set (70,000 observations)

- Combine data sets
  - Freight Analysis Framework (FAF^2, FAF^3), Commodity Flow Survey, West Texas Intermediate crude oil price
- Group into 10 commodities

Estimation results for mode split

- Training set (2/3 of observations) for parameter development
- Test set (1/3 of observations) for validation

All p-values <0.001

			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-value	12761.00	5868.29	28335.00	10357.00	8350.80	15685.00	21139.20	4176.90	5472.90	811.40
	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-value	8593.00	7124.43	1211.00	25389.00	7289.40	5238.40	4593.40	1948.40	3655.00	1545.80
	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-value	-2796.00	-1680.74	-2488.00	-3390.00	-2418.20	252.00	-3714.60	-2113.00	-1792.30	-472.10
	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-value	-2258.00	5.30	-4958.00	-5019.00	485.40	-2912.50	1613.70	1494.90	234.50	-138.70
	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-value	1634.00	-965.59	-5993.00	-14669.00	-2758.90	-818.30	-389.90	963.90	4948.40	432.10
(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

Preliminary share results

(a) WTI Crude Oil Price ($/barrel)	(b) Truck Share Prediction (%)	(c) Rail Share Prediction (%)	(d) Truck CO_2 Emission (g)	(e) Rail CO_2 Emission (g)	(f) Total CO_2 Emission (g)	(g) Truck PM_{10} Emission (g)	(h) Rail PM_{10} Emission (g)	(i) Total PM_{10} Emission (g)
20	70.0%	30.0%	70,392,314	8,039,421	78,431,735	8,439	3,600	12,038
30	68.4%	31.6%	68,824,557	8,456,655	77,281,212	8,251	3,787	12,037
40	66.8%	33.2%	67,214,027	8,885,271	76,099,298	8,058	3,978	12,036
50	65.2%	34.8%	65,563,423	9,324,553	74,887,976	7,860	4,175	12,035
60	63.5%	36.5%	63,875,802	9,773,686	73,649,488	7,657	4,376	12,034
70	61.8%	38.2%	62,154,561	10,231,766	72,386,327	7,451	4,581	12,032
80	60.0%	40.0%	60,403,414	10,697,806	71,101,220	7,241	4,790	12,031
90	58.3%	41.7%	58,626,370	11,170,737	69,797,108	7,028	5,002	12,030
100	56.5%	43.5%	56,827,697	11,649,425	68,477,122	6,813	5,216	12,029
110	54.7%	45.3%	55,011,882	12,132,675	67,144,557	6,595	5,433	12,027
120	52.9%	47.1%	53,183,594	12,619,245	65,802,838	6,376	5,650	12,026
130	51.0%	49.0%	51,347,630	13,107,857	64,455,486	6,156	5,869	12,025

Network loading algorithm

- User Equilibrium (Sheffi, 1985)
- Convex Combinations Algorithm
  - converges quickly (<2 sec)
- Considers congestion (including background traffic)

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

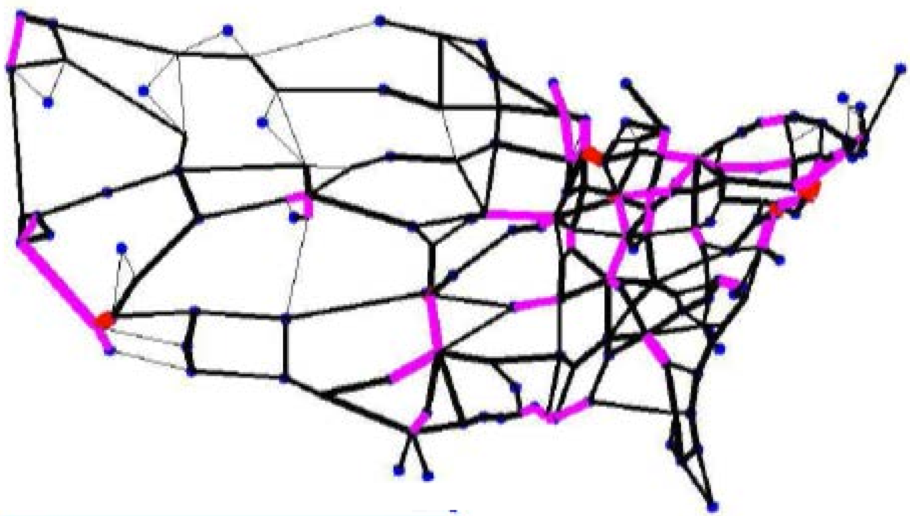
where t_f = link free flow travel time, x = link traffic flow $(\#of\ \ veh/hr)$,

C = link capacity $(\#of\ \ veh/hr)$, $\alpha = 0.15$ and $\beta = 4$

Truck and rail network loading

Truck

178 total nodes,
588 total links

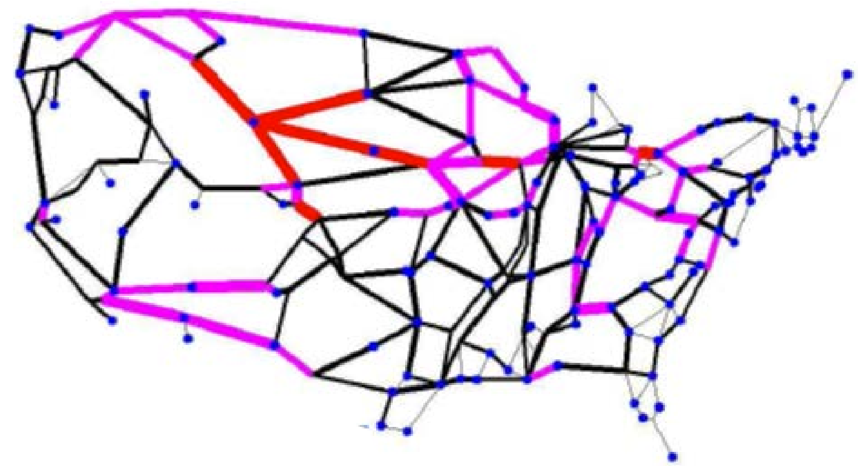


- FAF3 zones
- 0 ≤ Traffic Flow ≤ 2,000
- 2,000 < Traffic Flow ≤ 4,000
- 4,000 < Traffic Flow ≤ 6,000
- 6,000 < Traffic Flow ≤ 8,000
- 8,000 < Traffic Flow ≤ 10,000
- 10,000 < Traffic Flow ≤ 12,000
- 12,000 < Traffic Flow

passenger car equivalents

Rail

183 total nodes,
566 total links

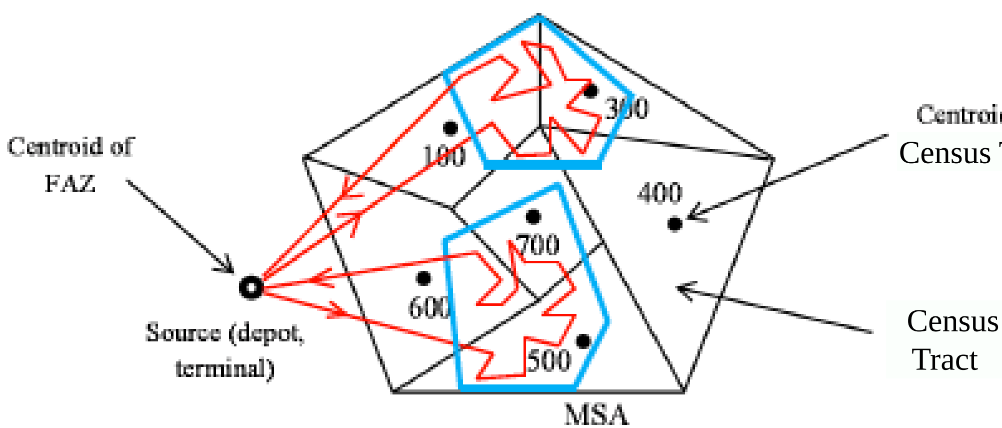


- FAF3 zones
- 0 ≤ Traffic Flow ≤ 30
- 30 < Traffic Flow ≤ 60
- 60 < Traffic Flow ≤ 90
- 90 < Traffic Flow ≤ 120
- 120 < Traffic Flow ≤ 150
- 150 < Traffic Flow

trains per day

4. Within-FAZ delivery

- Affected by job density and polycentricity
- Ring-sweep algorithm (Newell and Daganzo, 1986)
- Produces number of km driven under each scenario and their locations



FAZ: Freight Analysis Zone
MSA: Metropolitan Statistical Area

Each MSA is divided into a set of census tracts

TAMI BOND & STUDENT FANG YAN
CIVIL ENGINEERING - ENVIRONMENTAL

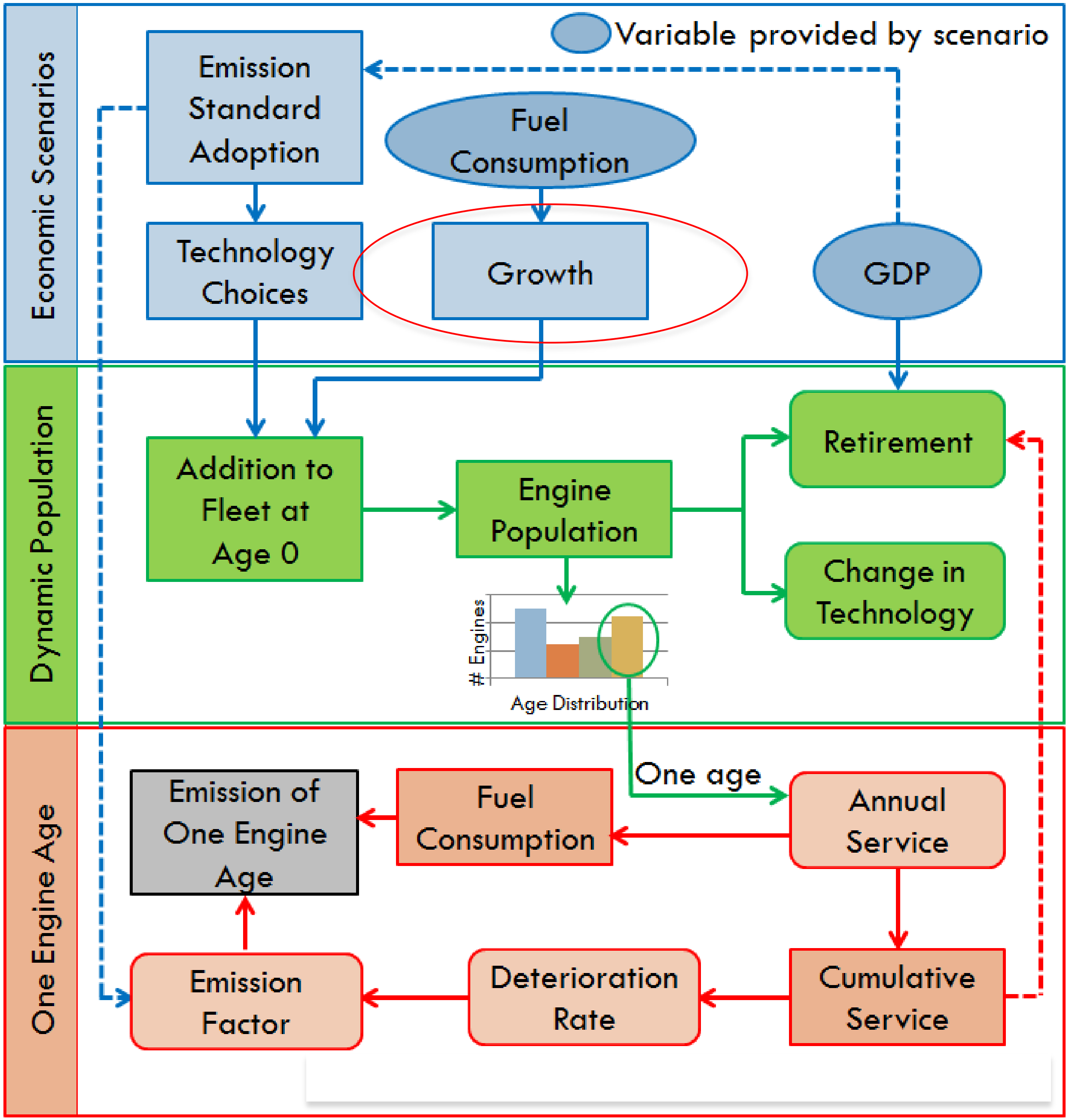
5. EMISSIONS, TECHNOLOGY, AND SPATIAL DISTRIBUTION

Bridge between activity and air quality

- GOAL: Given future activity, represent how air quality and climate change are affected
  - Affected by: Choice and location of inter- and intra-zone freight
  - Affected by: Choice of technology
  - Affects: National freight activity → total emissions
  - Affects: Local distribution of emissions & exposure
- NOT HERE (yet): Air quality impacts of *this* project
- Shown here: Global emissions with uncertainty

SPEW-Trend technology fleet model

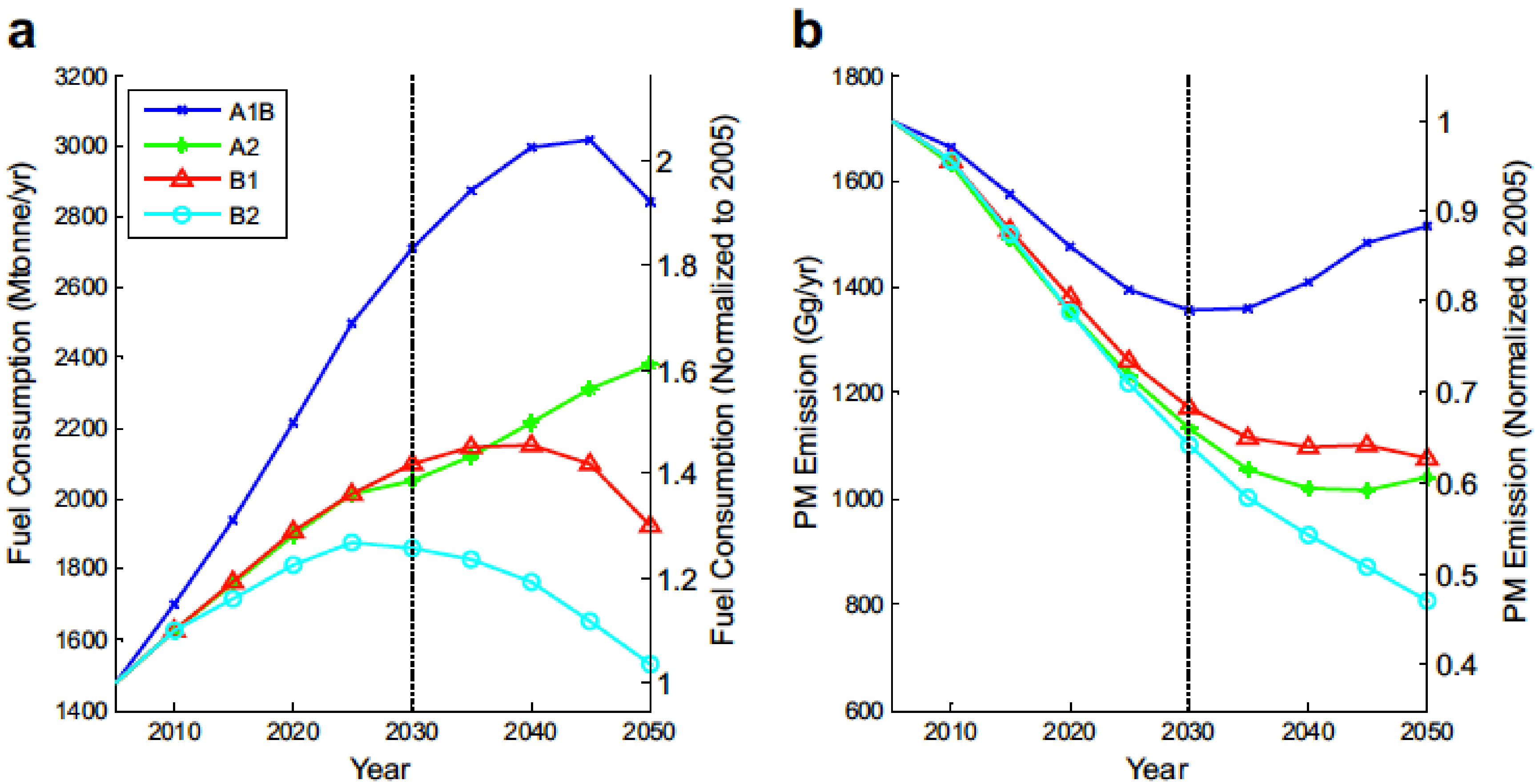
- Developed to examine inertia in the vehicle fleet
- Hybrid model driven by macroeconomic scenario
- Use Monte Carlo simulation for uncertain parameters



Technology and emission modeling approach

- Technology model responds to economic environment (fuel consumption, growth rates, standards)
- Compare emissions under different scenarios
- Estimate uncertainty with Monte Carlo approach

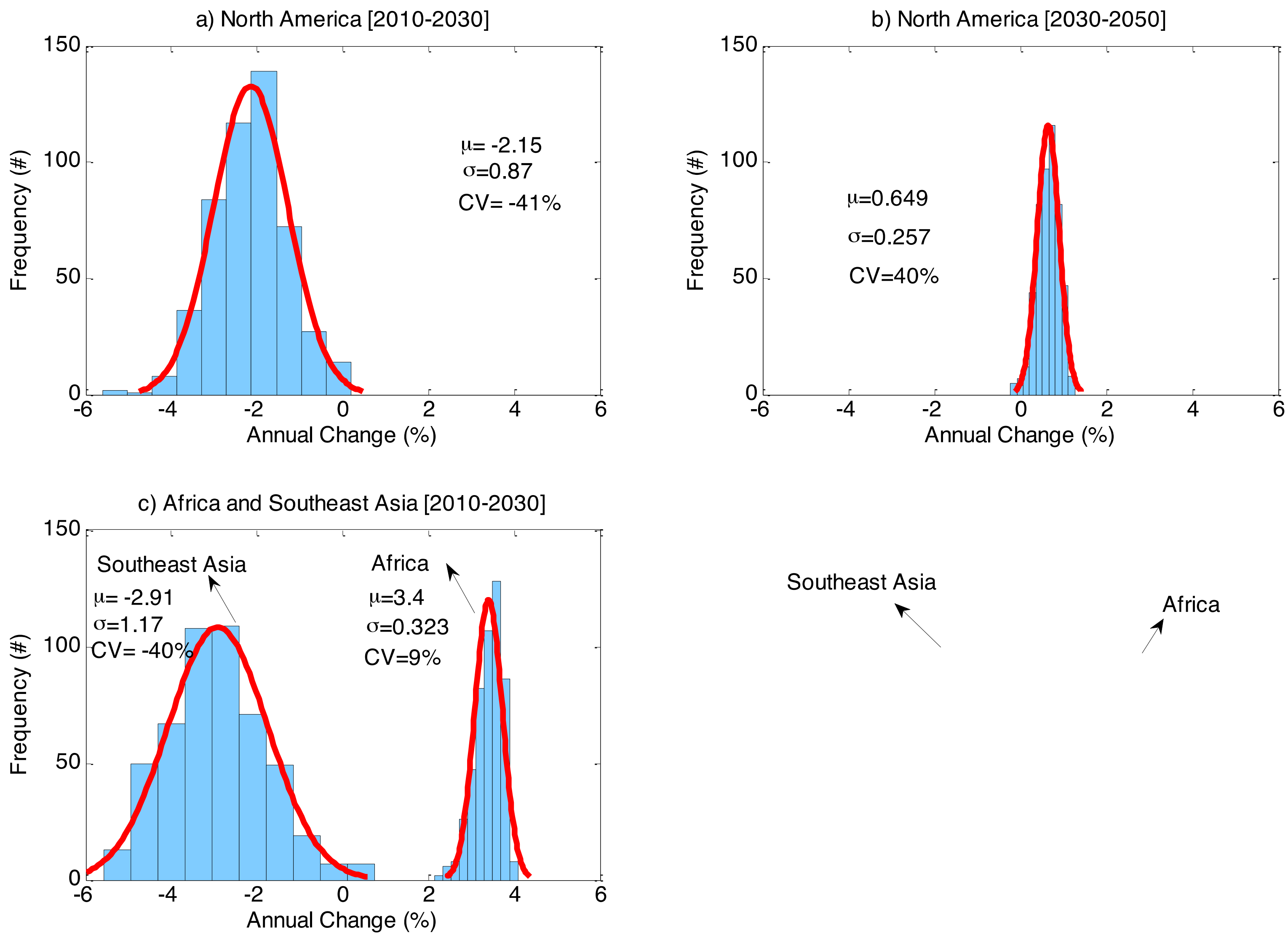
Uncertainty in on-road emissions due to economic scenario



Yan et al., Atmos Env, 2010

Uncertainty in *emission growth* caused by parameters in retirement rates

Monte Carlo simulation



Remaining work (capstone!)

- Freight and urban form scenarios drive technology model
- Predict emissions including uncertainty
- Spatially distribute emissions according to urban form scenarios

This synthesis will produce new distributions of air pollutant concentrations

Ultimate Question

What decisions are robust in the face of uncertainty?

Robust decisions are those which achieve the lowest possible impacts under a range of scenarios.

To be used for evaluation, our models must respond to conditions in each scenario.

Ultimate goal of this project

Evaluate air quality and climate impacts under a range of scenarios

Long-term climate (GHG emissions)

Short-term climate (short-lived climate forcers)

Long-range transport of air pollution

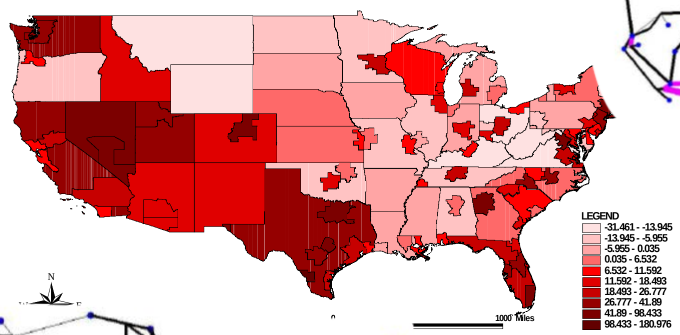
Background air quality

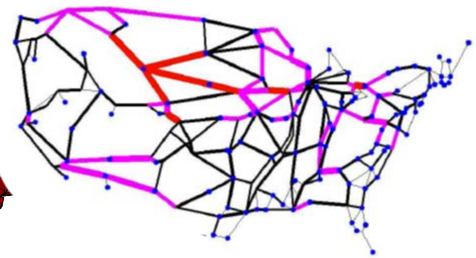
Urban air quality

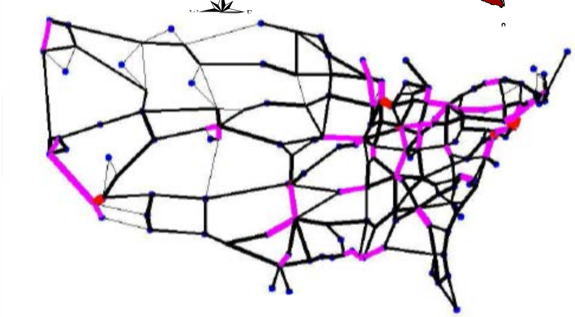
Population exposure

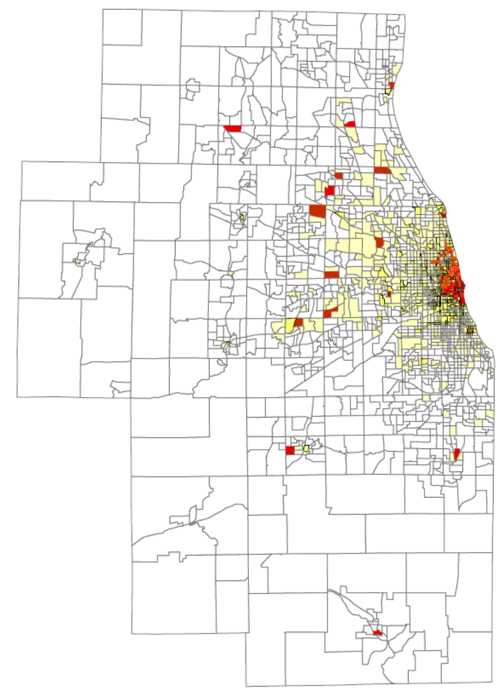
Uncertainty source/ # realizations	**Scenarios**
Technology (4)	BAU, technological slip, electrify railroads, electrify delivery trucks
Capacity (3)	BAU, investment in rail, investment in intermodal terminals
Economic global (4) regional (4)	 Scenario (RCPs) Scenario (homogeneous, MW, SW, SE)
Urban form (3)	BAU, centralization, polycentricity

Questions?


LEGEND
-31.461 - -13.945
-13.945 - -5.955
-5.955 - 0.035
0.035 - 6.532
6.532 - 11.592
11.592 - 18.493
18.493 - 26.777
26.777 - 41.89
41.89 - 98.433
98.433 - 180.976
1000 Miles
N







Supplemental Slides

Supplemental Slides

Future US employment by industry

	2005 Base year	2010	2020	2030	2040	2050
1. Agriculture Products & Fish	98,265	106,969	120,612	137,744	159,335	185,562
2. Grain, Alcohol, & Tobacco Products	1,610,397	1,728,300	1,860,368	1,979,738	2,095,277	2,216,557
3. Stones, Nonmetallic Minerals, & Metallic Ores	589,099	634,334	682,167	718,309	744,451	764,394
4. Coal & Petroleum Products	454,506	461,684	424,811	375,746	349,843	342,454
5. Basic Chemicals, Chemical & Pharmaceutical Products	1,710,694	1,854,024	2,030,507	2,163,695	2,256,235	2,327,122
6. Logs, Wood Products, & Textile & leather	2,388,444	2,570,484	2,757,355	2,909,530	3,034,451	3,144,774
7. Base Metal & Machinery	1,557,817	1,696,552	1,838,224	1,929,572	1,964,238	1,960,169
8. Electronic, Motorized Vehicles, & Precision Instruments	5,144,826	5,632,924	6,128,233	6,538,926	6,890,356	7,200,368
9. Furniture, Mixed Freight & Misc. Manufactures Products	4,237,243	4,592,820	4,901,744	5,042,194	5,012,172	4,869,242
10. Commodity Unknown	5,973,287	6,384,286	6,729,115	6,982,425	7,192,174	7,395,814

	2005	2010	2020	2030	2040	2050
Total Employment	113,568,362	121,975,519	130,283,078	136,671,616	141,779,255	146,240,338
Population	295,580,000	317,641,100	346,153,500	369,981,100	388,907,200	403,931,500
EMP/POP ratio	38.42	38.40	37.64	36.94	36.46	36.20