EEMS027

MULTI-MODAL ENERGY ANALYSIS FOR FREIGHT

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June 4, 2020

OVERVIEW

Timeline

- Project start date: October 1, 2018
- Project end date: June 30, 2020
- Percent complete: 100%

Budget

- Total project funding:
  - DOE share: 100%
  - Contractor share: 0%
- Funding for FY 2019/2020: $509,000

*Funding reflects total for NREL and ANL

Barriers

- Complexity of large-scale, multi-modal, integrated transportation networks
- Rapid evolution of vehicle technologies and services enabled by connectivity and automation
- Determining the value and productivity derived from emerging freight technologies

Partners/Collaboration

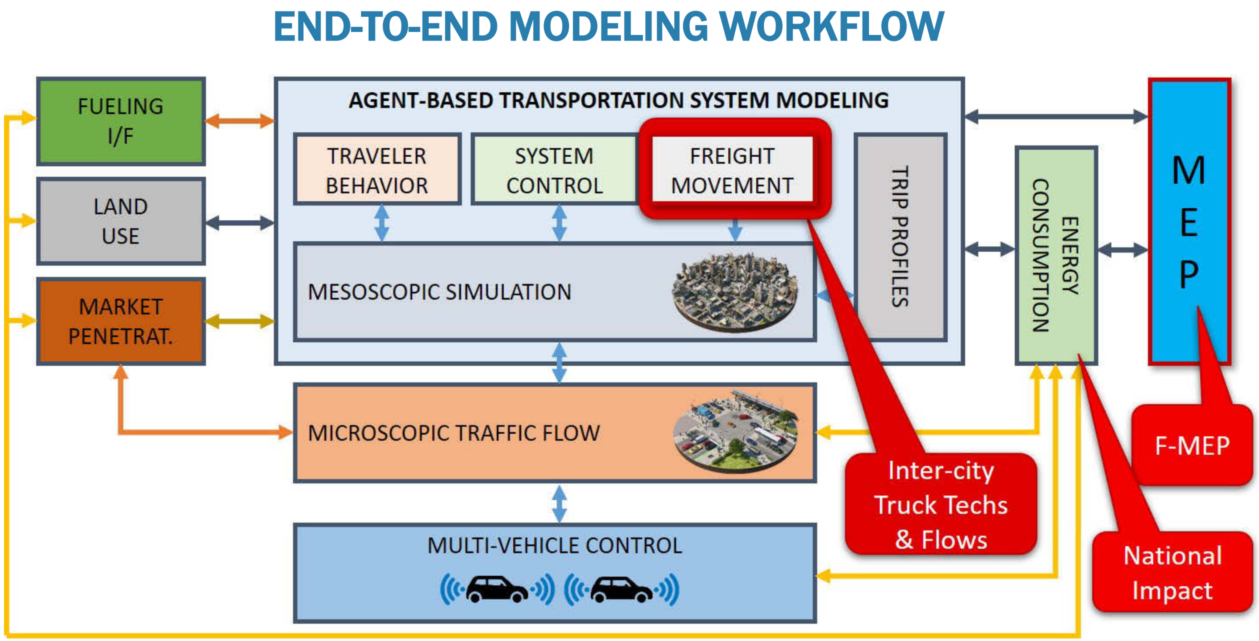
- NREL (lead) – Alicia Birky, Kyungsoo Jeong, Yi Hou, Venu Garikapati, Kevin Walkowicz
- Argonne National Laboratory – Joann Zhou
- University of Illinois at Chicago
- INRIX
- Coordination with SMART Multi-modal (MM) task 3.1 and Advanced Fueling Infrastructure (AFI) task 4.1

RELEVANCE

- **Overall objectives:**
  - Analyze energy reduction opportunities and challenges provided by new technologies and services in intercity freight movement; identify areas for strategic R&D
  - Create tools and methods that can be applied to other research questions and other geographic areas to address national and regional freight energy productivity
  - Establish repeatable methods for quantifying energy impacts of new technologies to enable efficient goods movement for intercity freight
  - Support larger SMART effort through analysis of intercity freight movement regional impacts
- **Specific project goals:**
  - Develop multi-modal energy models and analysis tools of intercity freight movement incorporating national freight demand and regional detail for Chicago
  - Develop metrics for inter- and intracity freight mobility energy productivity (F-MEP)
    - How is mobility energy productivity defined for freight and what is the baseline F-MEP for a region?
  - Assess national and Chicago regional energy savings opportunity space in intercity freight movement for selected “standalone” technology scenarios
    - What effect could connectivity, automation, and electrification technologies have on intercity freight energy, time, and cost for a region or nationally?
  - Address complexity and validation challenges through peer review and analysis of real-world truck movement data.
- **Impact:** Quantification of the intercity freight energy reduction opportunity space to define the regional and national energy impacts of SMART freight transportation technology and inform public and private sector decision makers.

RELEVANCE

Relationship to Workflow



Supports workflow by supplying intercity truck flows by type to mesoscopic simulation and measurement of scenario impacts on freight mobility energy productivity

MILESTONES SINCE 2019 AMR

Date	Type	Milestones Go/No-Go	Status
FY19 Q3	Quarterly Progress	Calibrated truck flow estimates for Chicago	Complete
FY19 Q4	Annual Milestone	Draft paper(s) documenting the multi-modal model and reporting results of stand-alone analyses of selected technology scenarios	Complete
FY19 Q4	Annual Milestone	Final version (2.0) of intracity F-MEP	Complete
FY20 Q2	Quarterly Progress	F-MEP presentation and publication	Complete
FY20 Q3	Quarterly Progress	Documentation of methodology and preliminary results for sampled and estimated sub-Freight Analysis Framework (FAF) level truck origin-destination (O-D) tables from Chicago INRIX data analysis. Draft paper on the multi-modal energy model.	On Track

APPROACH

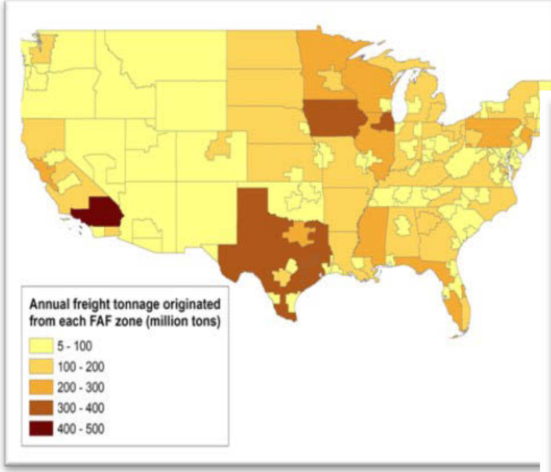
Multi-Modal Modeling and Analysis

- Maintain consistency across other freight modeling and analysis efforts within SMART, including Freight Analysis Framework (FAF) zoning structure and methodologies
- Convert freight demand (tons, ton-miles) to truck flows, translated from FAF
  - Increase geographic and temporal resolution
    - — Assign within-FAF-zone truck movements to the network (local/regional)
    - — Truck proximity (spatial and temporal) for platoon formation potential
  - Enable truck logistical efficiency scenarios
- Apply the national truck flow model to refine estimates of national potential for energy reduction from truck platooning
- Develop multi-modal intercity freight energy model to allow analysis of Chicago regional and national impact of emerging technologies
  - Incorporate time, energy, and cost into mode/route choice objective functions
  - Develop coarse cost models, including elements impacted by scenario technologies
  - Calibrate to FAF tonnage flow by mode
- Analyze INRIX GPS data and estimate truck movement model development/refinement
- Use trip distance and mileage distributions to update truck electrification analysis
- Apply the multi-modal intercity model to evaluate scenarios of intercity freight movement energy consumption
  - Altered truck types (cost and energy), logistical efficiency, freight mode shares.

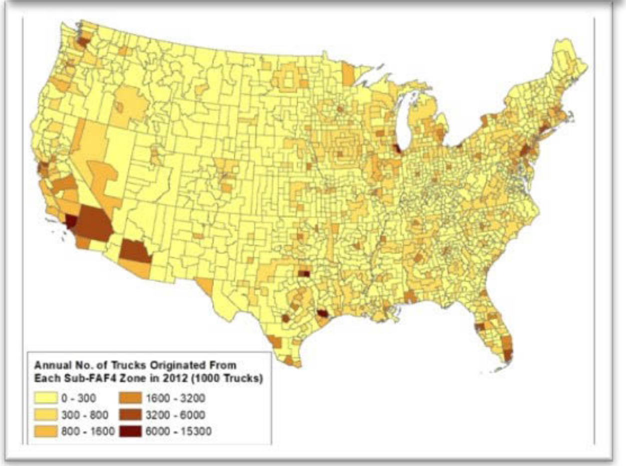
APPROACH: NATIONAL TRUCK FLOW MODEL

Freight Tons to Truck Movements at Finer Geographic Resolution than FAF

Annual freight tonnage originated from each FAF zone in 2012



Annual number of trucks originated from each sub-FAF zone in 2012



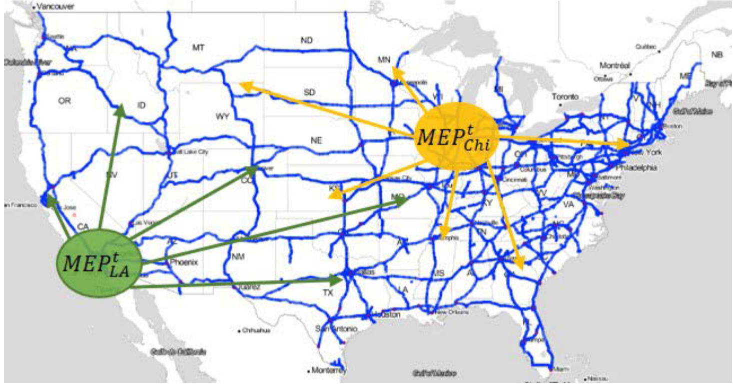
New zone definition efficiently resolves intra-zone freight flows

- **FAF: 129 zones, 67% of freight flow is intra-zone**
- **Counties: 3,100 zones, 15% intra-zone**
- **New 1,603 sub-FAF zones: 16% intra-zone**

APPROACH

Freight Mobility Energy Productivity

- A measure of the quality of freight mobility for a region (e.g., city)
  - Nationally generalizable and useful for interregional comparisons
  - Address freight-specific goals, needs, and costs, which differ from passenger mobility; include energy
  - Specified using available data, for all modes
  - Responsive to model scenarios
- Shipper perspective, consistent with passenger MEP (mobility opportunities for a traveler at a given location)
- Intracity F-MEP follows passenger MEP framework
  - Add measures of circuity by tour type
- Intercity F-MEP
  - New conceptualization based on gravity model
  - Mobility (accessibility) to other cities from originating city
- Feedback: presentation and publication

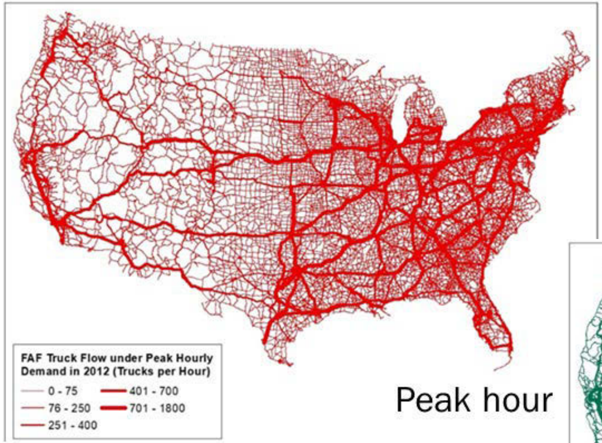


TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Assignment of Trucks to Road Network with Temporal Distribution

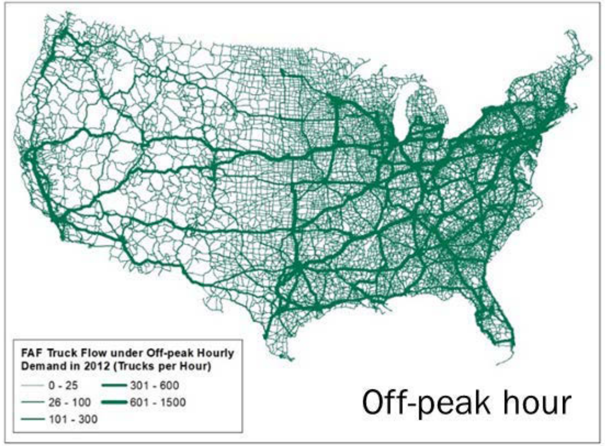
National truck flow model: assignment to local and highway links supports workflow modeling and informs platooning analysis

- **Truck proximity for platoon formation**
- **Link speed**
- **Capacity impacts**



Network assignment enabled by sub-FAF zone definition

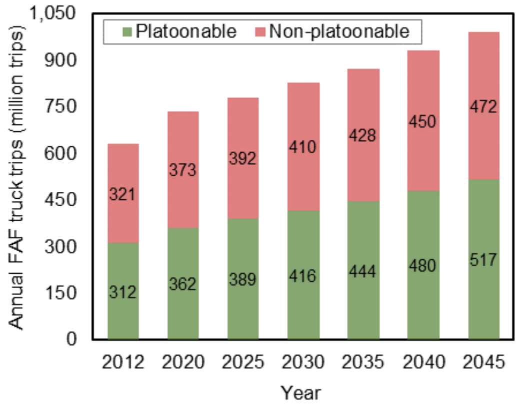
Flows calibrated with Federal Highway Administration data

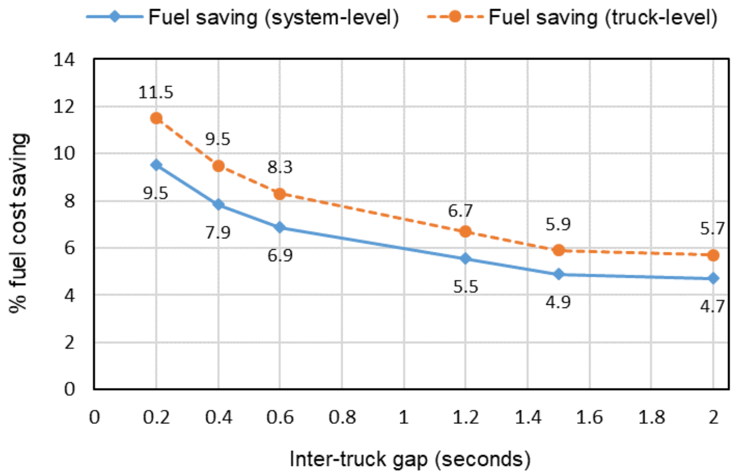


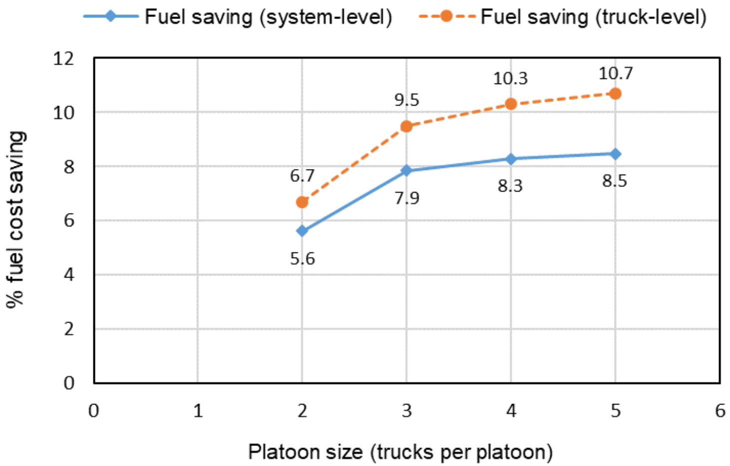
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

National Platooning Analysis

- Savings are 9.5% across the platoonable highway segments
- Savings depend on vehicle type, platoon size, inter-truck gap, and road type where platooning is allowed

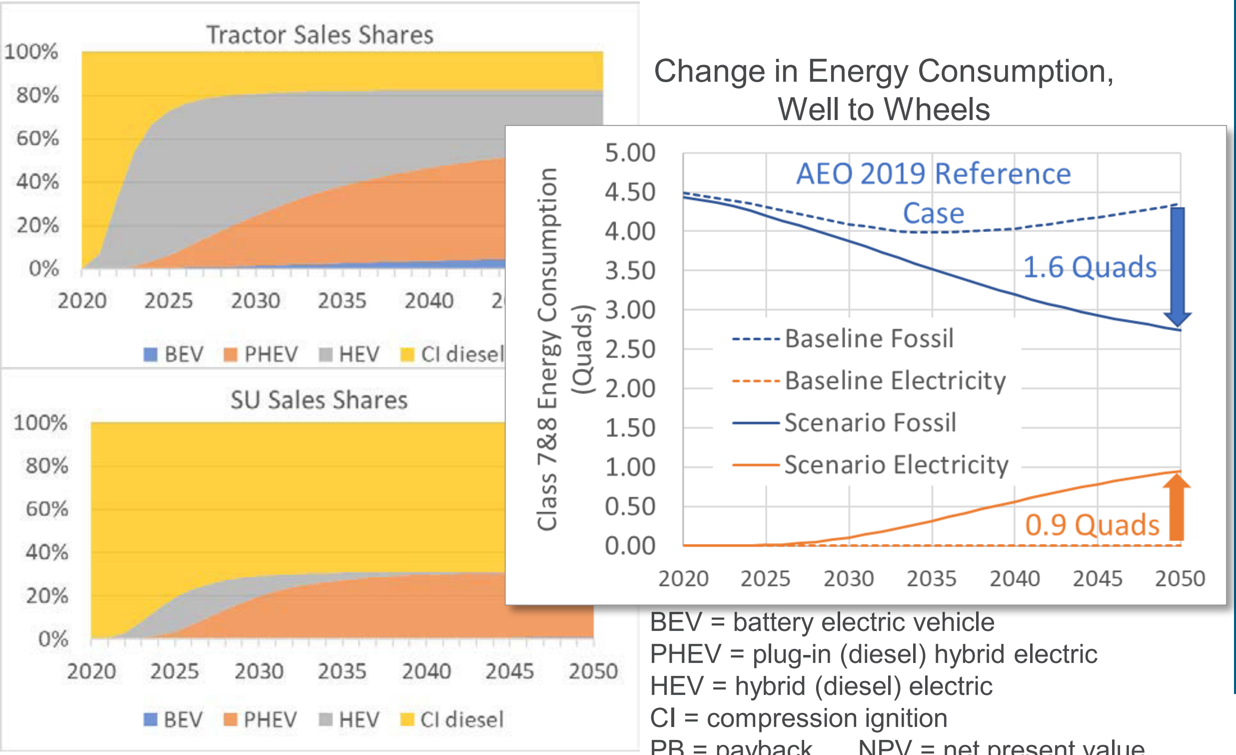






TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Freight Electrification Scenario



BEV = battery electric vehicle
PHEV = plug-in (diesel) hybrid electric
HEV = hybrid (diesel) electric
CI = compression ignition
PB = payback NPV = net present value

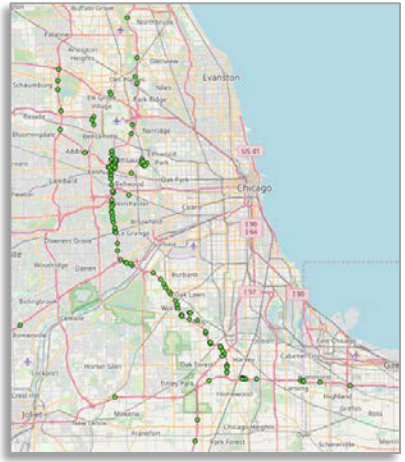
- **Market adoption based on payback and lifetime NPV**
  - **Electrification portfolio**
  - **Performance, range, cost from last completed VTO benefits analysis**
  - **Sleepers, day cabs, single-unit (SU) trucks**
  - **Consider trip distance and daily miles**
- **Optimistic assumptions (bounding analysis)**
  - **100% adoption if PB ≤ 4 yr**
  - **Maximize e-range**
  - **No charging infrastructure limitations**

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

INRIX Data Analysis for Truck Trip Calibration

Truck GPS Data Processing

Example of Trip Endpoints



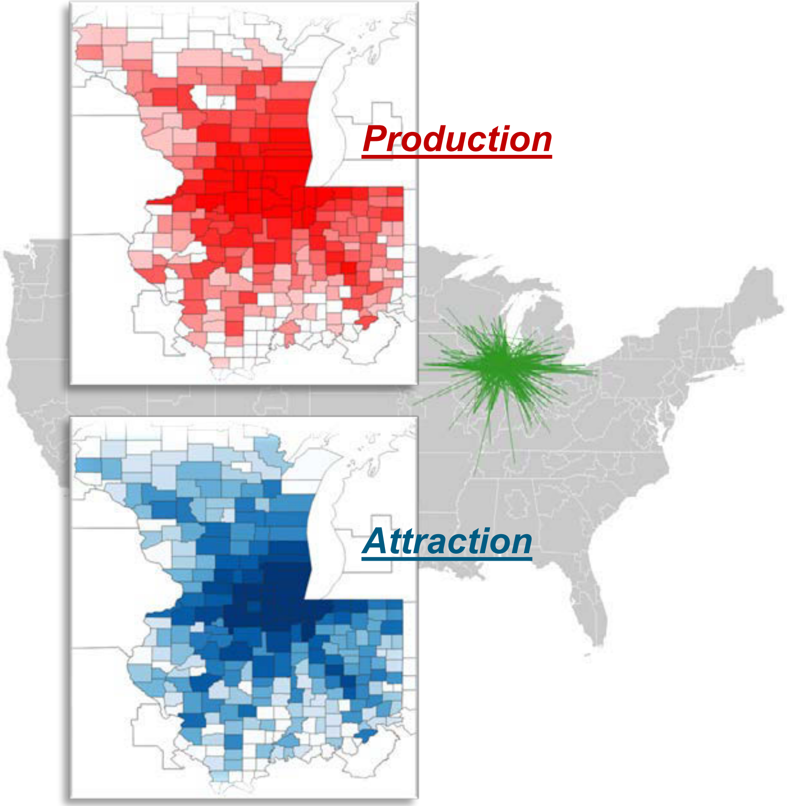
Identified issues in raw INRIX trip records

- Short travel distance (less than 2 km)
- Short stop duration (less than 5 minutes)
- Trip endpoints on highways or at fueling stops

Developed a rule-based algorithm to clean and combine anomalous trip segments using:

- Travel distance
- Stop duration/distance
- Fueling/stop location
- Land-use type

Estimation of County-Level P-A Matrix

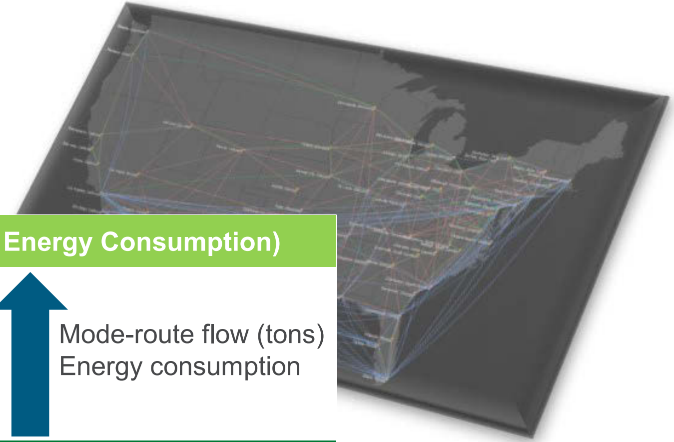


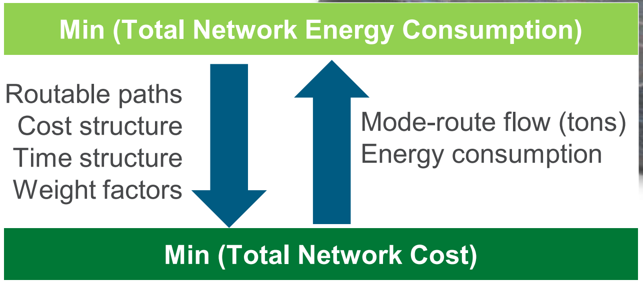
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

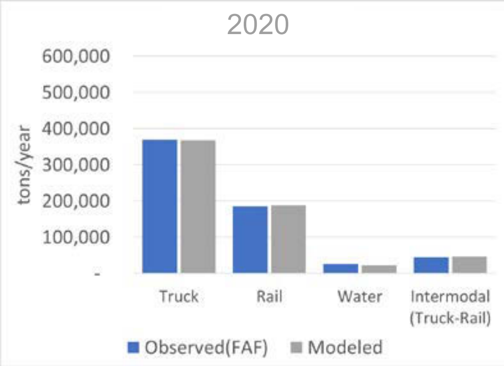
Multi-Modal Intercity Freight Energy Model

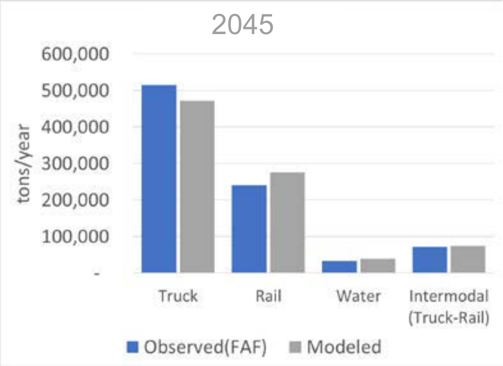
Model development complete

- Multi-modal network
  - Highway, rail, inland waterway links
  - Nodes: zone centroids, ports, and transfer facilities
- Model specification: bi-level optimization problem
  - Upper: minimize total energy consumption
  - Lower: minimize total cost
- Mode- and commodity-specific parameterization
- Parameters inferred via inverse modeling
  - Implemented for Chicago O-Ds
  - Calibrated with FAF 2020 modal shares
  - Confirmed FAF consistency using 2045 projection





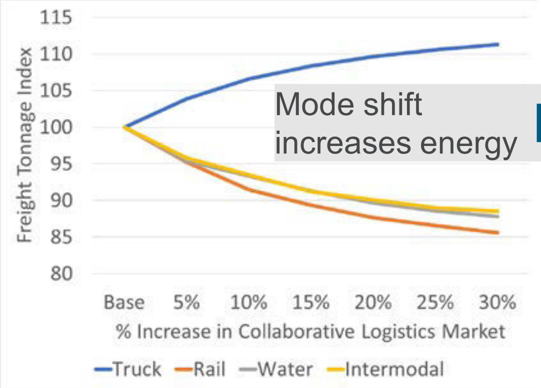




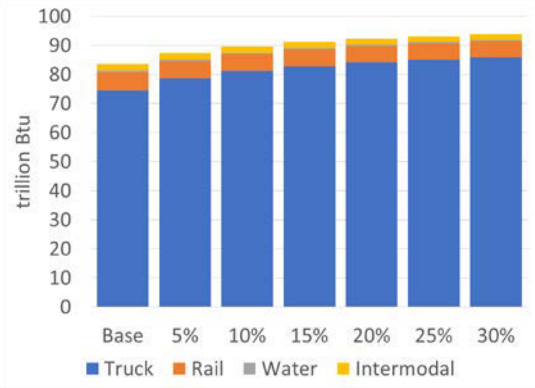
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Multi-Modal Intercity Freight Energy Model

What if collaborative logistics reduce trucking costs 5%?

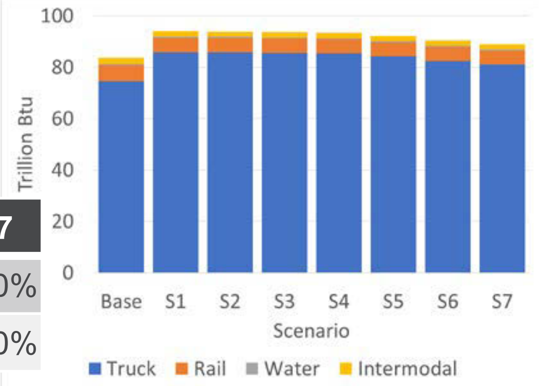


Mode shift increases energy



Large efficiency improvements don't offset the increase

	S1	S2	S3	S4	S5	S6	S7
Payload	10%	10%	10%	10%	20%	30%	40%
Empty	−10%	−20%	−30%	−40%	−10%	−10%	−10%



Exploratory scenarios demonstrate need for multi-modal analysis

- **Decrease in trucking costs leads to net increase in energy consumption**
- **High improvements in logistical or vehicle efficiency might be required to offset mode-shift impacts**
- **Mobility energy productivity gain / loss could be evaluated through F-MEP lens**

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

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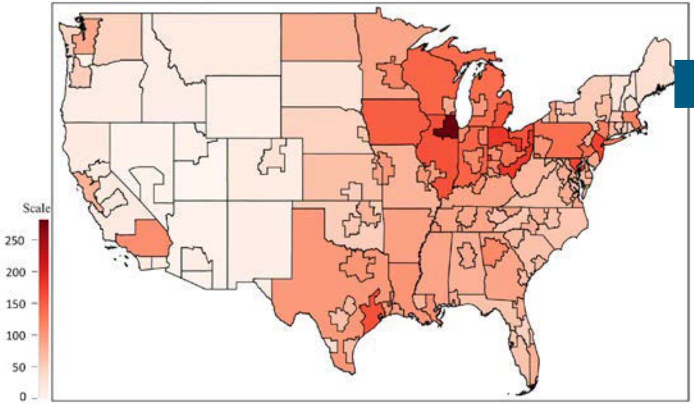
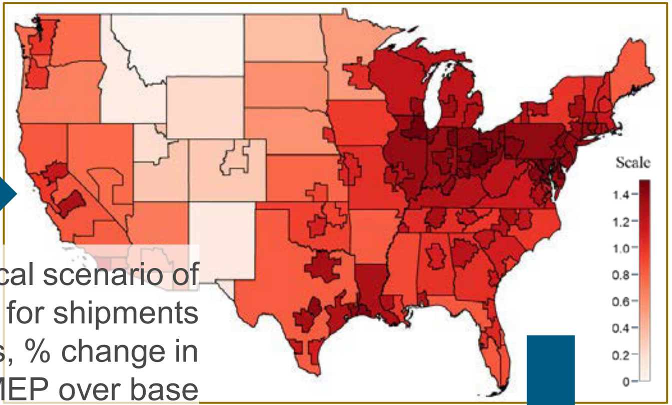
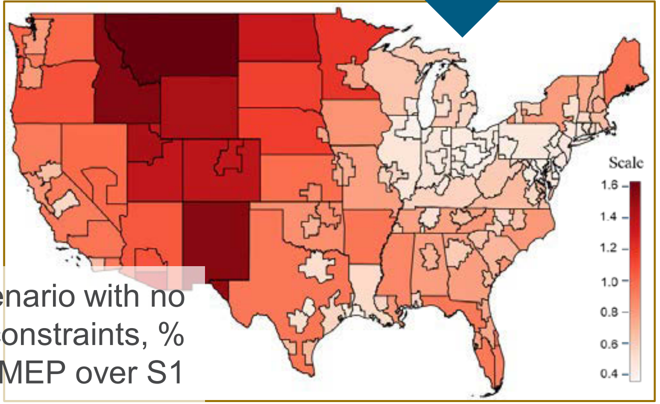
Intercity Freight MEP Demonstration





S1: Hypothetical scenario of electric truck use for shipments ≤500 miles, % change in F-MEP over base

Maps display national F-MEP score by originating FAF shipment zone



S2: Hypothetical scenario with no electric truck range constraints, % change in F-MEP over S1

- Flexible framework can be applied at various geographic scales and decomposed by commodity or mode
- Input easily obtained from existing data or freight models to compare scenario outcomes

RESPONSES TO PREVIOUS YEARS REVIEWERS' COMMENTS

- Multi-modal focus
  - Much of the focus is on trucks; nothing presented on rail freight.
  - Does not ensure a full modal picture; no information supplied about the multi-modal network

At the time of the 2019 AMR, the team had made progress on the truck trip analysis, but the multi-modal intercity freight energy (MMIFE) model was not as far along (consistent with schedule). The model is now complete and capable of analyzing multi-modal scenarios. The model includes a conceptual representation of the physical highway and rail infrastructure, port and airport locations, and transloading facility locations and capacity at the O-D level. We did focus on truck technologies and analysis within a multi-modal framework.

- Does not appear to incorporate emerging technologies, including freight-company logistics

Following the FY 2019 AMR, the MMIFE was used to explore scenarios of collaborative logistics. If funded, we would like to link this model to the national truck flow model to incorporate multi-modal feedbacks into the platooning analysis and evaluate additional connectivity and automation technologies.

- Intracity analysis within an intercity freight task
  - The project design seems to be weighed down by the use of POLARIS, with its focus on intracity movements, and without an apparent contribution of how intracity movements impact intracity modal choices by private firms
  - Technical accomplishments are focused on intracity freight movement

Our focus was on intercity freight movement. F-MEP development was added to the multi-modal intercity freight energy analysis task in FY 2019. While we did report on intracity F-MEP last year, we also developed an intercity F-MEP metric and F-MEP was only a portion of the team's efforts. All modeling and analysis focused on intercity freight.

Any proposed future work is subject to change based on funding levels

RESPONSES TO PREVIOUS YEARS REVIEWERS' COMMENTS

- We should be conscious of how valid the modeling will be

Model validation is a challenge with complex systems and the relative lack of freight data. We did use available freight flow data to calibrate/validate MMIFE, as reported today. We are pursuing the use of GPS data to validate truck flow estimates. If funded to continue development, we will pursue additional sources of freight data for calibration/validation.

- Results
  - The project does not appear to be on track to finish with a validated model
  - Difficult for the reviewer to assess if the accomplishments are on track to fulfill model obligations; would like to see some initial representative results
  - Hard to understand how this project will be wrapped up in FY 2019 (or even in FY 2020 with carry expenses)

We were able to complete model development, initial calibration/validation, and exploratory scenarios, as reported today.

- Future work
  - It may be challenging to get sufficient and timely input from 21st Century Truck Partnership (21CTP) during the project
  - Encouraged work on supply chain understanding for e-commerce, as this is important to understand
  - The project should differentiate between the net energy savings of profit-maximizing firms utilizing new technologies, and how R&D and/or infrastructure investments might affect future freight patterns and energy needs.

In the end of FY 2019 and early FY 2020, we began outreach to the 21CTP through their regular team meetings. If funded, future work will seek to engage logistics professionals and academics and pursue data collection to increase understanding of supply chain agent behavior and the impact of e-commerce on freight patterns.

Any proposed future work is subject to change based on funding levels

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- NREL (lead)
  - Collaborate on scenario definition
  - Multi-modal intercity freight model
    - —Development and calibration
    - —Application to analysis of standalone technologies and regional impacts (bounding)
  - Freight MEP
- Argonne National Laboratory
  - Collaborate on scenario definition
  - FAF freight analysis methodology
    - —Tons to trucks
    - —Geographic disaggregation, FAF sub-zone definition
    - —Temporal disaggregation
  - National scenario analysis
- University of Illinois at Chicago
  - Geographic disaggregation
  - Develop results in TransCAD software
- INRIX
  - Truck movement data: into, out of, around Chicago
- Coordination with SMART MM 3.1, AFI 4.1
- Indirect data providers:
  - U.S. Department of Transportation, U.S. Census Bureau, Bureau of Labor Statistics
  - IHS
  - American Trucking Associations, American Transportation Research Institute
  - Surface Transportation Board
  - Others

REMAINING CHALLENGES AND BARRIERS

- Data availability
  - Complexity of freight industry structure, decisions, and operations
  - Poor visibility into truck (and other mode) load factors and empty movements
  - Impact of emerging connectivity and automation technologies on freight costs and logistical efficiency
- Translation of GPS vehicle movement data to trip origins/destinations, inference of package origins/destinations, and acquisition of full segments of long-haul movement
- Multi-modal feedback/interactions induced by emerging technologies
- Impact of various combinations of technologies on freight movement.

PROPOSED FUTURE RESEARCH

- Expand and refine truck movement/platooning model to analyze energy impact of other connectivity and automation technologies
  - Validate network assignment and improve temporal distribution using INRIX data analysis
  - Integrate with multi-modal intercity freight energy (MMIFE) model to evaluate feedbacks
- With academic and industry partners, develop plausible inputs for MMIFE scenarios; refine parameterization
  - Trucking collaborative logistics: impact on costs, load factors, empty movements
  - Multi-modal collaboration
  - Transloading capacity expansion
- Refine intercity F-MEP
  - Engage academic, industry, and planners for stakeholder feedback
  - Integrate with multi-modal energy model to refine F-MEP as a tool for scenario evaluation
- With industry and university partners, improve freight data and methodologies to reduce uncertainty
  - Freight commodity, tonnage relationship to truck trips (e.g., load factors, empty back haul)
  - Consumer travel behavior and e-commerce
  - Shipper and carrier decision behavior.

Any proposed future work is subject to change based on funding levels

SUMMARY

- Intercity freight movement is a critical component of the economy and takes place within a complex, multi-modal transportation network
- Emerging technologies and services are transforming this landscape, presenting opportunities, challenges, and risks with respect to energy consumption and meeting demand for freight movement
- This task developed methodologies, models, analysis tools, and metrics to assess the quality of intercity freight mobility and the potential impact of emerging technologies on energy demand both regionally and nationally
- These methods and tools are applicable across regions, technologies, and research questions
- The team successfully developed national truck flow and multi-modal energy models capable of analyzing the emerging technology impacts. These models were applied to:
    - National energy reduction potential from platooning
    - Exploring energy implications of collaborative logistics (connectivity) scenarios.

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

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 NREL/PR-5400-76727

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TECHNICAL BACK-UP SLIDES

INTERCITY F-MEP FORMULATION

$$FMEP_i = \sum_k \sum_c \sum_{j \neq i} B_{cj}(X)\, f_{c,ij}^{k}(Y)$$

i = originating city

k = mode (truck, rail, air, water)

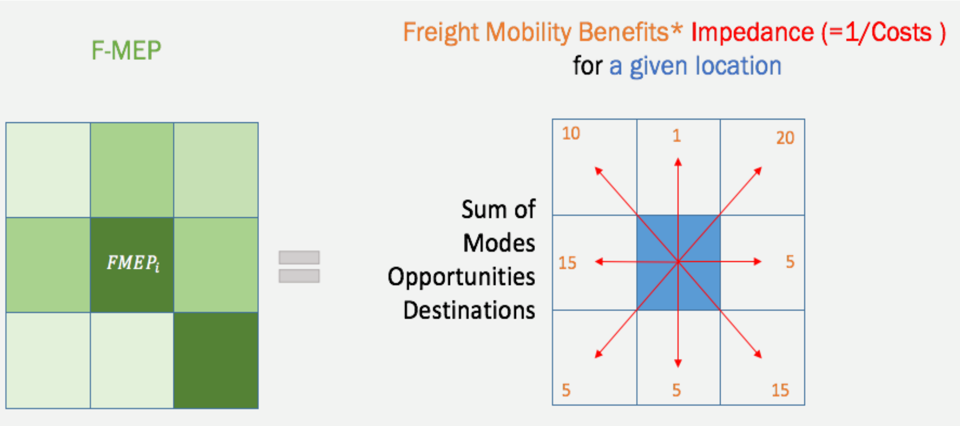
c = commodity

j = destination region/zone

l = distance range

B = mobility benefit (e.g., demand for commodity c)

f = impedance



$$f_{c,ij}^{k} = e^{(\alpha E_k + \beta p_k)} \cdot r_{ck}^{l_{ij}} \cdot s_{ik}$$

E = unit energy intensity (kWh/ton-mile)

r = weigh fractions related to travel time

p = unit logistics costs ($/ton-mile)

s = ease of shipping goods

l = distance range

α, β = weighting parameters

ESTIMATE REDISTRIBUTED TRUCK FLOWS WITH PLATOONING

U.S. DEPARTMENT OF ENERGY SMARTMOBILITY Systems and Modeling for Accelerated Research in Transportation

National Platooning Analysis

A fundamental tradeoff between the platooning pros (i.e., energy savings and efficient usage of road capacity) and cons (i.e., the time-related cost such as formation),

$$C_l^v = \omega^v d_l + c_l^v + \mu^v(t_l + \tau_l^v) \qquad \forall l \in L; v = \{\text{platoonable FAF trucks}\}$$

ω^v: unit price of platooning technology (in dollars per mile);
c_l^v: fuel cost incurred on the link considering the reduced fuel consumption of platooning trucks
t_l is the travel time on the link considering the improved link capacity
τ_l^v represents the platoon formation time incurred on the link.

- Step A: Obtain the platoonable truck flow on each highway link (assumption listed on slide 30)
- Step B: Calculate the average truck headway on the link, and estimate the platoon formation time, road capacity, and travel cost on the link.
- Step C: Perform traffic assignment using the updated generalized travel costs from Step B.

Other Assumptions:

- *Travel cost depends on fuel cost (EIA, SMART results) and value of time (DOT)*
- *Whether or not to form a platoon depends on truck operators' perception of the generalized travel cost*

MULTI-MODAL INTERCITY FREIGHT ENERGY MODEL

Network Model Specification

Upper level: Minimize Total Network Energy Consumption

$$\min f(\mathrm{A}, \mathrm{X}^*, E)$$

Subject to:

$$\alpha_{p,s} = \begin{cases} 1 \\ 0 \end{cases}, \qquad \forall\, p \in P \;\; \forall\, s \in S$$

$$TC_s^* \le TC_s, \qquad \forall\, s \in S$$

Lower level: Minimize Total Network Cost

$$\min f(W, \mathrm{X}, C_p^k, T_p^k)$$

Subject to:

$$C_p^k = f(p, k)$$

$$T_p^k = f(p, k, x_p^k)$$

$$\left(1 - \delta_p^k\right) x_p^k \le 0, \qquad \forall\, p \in P \;\; \forall\, k \in K$$

$$x_{o,d}^k = \sum_{p \in (o,d)} x_p^k, \qquad \forall (o, d), \qquad \forall\, k \in K$$

$$x_p^k \ge 0, \qquad \forall\, p \in P \;\; \forall\, k \in K$$

Notation

A: Binary array representing the availability of alternative paths
$\alpha_{p,s}$: *1* if path *p* is routable in the multi-modal network scenario *s; 0* otherwise
TC_s^*: Total cost of the optimal solution at the lower level problem for a given scenario *s*
TC_s: Total cost for a given scenario *s*
X^*: A set of the optimal path flow at the lower level problem
E: A set of parameters for the calculation of energy consumption
S: A set of multi-modal network scenarios
P: A set of alternative paths
W: Weight factors for cost and time
C_p^k: Total cost function of path *p* when moving one unit of commodity *k*
T_p^k: Total time function of path *p* when moving x_p^k
δ_p^k: *1* if path *p* is routable for commodity *k; 0* otherwise
x_p^k: flow of commodity *k* over path *p*
$x_{o,d}^k$: Total flow of commodity *k* for a pair of *o-d*
X: A set of the path flow