# Multimodal Freight Energy Model for Emerging Freight Technology Analysis

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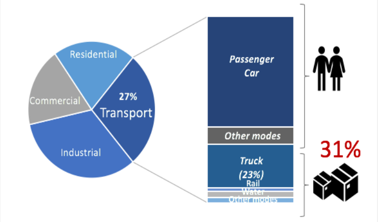
## MOTIVATION

### ❑ Current Freight Trend

- 4% of gross domestic production supported by domestic freight movement
- 31% of the energy consumption in the transportation sector
- Emerging freight technologies: levers to provide opportunities for greater efficiencies in freight movement and energy use
- Challenges for designing an efficient freight network and evaluating the impacts of these trends and technologies




Source: Transportation Energy Data Book: Edition 37.1 (Davis and Boundy, 2019)

### ❑ Emerging Technologies in Inter-city Truck

- Alternative fuel and powertrain: shift from conventional diesel trucks to electric or fuel cell fuel trucks
- Vehicle connectivity: speed harmonization among vehicles and truck platooning
- Collaborative logistics: shipment consolidation across firms within a geographical region into a common logistics service line

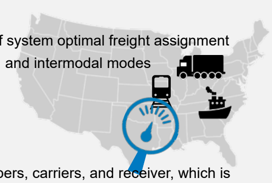
### ❑ Research Objectives

- Address the potential for and limitations to overall freight energy reductions from the application of emerging technologies and modal optimization that has not been answered well
- Develop a modeling framework that considers emerging freight technology in the multimodal transportation network
- Evaluate various scenarios systematically

## METHODOLOGY

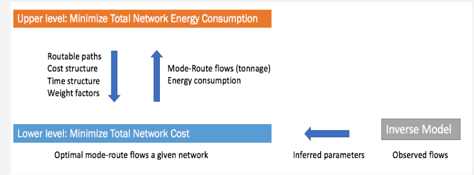
### ❑ Requirements

- Optimize inter-city freight movements in the context of system optimal freight assignment on the multimodal network, including truck, rail, water, and intermodal modes
- Search for an optimal emerging technology scenario



### ❑ Approach

- Bi-level optimization
- Lower-level: minimizing freight network costs for shippers, carriers, and receiver, which is designed to find optimal mode-path flows simultaneously, where parameters are inferred using an inverse modeling
- Upper-level: minimizing energy consumption from the perspective of government, which evaluate energy consumption for selected scenarios with corresponding optimized inter-city freight movement




***Upper-level: Minimize Total Network Energy Consumption***

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

*Subject to:*

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

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

| | |
|---|---|
| $A$ | *: Binary array representing the availability of alternative paths* |
| $\alpha_{p,s}$ | *: 1 if path p is routable in the multimodal network scenario s; 0 otherwise* |
| $TC_s^*$ | *: Total cost of the optimal solution at the lower-level problem for a give scenario s* |
| $TC_s$ | *: Total cost for a give 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* |

***Lower-level: Minimize Total Network Cost***

$$\min f(w, X, C_p^k, T_p^k)$$

*Subject to:*

$$(1 - \delta_p^k) x_p^k \le 0, \quad \forall p \in P \ \forall k \in K$$

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

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

| | |
|---|---|
| $W$ | *: Weight factors for cost and time* |
| $C_p^k$ | *: Total cost function of mode-path p when moving one unit of commodity k* |
| $T_p^k$ | *: Total time function of mode-path p when moving $x_p^k$* |
| $\delta_p^k$ | *: 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 mode-path flow* |

## MODEL DEVELOPMENT

### ❑ Case Study

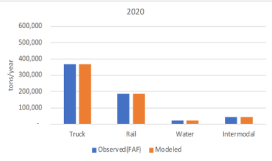
- Originated from or destined to the Chicago region in the United State
- Four modes for inter-city freight: truck, rail, water, intermodal modes
- Network
  - 3 zones in Chicago and 126 zones in the remaining mainland United States
  - A total of 1,557 links for four modes,, including 45 virtual commodity- and mode-specific transfer links
- 15 mutually exclusive commodity groups

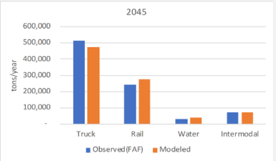
### ❑ Model Estimation

- Solve an inverse optimization problem that finds the optimal values for the parameters for the lower-level problem using the gradient projection algorithm and quasi-Newton algorithm
- After running the algorithm with ten different *a prior* values of the parameters, commodity- and mode-specific parameters on average are estimated

### ❑ Model Performance Results

- The flow estimated by the model for the 2020 OD flow well represents the flow by mode observed in the FAF with 5.7 % of the coefficient of variation of the RMSE
- The model runs for 2045 results in 16.3 % of the coefficient of variation of the RMSE



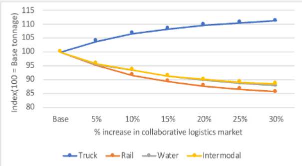




## IMPLEMENTATION

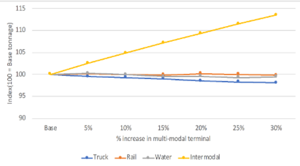
### ❑ Scenario Analysis with Stand-alone Technology

- Truck load-pooling assumptions
  - Collaborative logistics for truck load-pooling reduces truck operation costs to 95% of conventional operations
  - The market of truck load-pooling grows from 5% to 30% of an analysis year truck volume in increments of 5%
  - The increase in load efficiency is captured by an increase in the payload (truckload factors) and a reduction in the empty truck factor: payload increases by 10% to 40% while the empty truck factor decreases by 10 to 40%
- Multimodal load-pooling assumptions
  - The inter-city freight system at the strategic level will achieve a system optimal.
  - Increase in load-pooling is captured by increasing the capacity at intermodal terminals: capacity is increased by 5% to 30% of the observed baseline in increments of 5%
- Change in freight flows against scenarios in 2045

Truck load-pooling




Multimodal load-pooling



### ❑ Scenario Analysis with Mixed Technology

- Search for the best scenario with the most energy-saving under the scenarios that consider truck and multimodal load-pooling together
- Apply a genetic algorithm (GA) with ten scenarios (i.e., population size =10) and corresponding factors
- Assumption: the collaborative logistics market and the capacity of multimodal facilities increase from 1% to 30%, with an increment of 1%, respectively ( a total of 900 scenarios)
- Comparison of most energy consumption scenarios in 2045

| Mode | Base | Most energy-saving scenarios | | |
|---|---|---|---|---|
| | | Stan-alone applications | | Mixed applications |
| | | 0% increase in collaborative logistics market | 30% increase in multimodal capacity | 6% increase in collaborative logistics market and 22% increase in multimodal capacity |
| Truck | 74,428 | 74,428 | 72,239 | 72,321 |
| Rail | 6,352 | 6,352 | 6,340 | 6,234 |
| Water | 475 | 475 | 470 | 452 |
| Intermodal | 2,336 | 2,336 | 2,576 | 2,535 |
| Total | 83,591 | 83,591 | 81,625 | 81,542 |

## CONCLUSION

- Develop the framework for multimodal freight energy modeling to evaluate the impact of emerging freight technologies on multimodal inter-city freight movement and energy consumption based on a bi-level optimization approach
- Empirically test to analyze truck load-pooling and multimodal load-pooling scenarios separately and simultaneously with freight shipments originating from or destined to the Chicago region
- Limitations: coarse cost structure, assumptions on costs and capacities on transfer links, and conceptual physical logistics networks

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