A Comprehensive Approach to Measure the Mobility Energy Productivity of Freight Transport

Preprint

Kyungsoo Jeong, Venu Garikapati, Yi Hou, Alicia Birky, and Kevin Walkowicz

National Renewable Energy Laboratory

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ABSTRACT
Freight travel accounts for a major share of the energy consumed in the transportation sector in any country, and the United States is no exception. Understanding and modeling freight movement are critical, particularly in the context of capturing the impact of emerging technologies on freight travel and its externalities. The domain of freight modeling and forecasting is gaining pace in the recent years, but advancement in comprehensive freight performance metrics is still lagging. Conventional freight performance metrics such as truck-miles, ton-miles, or value-miles are unidimensional and aggregate in nature, making them unsuitable to accurately capture the impact of emerging transportation trends on the performance or productivity of freight systems. Addressing the research need, this paper presents the "Freight Mobility Energy Productivity" metric to quantify freight productivity of current as well as future freight systems, accounting for various costs associated with freight transport. The proposed metric was implemented using data from the Freight Analysis Framework along with other published sources, which shows intuitive results in quantifying freight productivity. Further, a scenario analysis exercise was conducted to test the capability of the metric in tracking improvements in system-level freight productivity as a result of vehicle electrification. The relative differences in Freight Mobility Energy Productivity scores help identify which zones benefit from the vehicle powertrain technology improvement. The results of the scenario analysis reinforce confidence that the proposed metric can be used as a decision support tool in assessing the productivity of existing as well as future freight trends and technologies.

Keywords: freight transportation, freight productivity, freight mobility, freight energy, performance metrics

INTRODUCTION

Vehicle miles travelled (VMT) on a nation's road network can be classified into two primary categories, namely passenger travel and freight travel. Currently, about two-thirds of freight movement (by weight) in the United States takes place via truck, with the remaining one-third distributed among several modes such as rail, water, air, etc. (*1*). Although commercial trucks represent only 9% of VMT in the United States (*2*), they account for 23% of all transportation energy demand, while all other freight modes (combined) account for about 5% of the transportation energy demand (*3*). This proportionally large share of energy consumption of commercial trucks can be attributed to their higher fuel consumption per mile compared to passenger (light-duty) vehicles. As the energy demand of the nation is increasing by the decade, it is of critical importance to understand the levers that will reduce energy consumption and increase mobility as well as energy efficiency of passenger and freight travel.

To do so, on the passenger movement front, significant advancements have been made in the past two decades in understanding the travel behavior of individuals (*4*). Passenger travel models are used to forecast travel patterns under a wide variety of socio-economic and technological scenarios (*5*). Freight travel modeling on the other hand has not advanced at a similar pace (*6*) owing to a number of factors such as data availability, complexity, and the interjurisdictional nature of freight movement. Traditionally, freight transport has been modeled as the aggregate flow of goods between geographic locations specified as origin and destination pairs. The need for sophisticated freight models has been recognized recently, with various regional and state planning agencies investing in advanced behavior-based freight models (*7*, *8*).

The transportation field is witnessing a profound transformation, and existing passenger and freight travel models are challenged with capturing these exciting new trends. For example, trends such as rise in e-commerce, increased vehicle electrification, connected mobility, automation, and new forms of delivery (e.g., crowdsourced delivery) are poised to bring a paradigm shift in people and freight movement. While enhancing models to understand and forecast these trends is critical, it is also important to have appropriate metrics to quantify the changes in system efficiency and productivity with the introduction of these technologies.

Conventional metrics such as VMT, volume-to-capacity ratio, vehicle-hours of delay, ton-miles, dollar-miles, and ton-miles per gallon have all been used to provide a high level picture of transportation system performance. Relative differences in such metrics can be used to gauge outcomes of various scenarios in passenger or freight travel models. However, such metrics also have the drawback of being too aggregated, or unidimensional, and are not capable of reflecting the combined effectiveness of the network. An effective transportation system performance metric should reflect the overall productivity (e.g., mobility + energy) of the transportation system in connecting demand with supply. As an example, a measure such as vehicle-hours of delay alone would not be able to capture an increase in system productivity due to vehicle powertrain enhancements. Similarly, a metric such as ton-miles (or passenger-miles) per gallon will not reflect system improvements (or the lack thereof) due to new delivery methods or modes (e.g., drones, autonomous ground vehicles).

Recognizing the lack of comprehensive metrics to quantify the effectiveness of connecting people to goods, services, and employment, researchers at the National Renewable Energy Laboratory (through the support of the U.S. Department of Energy) have developed a novel metric, labeled the Mobility Energy Productivity (MEP) metric. The MEP metric is a comprehensive measure that calculates the accessibility benefits offered by different modes in a given location while accounting for the costs (time, energy, and money) associated with each of the modes that provide accessibility (*9*). While the MEP metric was initially developed for quantifying passenger travel, this research effort extends the MEP concept to freight and proposes a metric that can effectively quantify the productivity of moving freight while taking multidimensional costs of goods movement into account.

From the freight perspective, mobility is defined as the ability of a system to transport goods to their destination (i.e., business establishments or private consumers). Productivity measures output for a unit of input, which reflects the efficiency of the freight network. The Freight Mobility Energy Productivity (F-MEP) metric can be viewed as an indicator that quantifies the productivity of the freight transportation system—its ability to transport the maximum amount of goods from a location to any other location that have freight attractions with a minimum expenditure of time, money, and energy. The F-MEP metric proposed in this research effort can be used as a planning or a scenario analysis tool for quantifying impacts of emerging technologies on freight mobility.

The remainder of the paper is organized as follows. The next section provides a review of existing metrics and methods to quantify productivity of freight transportation. Building on gaps identified from the literature review, the third section presents the F-MEP metric methodology. The fourth and fifth sections present implementation of the proposed approach and results of the F-MEP computation, as well as scenario analyses carried out with the metric.
The final section presents concluding thoughts as well as directions for future research.

LITERATRE REVIEW

Metrics for evaluating performance of freight transportation can be explored either from a business point of view or a system point of view. From the business perspective, Morash (*10*) identified five metrics, namely asset management, cost, customer service, productivity, and quality to evaluate freight performance. Mentzer (*11*) categorized a number of freight efficiency and effectiveness measures into five areas: transportation, warehousing, inventory control, order processing, and logistics administration, and claimed that both effectiveness and efficiency needed to be considered for freight performance measures. Lawrence et al. (*12*) listed a collection of freight performance measures into four categories: price, service, labor productivity, and capital productivity. Stainer (*13*) reported that productivity measures were the most significant indicators of freight logistics performance. Lai et al. (*14*) divided the freight performance measures into two groups: customer facing and internal (i.e., company) facing. Reliability, flexibility, and responsiveness were recognized as primary indicators for customer facing, while cost and assets were identified as primary indicators for internal facing. Jones and Sedor (*15*) proposed measures including fill rate, delay, travel time, travel time reliability, profitability, and return on investment. Most of the freight metrics from the business perspective do not consider aspects of the transportation system. For example, travel time or travel time reliability measured by a company might focus on corridors that the company serves, not the entire freight network. In addition, there has been much less attention in quantifying the energy efficiency of transporting goods, as shown by metrics in the literature.

Metrics that can measure performance of freight travel at the system level (e.g., a highway segment, city, county, state) can be classified into five categories: volume, system connectivity, mobility and reliability, system condition, and safety. The Federal Highway Administration (*16*) and Minnesota Department of Transportation (*17*) published reports with a detailed account of various freight performance measures, which are summarized in Table 1. Although those metrics presented have been widely adopted, the National Cooperative Freight Research Program pointed out a lack of well-defined performance measures clarifying priorities and goals for freight transportation, and emphasized the necessity for comprehensive freight performance measures to evaluate the success of policies, programs, and entities (*18*). Though there are some methodologies that simultaneously consider multiple performance metrics, there is no comprehensive approach to combine multiple dimensions (e.g., energy, cost, and time) of freight productivity into a single metric. For example, ton-miles/gallon is a metric that incorporates freight demand and energy together. Although this metric can measure changes in freight performance as a result of a more efficient powertrain in a vehicle, it is not able to capture the changes influenced by improvement in freight infrastructure such as an increase in the capacity of rail terminals. Even looking at freight performance measures at the system level, it is evident that there is little emphasis placed on energy efficiency of goods transport combined with ease of transporting goods between origins and destinations. Table 2 clearly shows that less attention has been paid to a holistic metric that can deal with various aspects simultaneously. The authors posit that some of these limitations can be overcome by combining accessibility theory with cost and energy efficiency of mode in order to develop a comprehensive freight productivity indicator.

Table 1 Existing metrics for freight transportation system

Category	Examples
Volume	• Number of trucks, rail cars, ten-foot equivalent units • Tons, value • Ton-miles, value-miles • Flights/day
System Connectivity	• Road, port, rail, or channel capacity • Miles of peak period congestion per day • Number of truck rest areas and capacity • Percent of shippers with access to triple trailer network, rail, etc. • Number or capacity of intermodal facilities • Shippers within 50 miles of facilities (intermodal, port) • Intermodal facility, warehouse capacity • Number of docks, cargo-handling acreage
Mobility and Reliability	• Travel time for select commodities, modes, and markets • Peak period travel time, percent of system with reliable travel time • Hours of delay, annual or average daily • Value of travel time, cost of delay • Travel time index (peak / free flow)
System Condition	• Percent of system in good condition, remaining service life • Percent of rail track-miles with speed > 25mph • Number of at-grade rail crossings • Number or percent of bridges with restricted weight or clearance • Miles per gallon, dollar per ton-miles
Safety	• Crash rate • Number of truck-related fatalities • Number of derailments • Cost of freight loss and damage per mile, per ton, or per total value • Insurance cost per ton of cargo

Table 2 Comparison of attributes of F-MEP against existing metrics

Category	Attributes considered in F-MEP				
	Opportunity (Demand)	Energy	Cost	Travel Time	Ease of shipping
Volume	✓				
System Connectivity					✓
Mobility and Reliability			✓	✓	
System Condition		✓			✓
Safety			✓		

Accessibility is defined as the ease with which activities can be reached from a given place using a given mode of transport (*19*). Accessibility theory and its application to passenger travel behavior have been an active area of research in social and geographical sciences dating back to pioneering research by Ravenstein (*20*). All the quantitative studies in this area have established that a close relationship exists among mobility, distance, and accessibility. Several researchers (*21*, *22*) have summarized the key elements of accessibility to be (i) the spatial distribution of opportunities, (ii) mobility provided by the road infrastructure and transportation system, (iii) temporal constraints of individuals and activities, and (iv) individual characteristics of people. The following three types of accessibility measures have been widely used by researchers and practitioners: i) distance-based measures, ii) isochrone-based measures, and iii) potential accessibility/gravity-based measures (*9*).

Very few researchers have adopted accessibility theory in the context of freight transportation. Thomas et al. (*23*) measured accessibility to freight transport networks to examine how the transportation network can be influenced by the distribution of population and economic activities. Van den Heuvel et al. (*24*) developed a freight accessibility metric using a gravity-based approach and further explored the relationship between freight accessibility and logistics employment in the United States. However, there has been no research (to the knowledge of the authors) that combines accessibility theory with energy, logistics cost, and ease of freight movement to develop a unified performance metric that is capable of capturing mobility and energy impacts of existing as well as emerging freight trends and technologies.

METHODOLOGY

Based on the previous research in the passenger travel side—the development of the MEP metric (*9*), this research effort recognizes the disparities associated with passenger and freight travel and appropriately accommodates such differences in the development of the F-MEP metric. Freight movement has a higher level of complexity than passenger travel, with multiple agents (e.g., shippers, receivers, carriers, brokers, and third-party logistics providers); multiple transport legs; multiple aggregation and disaggregation points; etc. The geographic coverage of freight movement is extensive and can be categorized into two main categories. While many freight activities take place within a city, called within-city (or intracity) freight, a substantial amount of goods is moved between cities and across the nation, called between-city (or intercity) freight. Some freight movements involve both within-city and between-city travel legs. In addition, there is a significant amount of heterogeneity in freight transport, especially depending on commodity type. For instance, while raw materials tend to be transported long distances by various modes, locally sourced consumer goods may be moved shorter distances by truck with each shipment specific to the customer.

To develop a comprehensive metric that captures various facets of freight movement, the following considerations have been kept in mind:

- The metric should be built on a generalized framework that can interact with existing freight modeling tools and publicly available data sources.
- The metric should have the capability to be fine-tuned to a region or commodity.
- The metric should be capable of measuring performance offered by various modes (and a combination of such modes), both existing and future.
- The metric should be capable of evaluating the impacts of emerging freight trends and technologies such as connectivity and automation, electrification, new delivery solutions, e-commerce, etc.

Within-city and between-city freight movements have fundamentally distinct characteristics, as noted below:

- Within-city freight: Mostly moved by different types of trucks; travel times usually less than one day with traffic congestion; high circuity; not influenced much by commodity type; mix of business-to-business, business-to-consumer and consumer-to-business movements.
- Between-city freight: Moved by various modes (truck, rail, air, water); wide variation in travel time within/between modes; low circuity; highly influenced by commodity type; mostly business-to-business deliveries.

Accommodating these distinctions, different approaches need to be adopted to develop F-MEP metrics for within-city and between-city freight movements. This paper focuses on the methodology and implementation of the F-MEP metric for between-city freight movements.

Because long-distance freight travel spans multiple modes (rail, air, road, water) and a wide time horizon (hours to days), a gravity-based approach was selected as the appropriate method for developing the between-city F-MEP metric. The approach proposed for within-city freight movement on the other hand will incorporate parameters that reflect high sensitivity to congestion within a city boundary (similar to the MEP metric in (9)). Although freight movement is a multiagent problem involving shippers, carriers, receivers, and logistics firms, a shipper perspective was chosen as appropriate for the development of the F-MEP metric, as shippers are the ones who must respond to economic and freight system conditions, especially for between-city freight movement where they determine mode choice. Even though a methodology from other agents' points of view can be developed in a similar fashion, these perspectives might stress different attributes, for example, travel time reliability is more important for receivers than logistics cost and easy of shipping goods. However, the authors believe that a shipper's perspective can help provide valuable insights on the productivity of freight transportation systems for decision makers in the public as well as the private sector, which is consistent with the recent development of agent-based freight modelling.

Conventionally, a gravity-based accessibility measure consists of two terms: i) weighted area of locations, and ii) impedance between two locations. In the F-MEP metric, the first term represents the mobility benefits and measures the potential freight delivery opportunities from a given location to any other locations. Mobility benefits can be measured by a combination of variables such as business locations, population, employment, commodity weights or values, and facility capacities as a function. The second term in the F-MEP is a function of integrated costs associated with satisfying freight delivery opportunities. Previous studies on accessibility-based metrics explored various forms of travel time impedance functions with coefficients such as inverse power, negative exponential, and modified Gaussian function (*25*). This is one of the first studies to extend the impedance function by incorporating multidimensional parameters that can weigh the mobility benefit (say freight delivery opportunities). Such parameters can be energy intensity, cost of logistics, ease of shipping goods using a mode, reliability, and risk.

The F-MEP can be defined as the sum of the mobility benefit for shipping from a location i to any other location j that has freight attraction, weighted by the friction factors from i to j that are associated with energy, cost, travel time, and ease of shipping goods. The general formulation of F-MEP for a location i is specified as:

$$\boldsymbol{FMEP_i} = \sum_k \sum_c \sum_{j \neq i} \boldsymbol{B_{cj}(X)} \cdot \boldsymbol{f^k_{c,ij}(Y)} \quad \textbf{(1)}$$

where

i, j are the originating location (or location of interest) and destination, respectively

c is the type of commodity (or business)

k is the type of transportation mode

$B_{cj}(X)$ is the mobility benefit of commodity type (or business type) c at location j which can be formulated by different classes of freight delivery opportunities, $\boldsymbol{X}$

$f^k_{c,ij}(Y)$ is the impedance function which can be formulated by various cost related parameters, $\boldsymbol{Y}$.

The impedance function $f^k_{c,ij}$, is further defined as:

$$\boldsymbol{f^k_{c,ij}(Y) = exp\ (\alpha e_k + \beta p_k + \gamma_{ck} t_{k,ij}) \cdot s_{ik}} \quad \textbf{(2)}$$

where

e_k is the unit energy intensity (kWh/ton-mile or \$/ton-mile) of mode k

p_k is the unit logistics costs (\$/ton-mile) of mode k

s_{ik} is the ease of shipping goods by mode k at location i

$t_{k,ij}$ is the travel time (or distance) from location i to j by mode k

$\alpha, \beta, \gamma_{ck}$ are the weight factors, which are negative numbers (i.e., decreasing benefit with increasing friction)

The impedance function is designed to be robust under future scenarios in that it accounts for all variables associated with efficiency enhancements in any given mode. Taking long-haul trucks as an example, suppose the energy efficiency of trucks increases dramatically due to vehicle electrification (with travel speeds, costs, etc., remaining the same), the e_k parameter in Equation

(2) captures the improvement in the productivity of freight transportation. Similarly, if the logistics cost of trucks decreases due to automation (with energy efficiency and travel speeds remaining the same), the p_k parameter will capture improvement in the freight system. Finally, if both energy and the cost of trucking remain the same but trucks are able to travel faster (due to vehicle-to-vehicle or vehicle-to-infrastructure connectivity), the $t_{k,ij}$ parameter captures the gain in efficiency of freight transportation. In a future where time, logistics cost, and the energy efficiency of transporting goods improve simultaneously, the proposed metric can readily capture the combined effect of these improvements in the enhanced system.

IMPLEMENTATION

To demonstrate the capability of the proposed approach, the F-MEP metric was used to quantify freight performance of mainland U.S. (the lower 48 states) shipping. A single variable, commodity-specific demand (tonnage value) at a location j, is used as the freight mobility benefit ($B_{cj}(X)$). The commodity-specific demand information for the mainland United States is obtained from the Freight Analysis Framework (FAF) (*1*).

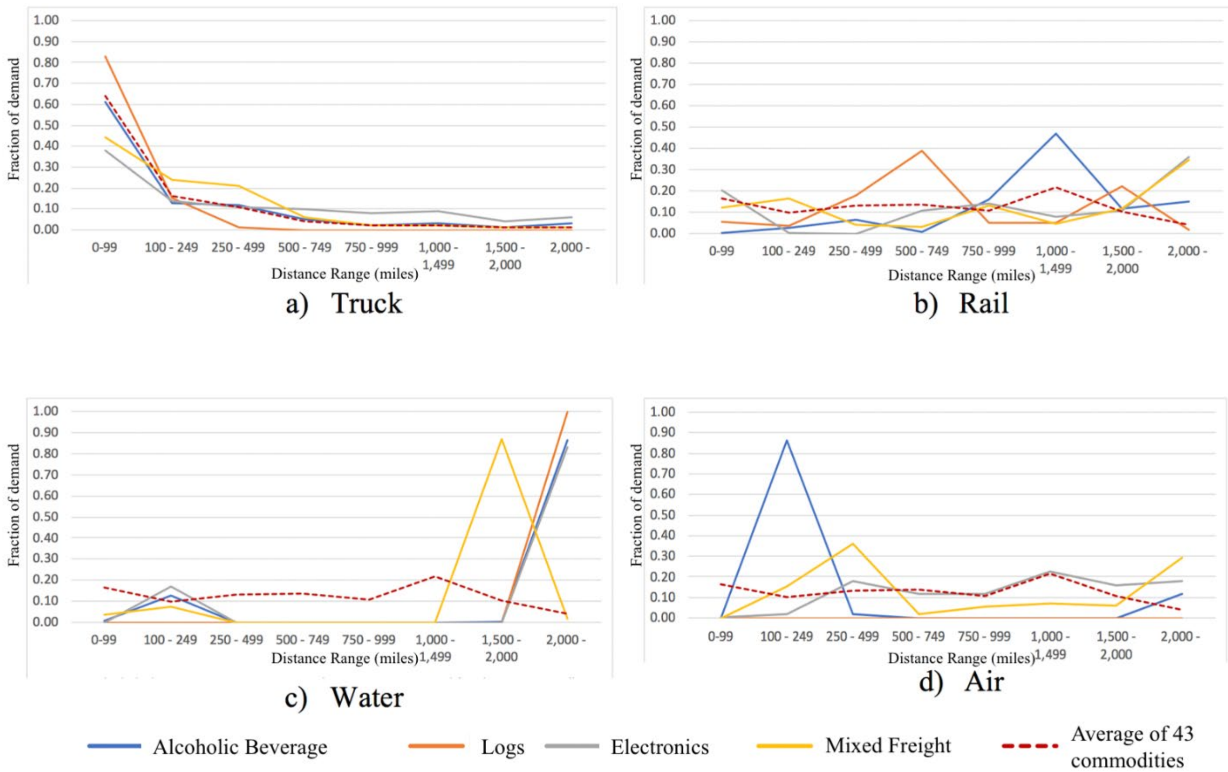
Typically, the travel time decay is formulated as an exponential function of time in accessibility metrics (see exp $(\gamma_{ck} t_{k,ij})$ in Equation (2)). This simply means that the longer one has to travel to reach a destination (or deliver a good), the less attractive that opportunity becomes. Travel time decay is an excellent factor in explaining accessibility disparities across different modes, when the decay function across those modes follows a similar trend (*9*). However, in the context of between-city freight, the heterogeneity of travel time (or distance) distribution across different modes is large, making a unified decay function unsuitable to weight travel or distance across all modes (and commodities). To accommodate this nuance, a commodity- and mode-specific distance decay function can be used in the formulation of F-MEP metric. To illustrate this point, Figure 1 shows fractions of demand distributions of four commodities with respect to travel distance by different modes. While a single distance decay distribution fits reasonably well (for all commodities) for truck mode (Figure 1a), it can be seen that for rail, water, and air modes (Figure 1b–d), each commodity has its own decay function (and some do not have a standard function that can be fit around them). Therefore, commodity movement data from the FAF are used to generate the fraction of commodity tonnage transported in a given mode with respect to travel distance. Thus, $exp\ (\gamma_{ck} t_{k,ij})$ is replaced with $r_{ck}^{l_{ij}}$ in this study. Equation (2) is rewritten as:

$$\boldsymbol{f_{c,ij}^{k} = \exp\left(\alpha e_k + \beta p_k\right) \cdot r_{ck}^{l_{ij}} \cdot s_{ik}} \qquad \mathbf{(3)}$$

where

$r_{ck}^{l_{ij}}$ is the weight fraction of commodity *c* moving within distance range *l* by mode *k*

l_{ij} is the distance range from *i* to *j (e.g., below 100, 100–250 miles)*



Note: the fractions were calculated using commodity-specific tonnage by distance band for each mode provided by the FAF (*1*).

Figure 1 Examples of commodity- and mode-specific fraction of freight movement, $r_{ck}^{l_{ij}}$

To account for the impact of energy and cost intensity for different modes on freight performance, mode-specific energy intensity and logistics cost parameters are included in the impedance function. In this study, unit energy intensities are translated first to British thermal units (Btu) per ton-mile and then converted further to the unit of dollars per ton-mile based on data obtained from *Transportation Energy Data Book* (*3*). However, the *Data Book* does not provide the energy intensity for trucks in the same units as air for freight. Therefore, the energy intensity value for trucks was obtained by dividing the 2016 total energy consumption for heavy-duty trucks by the total truck ton-miles provided by the Bureau of Transportation Statistics (*26*). Air energy intensity was calculated by using information (ratio of air energy intensity to truck energy intensity) obtained from a report on Transportation Energy Futures (*27*). The logistics cost parameters were computed based on information from U.S. business logistics costs (*28*) and total ton-miles by mode. Table 3 presents values estimated and used in this study for the unit energy intensity and unit cost by mode. Future efforts will focus on obtaining these values using more sophisticated estimation approaches and sources.

Table 3 Value of unit energy intensity and unit logistics cost by mode

Mode	unit energy intensity ($/ton-mile)[1]	unit logistics cost ($/ton-mile)[2]
Truck	0.0734	0.139
Rail	0.0007	0.046
Water	0.0005	0.097
Air	0.5502	5.384

1. Estimated by converting Btu per ton-mile to dollar per ton-mile based on 1 gallon = 137,381 Btu and diesel fuel prices = $3.30/gallon
2. Estimated by dividing the 2016 U.S. business logistics costs by the total ton-mile for each mode

The factors for both energy and cost weighting are assumed to be equal and are set to −0.5 for the analysis presented in this paper. It should be noted here that the focus of this research effort is to develop a robust approach for measuring freight performance, but not to dictate the weights that should be used for various parameters. Such a line of effort is outside the scope of this effort and is worthy of its own research endeavor. Generally, the authors expect that the weight factors can be estimated using a survey that collects shippers' or planners' perceptions regarding the relative importance of cost and energy factors in freight transport decisions. In addition, the methodology presented in this paper is flexible in that researchers can adjust the weight factors depending on their emphasis on each dimension.

The term of ease of shipping goods (s_{ik}) is included in the impedance function to reflect the ease of shipping goods using a given mode at a given location. While various parameters can be used for this purpose, the number of facilities related to a specific mode (obtained from the Bureau of Transportation Statistics) is used to reflect ease of shipping in this study.

$$s_{ik} = \begin{cases} 1 & if\ k = truck \\ \frac{n_{ik}}{\max(n_{jk}, \forall j)} & Otherwise \end{cases} \quad \textbf{(4)}$$

where n_{ik} represents the number of intermodal facilities associated with mode k at location i.

A value of 1 is assigned for the truck mode in all locations since any shipper can use trucks to transport goods anywhere and anytime. However, the use of other modes is restricted by factors such as market size, infrastructure availability, etc. Since the F-MEP aims at providing the "relative" differences in the freight system performance across various locations of interest, the scores are normalized between 0 and 1. For example, if Los Angeles, CA has the highest value for waterway facilities among the all locations in the United States ($n_{LA,water} = 100$) and the value for Seattle, WA is 50 ($n_{Seattle,water} = 50$), then $s_{LA,water} = 1$ and $s_{Seattle,water} = 0.5$. While it can be seen that higher values of s_{ik} are better in general, it should be noted that these values are normalized, and top coded to a value of 1.

RESULTS

This section presents visualizations of overall F-MEP scores in the United States and an assessment of consistency with expectations, followed by demonstrations of the capability for mode-commodity disaggregation. To validate the concept, correlation analyses are provided. Finally, scenario analyses are presented to further support the usefulness of the F-MEP as a metric.

F-MEP Calculation

The F-MEP methodology was used for calculating the energy productivity of freight mobility in mainland United States FAF zonal structure was adopted as the geographical resolution for analysis. It is assumed that movement of goods between two different FAF zones is considered as between-city freight movement, thus intrazonal demand in the FAF was excluded from this calculation. Figure 2 presents the overall F-MEP scores aggregated over truck, rail, water, and air modes for all FAF zones. The map is color coded in a red gradient scale where dark red indicates high scores representing high mobility energy productivity for freight from that zone. It should also be noted here that the F-MEP metric scores are scaled by a factor of 5,000 for relatability. The Chicago FAF zone has the highest F-MEP score (283), while the Salt Lake City FAF zone has the lowest F-MEP score (21). Overall, zones in the Midwest and Mid-Atlantic have better F-MEP scores, indicating the attractiveness of shipping from those zones. The findings seem intuitive because: 1) many FAF zones with high F-MEP values are located in central United States, and these zones have relatively short distances to all other zones. 2) The FAF zones with high F-MEP scores have good accessibility to all transportation modes, including ports. 3) The FAF zones with high F-MEP scores are close to the big freight demand markets in the Northeast portion of the United States. 4) Many FAF zones with high F-MEP are located near manufacturing centers.

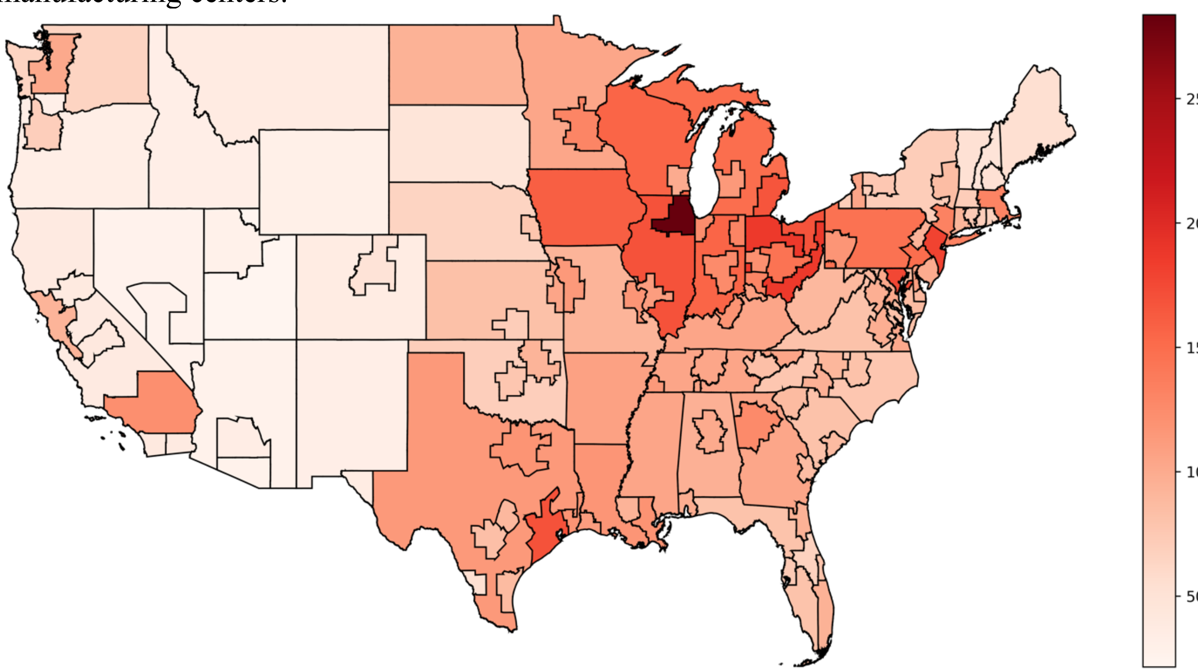
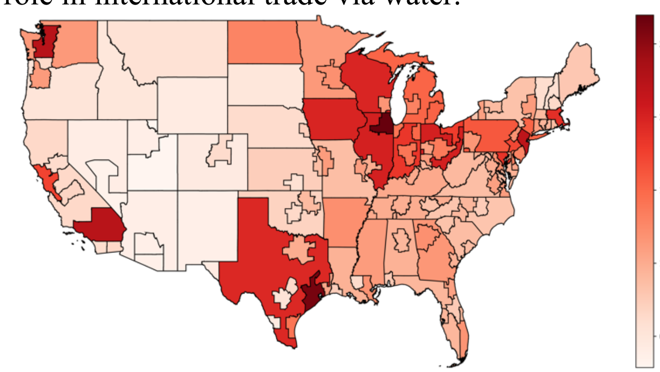
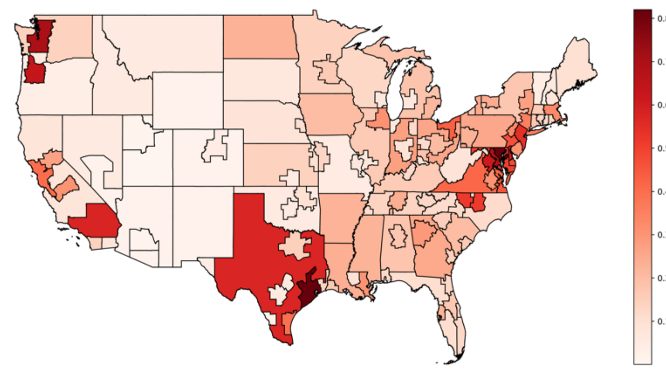


Figure 2 F-MEP map (National Scale – FAF zonal structure)

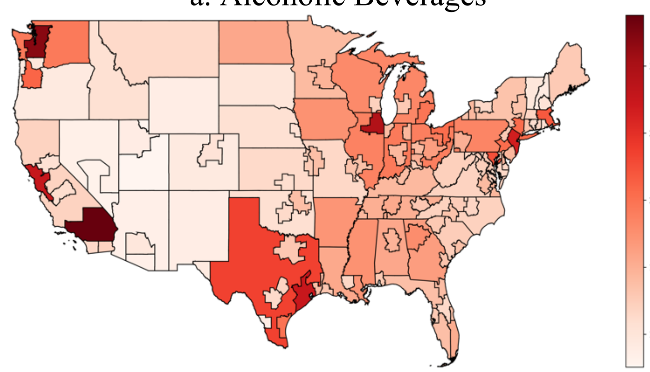
As mentioned before, freight movement across commodity types and modes is non-homogenous in nature. The approach of the F-MEP metric proposed in this paper is equipped with the capability to capture this heterogeneity and to generate productivity scores by commodity and/or mode as shown in Figure 3–Figure 5. Figure 3 depicts F-MEP maps by commodity type, while Figure 4 shows F-MEP maps by mode. Compared to overall F-MEP scores (Figure 2), the F-MEP maps by commodity and mode uncover some interesting patterns. While the specific parameterization used here is intended only to demonstrate the approach and is not intended as a definitive ranking of FAF zones, decomposing the metric and comparing these patterns illustrates the power and complexity of the F-MEP approach. For example, the F-MEP maps for electronics and mixed freight (see Figure 3c and 3d, respectively) show relatively high scores in California and Washington. The reason for this could be that these commodities can be moved easily by rail, air, or water modes from these locations (which is captured in the F-MEP computation through ease of shipping parameter). The F-MEP scores for truck mode seem to be influenced more by the distance term (since ease of shipping for trucks is assigned a value of 1 across all zones), showing a gradual decay in F-MEP scores for FAF zones from the center to east and west. On the other hand, richness of infrastructure is shown to play a key role in freight performance for rail, water, and air modes, which is reflected by high F-MEP scores for these modes in zones having high densities of ports and terminals (Figure 4b–d). It should be noted that the current F-MEP methodology is not designed to deal with goods demand in international zones, which results in a relative low F-MEP score for water mode in the Los Angeles FAF zone even though that zone, where the largest port in the United States is located, plays a significant role in international trade via water.



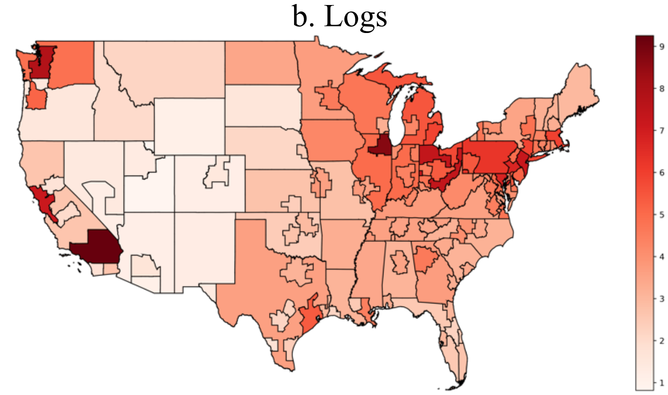
a. Alcoholic Beverages



b. Logs



c. Electronics



d. Mixed Freight

Figure 3 Commodity-specific overall F-MEP map

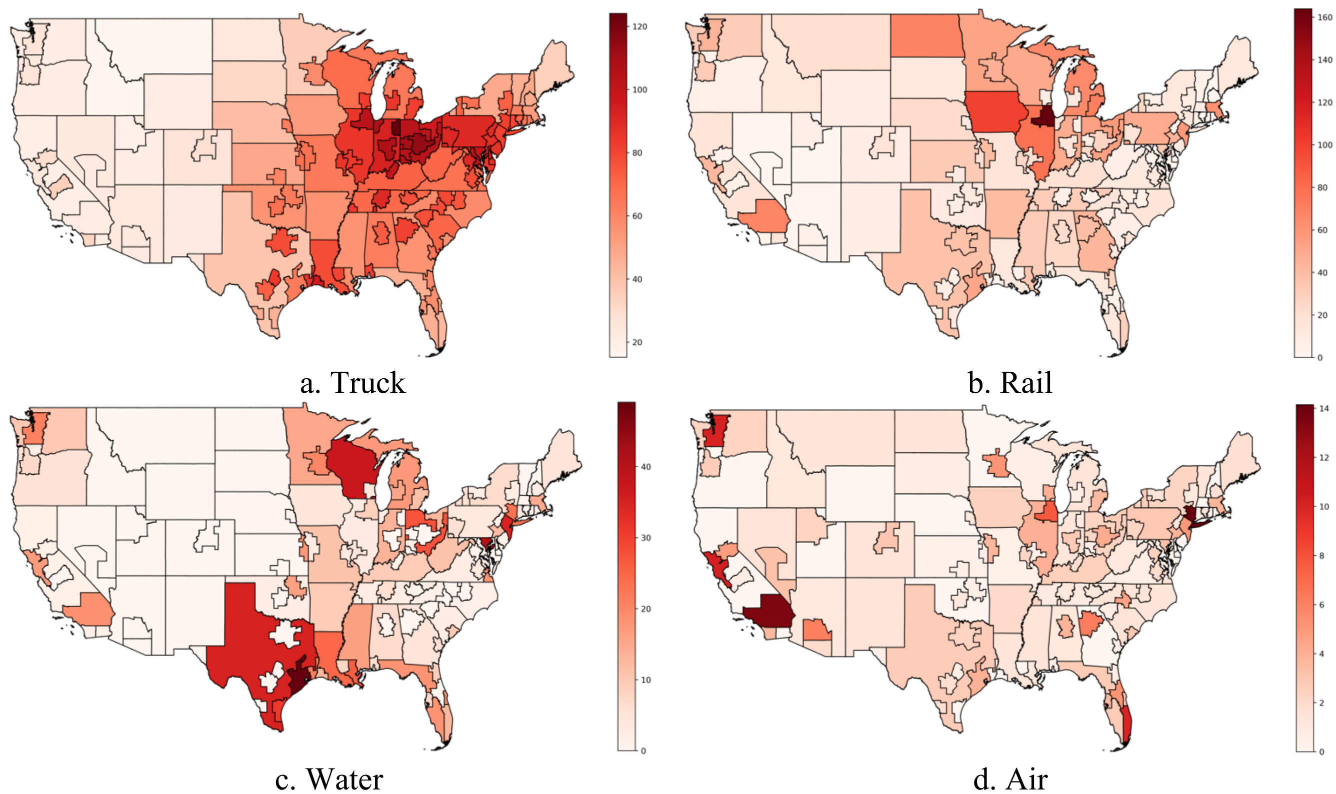


Figure 4 Mode-specific F-MEP map

Figure 5 presents F-MEP maps for different commodities further classified by mode to examine how commodity type affects the freight performance metric (reflected by the F-MEP score) for different modes. For example, since logs are not moved by air, no score is assigned for the F-MEP for that mode–commodity combination (Figure 5b-2). In contrast, mixed freight can be easily moved by various modes, including rail and water, depicted by relative high F-MEP scores those modes (Figure 5d). The mode–commodity disaggregation is an extremely useful feature of the F-MEP metric that enables users to conduct customized analyses to understand the impact of different technologies on freight performance improvements for specific mode–commodity combinations.

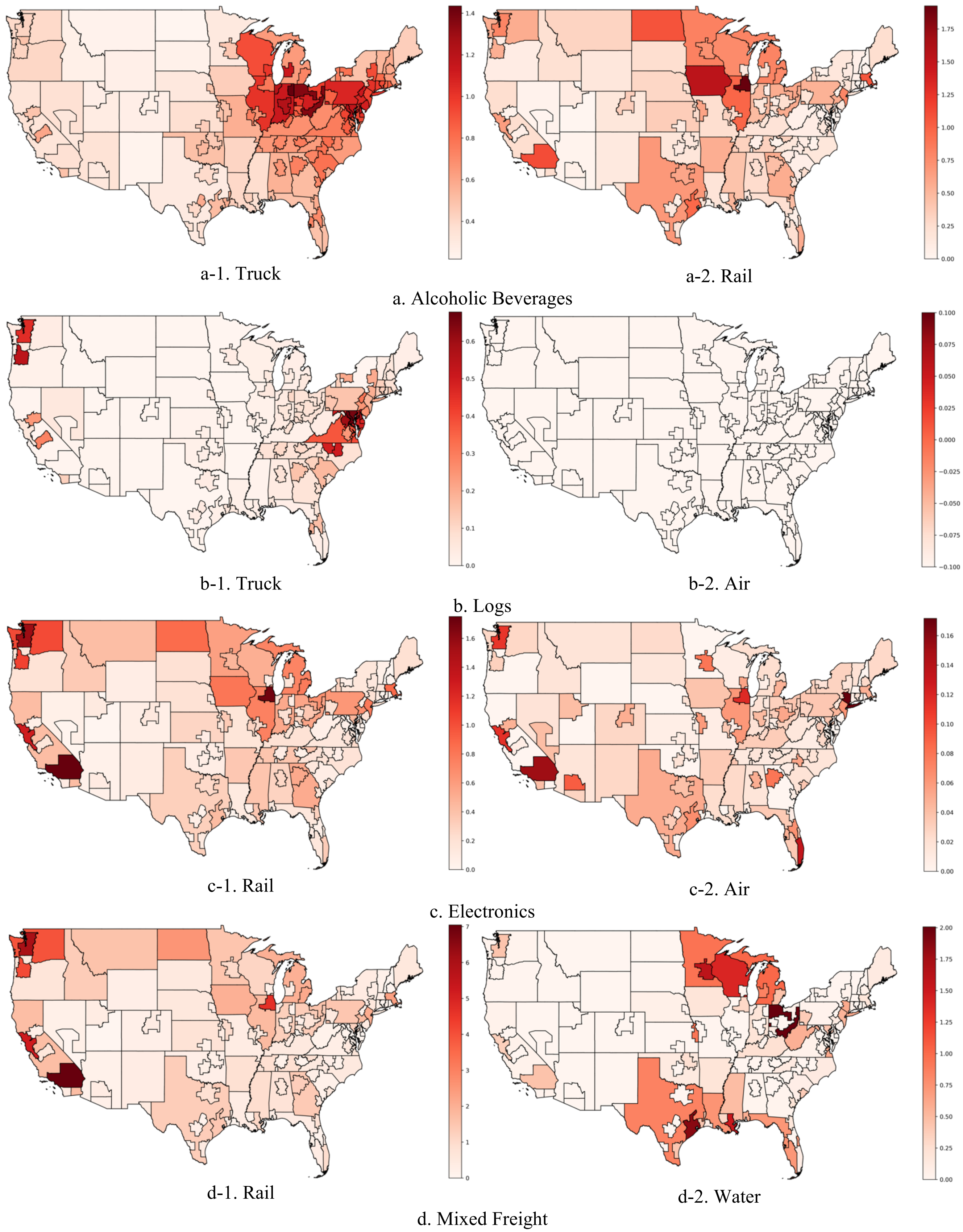


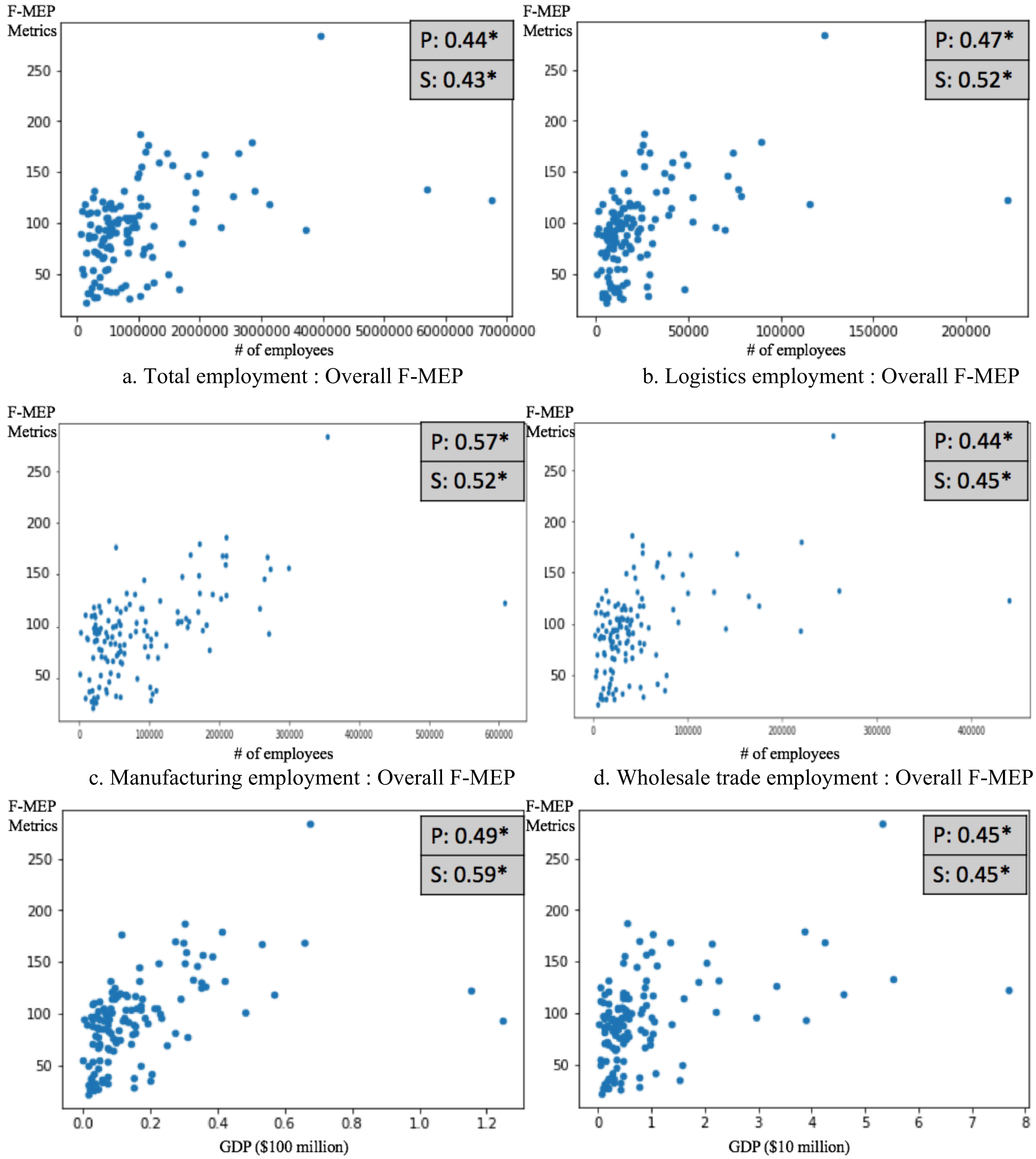
Figure 5 F-MEP maps by commodity and mode

Correlation of F-MEP scores with Employment

Once the proposed metric passed intuitiveness checks, it was felt necessary to corroborate that the findings from the metric are valid. This can generally be done by comparing the trends from the metric with trends from similar metrics or observed trends that explain freight productivity. Since the proposed metric is the first of its kind in simultaneously accounting for time, energy, cost, and ease of shipping factors in quantifying freight productivity, the authors were not able to find similar metrics to which results of F-MEP can be compared. In addition, if the metric is validated against any of the five single metrics that were included in the F-MEP formulation, the correlation would be endogenous (and expected). It should be noted that generating a freight productivity metric for this validation purpose requires the same amount of effort as developing the F-MEP, which is quite challenging. Instead, following Van den Heuvel et al. (*24*), the correlation between F-MEP scores and sector-specific employment for the corresponding zones was analyzed, with a hypothesis that a location with higher freight productivity is likely to attract higher employment in a sector associated with freight movement. For example, a high F-MEP metric for a FAF zone might be associated with high wholesale trade employment for that zone, under the theory that a productive freight system might influence business location and size. With a similar hypothesis, the correlation of F-MEP score to gross domestic product (GDP) was calculated. While this is not a strict validation of the metric, the correlation analysis should give an indication of the validity of F-MEP metric in quantifying freight performance. Future efforts will focus on finding comparable metrics for a more robust validation exercise.

County-level employment information and GDP were obtained from the 2016 County Business Patterns data (*29*) and the 2016 Bureau of Economic Analysis (*30*). The data were aggregated by FAF zone and categorized into the following four groups based on North American Industry Classification System codes: 1) total employment, 2) logistics (*24*), 3) manufacturing, and 4) wholesale trade. Correlation between employment or GDP variables and corresponding F-MEP metrics by FAF zone was evaluated using a Pearson correlation coefficient. A Spearman correlation was also carried out to capture any non-parametric relationships among the variables in question.

Figure 6 presents the correlation coefficients and their statistical significance. All employment groups have a statistically significant correlation with the F-MEP metric. The correlation between manufacturing employment or GDP and the F-MEP metric is relatively high. The results of the correlation analysis seem encouraging, particularly given that employment information is orthogonal to all the information used for F-MEP calculation (except for logistics employment, which is associated with the number of facilities related to a specific mode). Acknowledging that the assumptions made have limitations, the findings from this correlation analysis suggest that the F-MEP can be a reasonable indicator to evaluate productivity of freight systems.



a. Total employment : Overall F-MEP

b. Logistics employment : Overall F-MEP

c. Manufacturing employment : Overall F-MEP

d. Wholesale trade employment : Overall F-MEP

e. Manufacturing GDP : Overall F-MEP

f. Wholesale trade GDP : Overall F-MEP

Note: 1. P represents Pearson correlation coefficient; S represents Spearman correlation; * p-value <0.05
2. Logistics GDP could not be obtained.

Figure 6 Correlation between employments and F-MEP

Scenario analysis

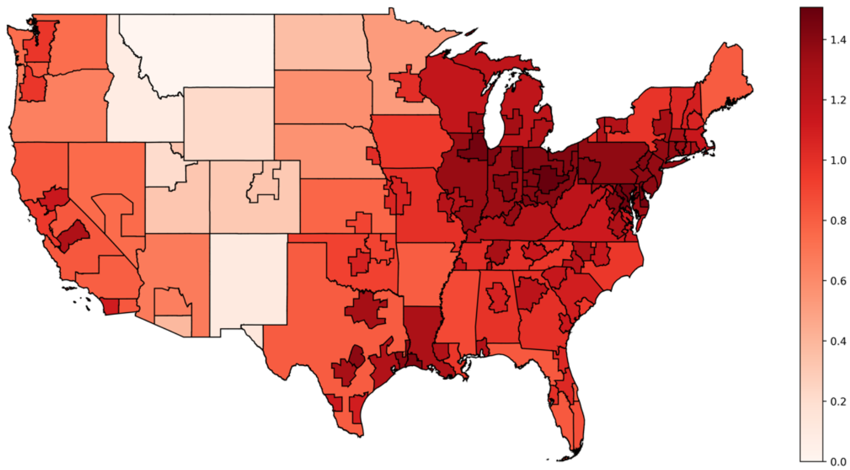
One of the most important facets of the F-MEP metric is that it can be used to evaluate the impacts of emerging freight technologies and trends on freight performance at the system level. The ideal way to do this is to obtain outputs of scenario analyses from freight demand forecasting models and provide them as input to the F-MEP calculation procedure. Such an integrated metric will be an invaluable tool in assessing the relative benefits across multiple freight scenarios. For example, if a city plans to approve building a new freight distribution warehouse, mixed freight shipping is expected to increase. The change in freight productivity (for that city/zone as well as adjacent zones) from such a scenario can be easily captured using the F-MEP methodology. Similarly, the increase in freight efficiency with the introduction of new modes for freight delivery with lower energy or cost footprints (such as high-speed rail or autonomous electric delivery shuttles) can also be quantified using the F-MEP metric. In order to demonstrate the responsiveness of F-MEP metric to freight technologies, two hypothetical scenario analyses pertaining to long-haul truck electrification are presented here:

- S1: Electrification of the powertrains with range constraints:
    - $e_{truck} =$ \$0.0245/ton-mile for $l_{ij} \leq 500\ miles$
    - $e_{truck} =$ \$0.0734/ton-mile for $l_{ij} > 500\ miles$
- S2: Electrification of the powertrains without range constraints:
    - $e_{truck} =$ \$0.0245/ton-mile for all l_{ij}

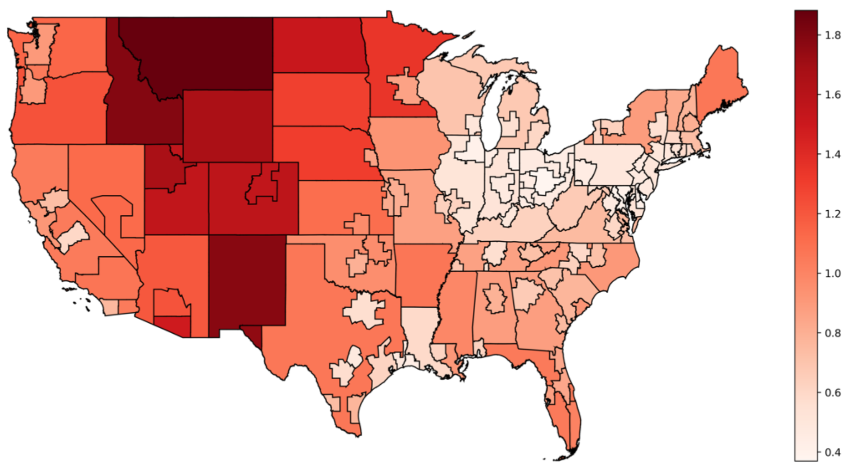
In both scenarios, it is assumed that electric trucks require one third of the energy used by conventional trucks. In the first scenario (S1), electric trucks are constrained to travel 500 miles or less, owing to charging infrastructure constraints (reflecting a near-term future). Under this scenario, it is envisioned that all road freight delivery within a range of 500 miles or less will be handled by electric trucks. For deliveries greater than 500 miles, conventional trucks will be used. In the second scenario (S2), the charging constraints are expected to be mitigated, and it is anticipated that all conventional trucks will be replaced with electric trucks. It should be noted here that the intent of this scenario analysis is to test the formulation of the metric and to demonstrate the capability of F-MEP metric for scenario analysis. The authors acknowledge that the assumptions made are aggregates and do not account for secondary impacts of market penetration of electric trucks. Such impacts can be captured using freight forecasting models, outputs of which serve as ideal inputs for the F-MEP scenarios. Future efforts will focus in integrating the F-MEP calculation with sophisticated freight forecasting models.

The results of the scenario analysis shown in Figure 7 depict the relative improvements in F-MEP metric from baseline to S1, and from S1 to S2. For S1, the F-MEP for zones that have high freight demand zones within 500 miles (e.g., FAF zones in the Northeast or South) benefited from the vehicle electrification (see Figure 7a). Once the range constraints are removed, the F-MEP gains (or increases in freight productivity) become significant for zones that are farther from current freight hubs (see Figure 7b).

Similar analyses conducted for reduced freight costs show discernible freight performance improvements that can be depicted effectively through the F-MEP methodology. The results are omitted here for brevity.



a. S1 compared to Baseline



b. S2 compared to S1

Figure 7 Relative truck F-MEP gain (%)

CONCLUSION

Freight transportation accounts for a significant portion of the travel energy consumed in the United States. Therefore, an accurate understanding of factors that influence freight travel is critical in planning for the future of freight transportation. Advances in freight forecasting models have gained momentum only in recent years, with many cities investing in sophisticated freight models that can accurately depict freight travel behavior. In parallel, the field of transportation is experiencing an unprecedented transformation that will impact the future of passenger as well as freight travel and ripple effect. Freight forecasting models will shoulder the responsibility of understating the impacts of emerging transportation technologies such as vehicle automation, vehicle electrification, new modes, and new forms of delivery. While modeling and forecasting freight trends is important, it is also critical to have metrics that can accurately capture the performance of freight systems in current as well future scenarios. Current metrics available to quantify freight performance are too coarse, unidimensional, and have not seen much progress and development in the recent past. Conventional freight performance metrics such as ton-miles and value-miles fall short of accurately capturing the impact of emerging technologies such as vehicle electrification and automation on the performance of freight systems. There is a need now more than ever for comprehensive metrics to quantify productivity of freight systems.

Addressing this gap, this research effort develops a practical and holistic metric for quantifying the performance of freight systems from the shipper's perspective. The F-MEP metric builds on research from accessibility theory and provides a way to quantify freight productivity (connecting freight demand to freight supply) while accounting for all inputs (time, energy, and logistics cost) associated with freight movement in various modes. Since freight movements within a city are governed by factors that are clearly different from those that govern between-city freight movement, it was felt prudent to develop separate metrics to quantify productivity of both within-city and between-city freight movements. This paper presents the methodological framework and application of the F-MEP metric for quantifying productivity of between-city freight movements. FAF, along with other published sources were used to implement the F-MEP metric for quantifying productivity of freight transportation in mainland United States.

Preliminary results from the F-MEP implementation show intuitive trends, both at the aggregate level as well as at the disaggregate level of mode- and commodity-specific F-MEP calculation. The proposed methodology assigns highest F-MEP score to the Chicago FAF zone, with FAF zones in the Midwest obtaining better F-MEP scores overall, which is indicative of their attractiveness to shippers and logistics firms. A correlation analysis was conducted to test the validity of F-MEP scores. In the correlation analysis, sector-specific employment (in long-haul truck, rail, water, and air sectors) were correlated with corresponding F-MEP score, and a high statistical significance was found for all modes except long-haul trucking. The metric was further tested by carrying out a scenario analysis in which the energy intensity of long-haul trucks was improved in stepwise increments. The F-MEP metric was able to successfully capture and illustrate the improvement in freight system performance due to vehicle electrification with geographic specificity, proving that the metric can be used as a scenario evaluation tool to assess impacts of various emerging transportation trends on the performance of the freight systems.

This research represents a first attempt at developing a comprehensive metric that is capable of quantifying the productivity of freight transport under a variety of scenarios. However, the authors acknowledge that the F-MEP metric has a few shortcomings that need to be addressed. Although the scenario analysis presented in this paper showcases the utility of F-MEP as a decision support tool, it is important to note the necessity of integrating this metric into freight forecasting models that can capture a variety of secondary and tertiary effects of emerging trends on freight travel. As part of model integration efforts, the sensitivity of the metric to weight factors should be assessed. Also, while the initial implementation of the metric adopted the FAF zonal structure owing to data availability, future efforts will focus on computing the metric at finer geographical resolutions. While the first iteration of the metric focused on a base methodology that can accommodate all modes, all commodities, and all externalities of freight travel, the fact that end-to-end freight travel is sometimes multimodal in nature (e.g., truck + rail + water) is overlooked in the initial implementation. Future research efforts will address this shortcoming by accounting for multimodal freight characteristics where appropriate. Lastly, while this paper presented an efficient quantification metric for between-city freight travel, the importance of within-city freight travel is not forgotten. The development of a within-city F-MEP metric is currently underway as a separate research effort.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Kyungsoo Jeong, Venu Garikapati, Yi Hou, Alicia Birky, Kevin Walkowicz; data preparation: Kyungsoo Jeong, Yi Hou; analysis and interpretation of results: Kyungsoo Jeong; draft manuscript preparation: Kyungsoo Jeong, Venu Garikapati. All authors reviewed the results and approved the final version of the manuscript.

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