

Article

# Assignment of Freight Truck Shipment on the U.S. Highway Network

Taesung Hwang

Asia Pacific School of Logistics, Inha University, Incheon 22212, Korea; thwang@inha.ac.kr; Tel.: +82-32-860-8230

**Abstract:** With the ever-increasing demand for freight movements, nationwide freight shipments between geographical regions by freight trucks need to be investigated since they comprise the largest share of total freight movements in the United States. To this end, the procedures for freight truck shipment demand network assignment on the entire U.S. highway network considering congestion effect are discussed, and the results are explained in detail, with visual illustrations. A fundamental traffic assignment model with a convex combinations algorithm is proposed to solve the nationwide freight truck shipment assignment problem under the user equilibrium principle. A link cost function is modified, considering the traffic volume that already exists on U.S. highways. A case study is conducted using big data including the entire U.S. highway network and freight shipment information in 2007. Total and average freight shipment costs for both truck and rail transportation for a specific origin–destination pair in the database are computed to compare the characteristics of these two major freight transportation modes in the United States. Application of the proposed model could be possible to address many other related problems, such as improvement of highway infrastructure, and reductions in traffic congestion and vehicle emissions.

**Keywords:** long-haul freight truck shipments; large-scale traffic assignment problem; big data; convex combinations algorithm



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## 1. Introduction

Freight shipment demand within the continental United States has been growing continuously, and the rate of increase has grown significantly over the past three decades [1]. For instance, freight movement in ton-miles surged by more than 70% between 1970 and 2000 [2]. With the ever-increasing freight shipment demand, efficient freight transportation operations in the trucking industry have become more crucial because trucks carry the largest share of total freight movement in the United States in both tonnage and value of the freight [3]. Moreover, significant social welfare, such as reductions in vehicle emissions and the subsequent enhancement in human health, could be expected through improvements in nationwide freight truck operations. Although advanced technologies in Intelligent Transportation Systems, such as stand-alone GPS devices, smartphones with GPS, or time-varying toll pricing strategy, could be useful in achieving efficient freight truck movements within the continental United States, a more accurate traffic model and its real-world application on a large network should be investigated to ensure better network performance. However, to the best of the author's knowledge, only a few studies have analyzed freight truck transportation systems over the entire road network in the United States.

The objectives of this study are to (i) conduct freight truck shipment analysis from a macroscopic point of view, and (ii) estimate freight flow and congestion patterns on the full-scale U.S. interstate highway network by using big data which includes complete freight shipment origin–destination (O-D) information in 2007. This study estimates nationwide freight movements between geographical regions by freight trucks, which can be considered as a traffic assignment problem. The conventional network assignment model and solution approach (i.e., the convex combinations algorithm) is applied to achieve

the truck shipment routing equilibrium. In this study, the concept of background traffic volume on each highway link is incorporated into the proposed model to represent the traffic flow that already exists in the given highway network. The optimal solution can be found within a short execution time. Additionally, the difference in shipment costs along truck and rail routes for the same O-D pair was analyzed to draw insights into the characteristics of the two main freight shipment modes in the United States.

As such, the work presented in this paper focuses on developing freight shipment demand assignment model on the entire U.S. highway network and its application using publicly available databases. The findings of this study could be useful for transportation planners and government officials in assessing the impacts of freight truck activities on nationwide network efficiencies. Additionally, the efforts in this study could be used to reduce vehicle emissions and enhance human health and social welfare since traffic congestion is known as one of the leading causes of vehicle emission problems.

The exposition of this paper is as follows. The next section reviews the related literature. The proposed model and solution algorithm are described in Section 3. Section 4 explains the results from a case study, and compares truck and rail freight shipment costs. Lastly, Section 5 concludes the study and provides discussions for future research.

## 2. Literature Review

The freight truck routing problem on the U.S. interstate highway network can be considered part of the traditional traffic assignment problem. Given a set of freight shipment demands and a graph representation of the highway network, the traffic assignment problem determines the optimal freight flow pattern between all O-D shipment demands in the given network. The convex link performance function defines the relationship between link travel time (i.e., link cost) and the assigned shipment flow on the link, assuming the link cost increases as the shipment flow on the link increases due to the congestion caused by limited link capacity [4]. This study investigated the systematic mechanism on how shipment traffic between multiple origins and destinations can be assigned onto the continental U.S. interstate highway network subject to congestion. The most efficient shipment routes for every O-D pair of freight demand need to be constructed to minimize the delivery time of each truck. This framework requires us to follow the user equilibrium principle since eventually, no trucks will be able to reduce their delivery time by unilaterally choosing another route [4]. Following the user equilibrium principle [5], each motorist is assumed to know all network information and selects the shortest O-D route based on travel time. Shipment flows will reach equilibrium, in which all used routes connecting each O-D pair will have the same cost, less than or equal to the costs of unused routes.

Since Frank and Wolfe [6] suggested an iterative optimization technique (the so-called convex combinations algorithm) to solve a constrained quadratic mathematical program, a number of studies have been proposed to enhance performance in solving the traffic assignment problem [7–9]. The Frank–Wolfe algorithm has also been implemented to solve large-scale problems [10,11] since it is a type of link-based algorithm that requires less memory during computation processes, and results in more stable solutions. The traditional Frank–Wolfe algorithm has been extended to overcome its inefficiency in convergence near the optimal solution [12–14]. Later, the path-based disaggregated simplicial decomposition algorithm was investigated by Larsson and Patriksson [15], and was then improved as the gradient projection algorithm by Jayakrishnan et al. [16]. Bar-Gera [17] and Dial [18] proposed the origin-based assignment algorithm to solve the traffic assignment problem.

Traffic assignment problems for freight shipment demand have been studied mostly in the fields of civil engineering and operations research. Crainic et al. [19] proposed a multi-commodity flow model and a heuristic algorithm to investigate freight traffic routing, train service scheduling, and allocation of classification work between yards in a rail network in Canada. Agrawal and Ziliaskopoulos [20] constructed a dynamic freight assignment model based on an iterative variational inequality formulation in the freight industry, including both shippers and carriers. The authors proposed a user equilibrium principle for shippers’

behavior such that each shipper tries to minimize his/her costs by selecting carriers with the lowest shipping costs, which eventually leads to market equilibrium. Hwang and Ouyang [21] investigated the rail freight shipment network assignment problem using the national U.S. rail network data. The authors constructed a modified convex combinations algorithm considering undirected links between two nodes in the rail network. Freight shipment demand assignment has also been applied in various ways. For example, Winebrake et al. [22] suggested a geospatial model based on an intermodal network that considers rail, road, and waterway networks as its components. Since the total cost along the given route is determined by various factors including travel time, distance, and emissions (e.g., carbon dioxide or particulate matter), as well as costs incurred by transshipments at intermodal terminals, decision-makers are able to investigate the tradeoffs among different route choices associated with different objectives (e.g., finding the path with the shortest travel time or that causes the lowest carbon dioxide emissions). Hwang and Ouyang [23] investigated a stochastic freight truck routing problem in which vehicle travel time, various vehicle emissions, and penalties for late or early arrival are incorporated into the total cost. A dynamic programming approach and deterministic shortest path heuristics were presented to conduct numerical tests based on U.S. urban networks. More recently, Lee and Hwang [24] constructed a large-scale freight truck routing model to investigate a regional freight shipment problem and its relationship to environmental issues, such as greenhouse gas emissions. A set of case studies was provided to estimate total freight delivery costs and associated vehicle emissions in 22 major metropolitan areas in the United States.

As such, the previous work developed a number of solution algorithms to the traffic assignment problem and presented their application to various research fields. However, the networks considered in the previous efforts are mostly small or medium in size, for instance, transportation networks established from city-level or state-level traffic demand zones. In this study, multiple O-D freight demands are loaded onto the full-scale U.S. interstate highway network to minimize the travel time of each freight truck. The complete freight truck shipment database for the continental United States is applied in the proposed model. The existing background traffic flow on the U.S. highway network was obtained from real-world data and incorporated into the model to enhance the accuracy of the results. The convex combinations algorithm requires a solution of a simple linear program at every iteration of the direction-finding procedure, and the obtained solution is always included in the feasible set [4]. Due to its computational efficiency compared to other competing methods in solving the user equilibrium program, the convex combinations algorithm was applied in this study. This process yields optimal freight truck flow on each link of the network that experiences the minimum path cost between each O-D pair. Travel time delays caused by limited roadway capacity are considered to estimate congestion patterns and the assigned traffic volumes on each link in the network.

### 3. Freight Truck Shipment Demand Network Assignment

#### 3.1. Model Formulation

In general, there can be two different rules including user equilibrium and system optimum for route choices in a transportation network [4]. In the user equilibrium principle, we assume that carriers or shippers are able to acquire the total travel time for all combinations of travel routes for any O-D pair in real-time. Since they repeatedly tend to select the path with the minimum travel time, their shipment plans will eventually approach equilibrium, in which any transportation flow for a given O-D pair will have the same travel cost. In this study, the user equilibrium principle was applied in constructing the truck routes, since it represents actual drivers' behavior better than the system optimum principle.

The standard network assignment problem for freight truck shipment demand based on the user equilibrium principle can be constructed as follows. We primarily follow the definitions and notations in Sheffi [4]. Suppose that the graph representation of the roadway network,  $S(V, A)$ , is given, where  $V$  represents a set of nodes and  $A$  represents a set of directed links. Each highway link travel time (in hours) is assumed to follow

the Bureau of Public Roads (BPR) link cost function [4] modified to include the concept of background traffic volume to represent the traffic flow that already exists in a link, as follows:

$$t_a(\omega_a) = k_a \left[ 1 + \alpha_a \left( \frac{\omega_a + b_a}{C_a} \right)^{\beta_a} \right], \forall a \in A, \quad (1)$$

where  $k_a$  is free flow travel time (in hours) on link  $a \in A$ ;  $\omega_a$  and  $b_a$ , respectively, represent assigned and background traffic flow (in vehicles per hour) on link  $a \in A$ ;  $C_a$  is link capacity (in vehicles per hour), while  $\alpha_a$  and  $\beta_a$  are parameters at 0.15 and 4.0, respectively.

For each highway link  $a \in A$  in the network, we define decision variable  $x_a$  to describe traffic flow loaded on the link. Let  $O \subseteq V$  be a set of trip origins, and let  $D \subseteq V$  be a set of trip destinations. The set of all routes that connect origin node  $o \in O$  and destination node  $d \in D$  is denoted by  $R^{o,d}$ . Additionally, we define the shipment flow on any route,  $r \in R^{o,d}$ , as  $f_r^{o,d}$ , and the given traffic demand from origin  $o \in O$  to destination  $d \in D$  is denoted  $q_{o,d}$ . Finally, transportation flow on link  $a \in A$  is defined as  $x_a = \sum_{o \in O} \sum_{d \in D} \sum_{r \in R^{o,d}} f_r^{o,d} \delta_{a,r}^{o,d}$ , where  $\delta_{a,r}^{o,d} = 1$  if link  $a$  is included on route  $r \in R^{o,d}$ ; otherwise  $\delta_{a,r}^{o,d} = 0$ . Using the parameters and decision variables provided above, the network assignment model for freight truck shipment demand subject to the user equilibrium principle can be formulated as follows:

$$\text{minimize } \sum_{a \in A} \int_0^{x_a} t_a(\omega) d\omega, \quad (2)$$

$$\text{subject to } \sum_{r \in R^{o,d}} f_r^{o,d} = q_{o,d}, \forall o \in O, d \in D, \quad (3)$$

$$x_a = \sum_{o \in O} \sum_{d \in D} \sum_{r \in R^{o,d}} f_r^{o,d} \delta_{a,r}^{o,d}, \forall a \in A, \quad (4)$$

$$f_r^{o,d} \geq 0, \forall r \in R^{o,d}, o \in O, d \in D. \quad (5)$$

Objective function (2) minimizes the sum of link cost functions integrated over the link flow from zero to the decision variable,  $x_a$ . Constraints (3) impose a flow conservation principle such that the sum of the traffic flows across all combinations of routes that connect each O-D pair should be equal to the shipment demand between that O-D pair. Constraints (4) ensure the traffic flow on a link to be the sum of flows for all possible routes the given link belongs to. Finally, constraints (5) define nonnegative traffic flow for all possible routes.

### 3.2. Solution Algorithm

The convex combinations algorithm [6] has been widely used to solve the standard traffic assignment problem (2)–(5). The detailed step-by-step procedure in Sheffi [4] is adapted as follows:

- Step 0: Define tolerance  $\kappa \ll 1$ . Compute free-flow link travel time  $t_a^0 = t_a(0)$  for all links  $a \in A$ . Freight shipment demand for each O-D pair is loaded on the shortest travel time route using  $t_a^0$ . Let counter  $i = 1$  and network link flow  $x_a^i = x_a^1, \forall a \in A$ .
- Step 1: Recalculate link travel time  $t_a^i = t_a(x_a^i)$  for all network links based on the up-to-date link flow,  $x_a^i, \forall a \in A$ .
- Step 2: Freight shipment demand for each O-D pair is assigned to the updated shortest travel time routes based on  $t_a^i$  obtained in Step 1. Let the new auxiliary link flow be  $y_a^i, \forall a \in A$ .
- Step 3: Solve the following: minimize  $\sum_{0 \leq \beta_i \leq 1} \int_0^{x_a^i + \beta_i(y_a^i - x_a^i)} t_a(\omega) d\omega$  to obtain a control parameter  $\beta_i$ .

- Step 4: Compute link flow  $x_a^{i+1}$  using the following convex combinations equation:  $x_a^{i+1} = x_a^i + \beta_i(y_a^i - x_a^i)$ ,  $\forall a \in A$ .
- Step 5: Terminate the algorithm if the amount of change in the objective value is less than, or equal to, tolerance  $\kappa$  as defined in Step 0. Up-to-date link flow  $x_a^{i+1}$ , computed in Step 4, is the optimal solution; otherwise, define  $i \leftarrow i + 1$  and go to Step 1.

Following this algorithm, freight shipment demand for all O-D pairs can be assigned onto the U.S. highway network. Eventually, the travel time of all routes connecting each O-D pair will be equal, as long as they are loaded with freight shipment traffic. Additionally, the cost (i.e., the travel time) will be less than, or equal to, that of the routes on which no traffic is assigned.

#### 4. Case Study

The proposed model and the solution algorithm are applied to assign freight truck shipment demand for each O-D pair on the full-scale U.S. interstate highway network. Given the network assignment program, input that contains network geometry and freight shipment demand will be constructed. The program generates output that includes freight flow patterns between all freight shipment O-D regions and the estimated transportation costs in the given network.

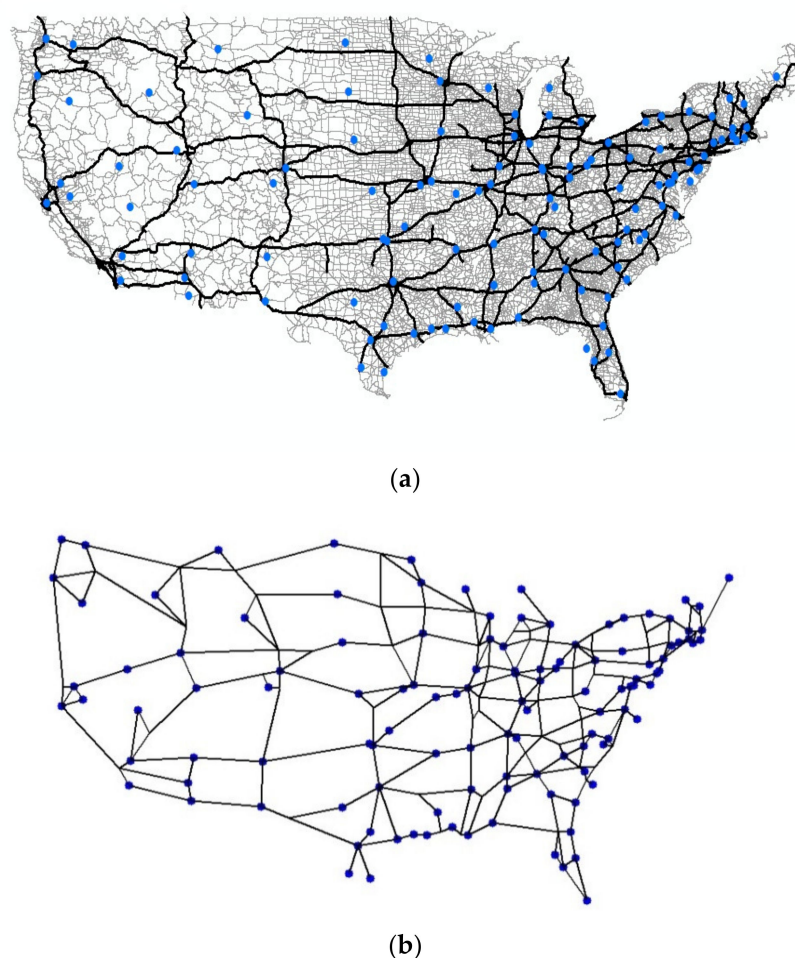
##### 4.1. Data Sources and Preparation

Input data need a graph representation of the freight truck road network, which includes an identification number for each link and node, the length and transportation capacity of each link, and background traffic volumes and free-flow travel times for each link. In this study, the geographical regions for freight activities were created using Freight Analysis Zone (FAZ) data defined in the Freight Analysis Framework version 3 (FAF3) database from the Federal Highway Administration [25]. We assume that both freight shipment origins and destinations are concentrated in the centroids of the FAZs in a network. Note that two zones in Hawaii and one zone in Alaska were excluded from the original database, and thus, a total of 120 FAZs are used for both origin and destination zones to generate 14,400 O-D pairs for this study.

To construct the U.S. freight truck road network, road geometry data from the FAF3 database were utilized, which also provided information on background traffic volumes and the transportation capacity of each link. There was a potential challenge in preparing the input data due to the huge size of the full freight truck road network, which consists of more than 170,000 links. Since we are analyzing freight truck activities from a macroscopic point of view, only major interstate corridors were considered so as to keep the network simple and tractable. This assumption is reasonable since long-distance inter-regional freight truck deliveries are mostly made by using major interstate highways.

Figure 1a presents the full-scale FAF3 freight truck road network [25] with the selected major interstate highways represented by thick black lines. Blue nodes in the figure represent the centroids of the 120 FAZs, and they are considered both origin and destination for freight truck shipments. Figure 1b shows the simplified freight truck road network. The FAZ centroids close to the major interstate highways or the junctions of different interstate highways are combined in the given network (distances of the removed links in this simplification are considered while executing the algorithm). For the FAZ centroids placed far from a major interstate highway network, some local roads in Figure 1a are included to connect those nodes to the given network. Finally, the complete network in Figure 1b contains 178 nodes (i.e., 120 FAZ centroids and 58 highway junctions) and 588 links altogether. Note that lengths of each link were directly measured from the ArcGIS platform.





**Figure 1.** The continental U.S. freight truck shipment network: (a) the entire FAF3 freight truck road network with 120 FAZ nodes [25]; and (b) the simplified U.S. highway freight truck road network.

The input data also contain freight shipment demand for all O-D pairs. In this study, real freight truck shipment demand data in 2007 were obtained from the FAF3 database. The original freight shipment demand data in terms of tonnage were recalculated into equivalent numbers of trucks that need to be loaded onto the network, assuming both class 7 and class 8 combination trucks are used for U.S. inter-regional freight deliveries. The average payload was estimated at 16 tons per truck [26,27], and passenger car equivalents were assumed to be 2.5, based on rolling terrain [28]. Lastly, free-flow vehicle speed was set at 65 mph [29], and freight truck delivery industries were assumed to run 365 days per year, 24 h per day.

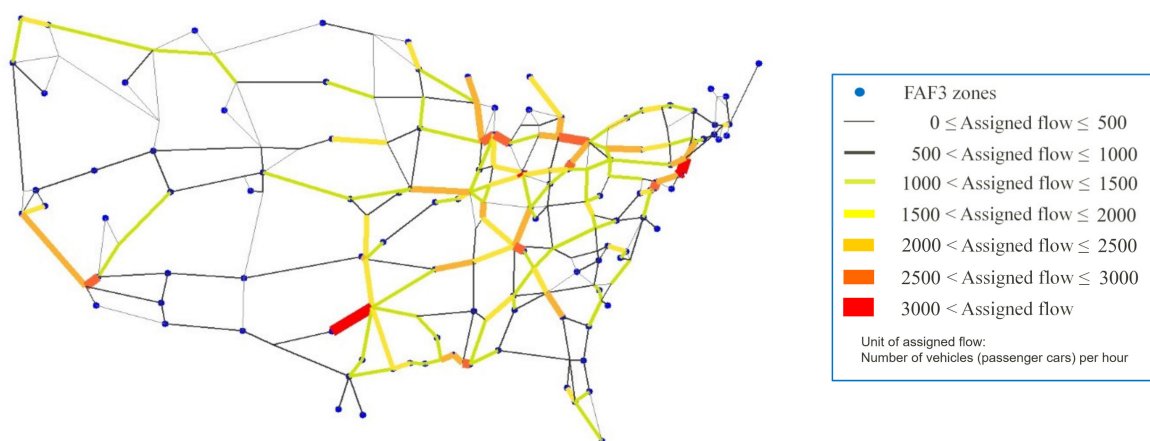
#### 4.2. Results and Discussion

The proposed algorithm was coded in VC++ and run on a PC with a 3.4 GHz CPU and 8 GB memory. To compute the total freight shipments in a given network each hour, total cost is defined in the form of total vehicle hours, as follows:

$$\begin{aligned} \text{Total cost} &= \sum (\text{Assigned vehicle flow on each link} \times \text{Travel time in each link}) \\ &= \sum_{a \in A} x_a \cdot t_a(x_a). \end{aligned} \quad (6)$$

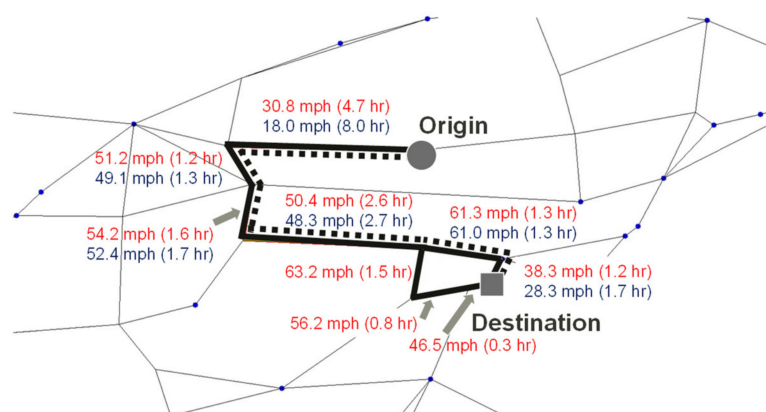
After 12 iterations and 0.640 s of CPU time, convergence was achieved within a tolerance of 0.0001%. The total cost under the user equilibrium principle was computed as 699,827.88 veh-h/h. Other important information, such as total and assigned traffic volume on each link, vehicle travel time, and average vehicle speed in each link at equilibrium, are also included in the output file. For comparison, each O-D freight shipment demand was assigned only to the shortest-distance path (i.e., an all-or-nothing assignment algorithm) ignoring congestion effects, and the total cost was calculated as 715,407.31 veh-h/h. Thus, drivers can reduce the total cost by 2.18% if user equilibrium is implemented.

Figure 2 presents the user equilibrium results from freight truck shipment demand network assignment. The sums of the assigned traffic flows on two links that connect the same pair of nodes in opposite directions are classified by various line thicknesses and colors as shown in the legend. We can observe large assigned traffic volumes and perhaps severe traffic congestion on some of the highway links in Washington, Montana, California, Nevada, Kansas, Texas, Florida, the mid-west states near Chicago, and the northeastern areas of the U.S.



**Figure 2.** Results of freight truck shipment demand network assignment under the user equilibrium principle.

Figure 3 illustrates a detailed result from a freight truck network assignment for one O-D sample pair in the data to provide insights into how routing equilibrium is reached. In Figure 3, the origin and destination of freight shipment demand are respectively represented by the circle and the square, which are “Remainder of Pennsylvania” and “Remainder of Maryland” in the original database. Other FAZ centroids are represented by small circles, and the network links are shown as thin lines. The result from the user equilibrium principle is described by a set of thick solid lines, and two different routes are computed for this O-D pair. For comparison, a set of thick broken lines denotes the selected links to be loaded with vehicles for the same O-D pair when the all-or-nothing assignment algorithm is applied. The numbers in red near each link represent average vehicle speed (in miles per hour) and link travel time (in hours) under the user equilibrium principle, while those in black denote the same information considering congestion effects when the all-or-nothing assignment algorithm is applied.



**Figure 3.** Detailed result from a network assignment for one O-D sample pair in the database.

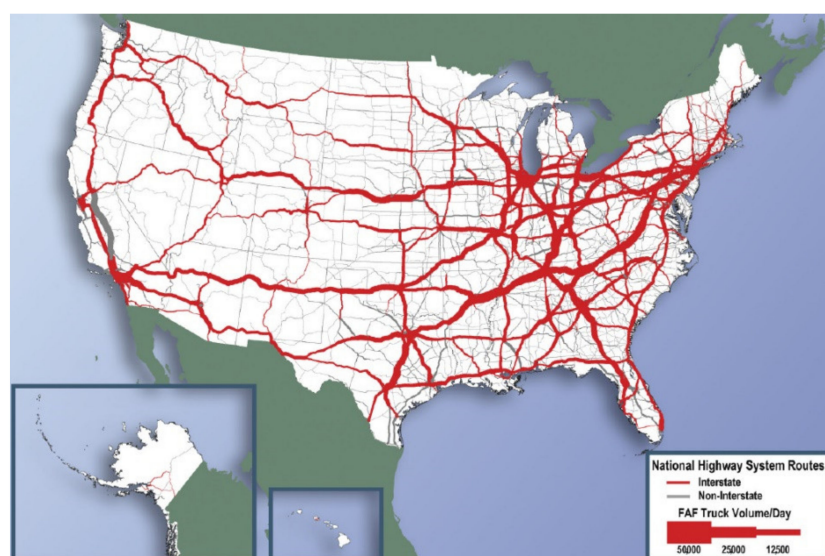
In this example, we assigned 218 vehicles per hour to the given O-D pair. When equilibrium is achieved, there are two possible routes for freight vehicles to use to reach the destination. Note that one route shows a slightly longer distance near the destination, compared to the other, due to congestion on the latter path under the user equilibrium principle. As a result, all motorists need to spend 16.7 h to reach the destination if the shortest distance is adopted (i.e., every O-D freight shipment demand is assigned only to the shortest distance path), while the travel cost for each truck driver is reduced to around 12.7 h (i.e., each driver can save an average 4.0 h) if the user equilibrium principle is implemented. Note that the primary benefit in terms of the total travel time occurs in the first link from the origin, where the motorists can reduce their travel time by 3.3 h when they follow the user equilibrium principle. While only 0.5 h of benefit could be observed at the link near the destination, and almost the same travel times are calculated along the other intermediate links. When the all-or-nothing assignment algorithm is executed, it was applied to not only the selected O-D pair sample in this example, but also the other O-D pair shipment demand. The first link mentioned above was found to be mostly used for freight shipment demand from the given origin to all destinations under the all-or-nothing assignment algorithm, which caused severe congestion and longer travel time at the link.

#### 4.3. Model Validation

In this section, model validation is performed to confirm the accuracy and reliability of the results obtained from the proposed model and the solution algorithm. According to the FAF3 [25], the total amount of freight truck shipments in 2007 in millions of ton-miles is estimated at 2,348,423. The network assignment model proposed in this paper resulted in 2,359,810 million ton-miles, which is almost the same as the value from the FAF3 (less than 1% gap).

Figure 4 adapted from Schmitt et al. [30] describes the average daily long-haul truck shipment volumes observed in the real world on the entire U.S. highway network. Traffic volumes on the highway network are illustrated with red lines at various thicknesses to show the amount of assigned daily truck flow in 2007. The figure shows a large amount of assigned traffic on many highway links in Washington, Oregon, California, Florida, the mid-west states near Chicago, and the northeastern parts of the U.S. This trend is generally consistent with the annual freight traffic distribution in the U.S. highway network obtained from the proposed model. The figure also shows high traffic flows on some main highway links that connect southern California, Arizona, and Oklahoma, which are less emphasized in the results shown in Figure 2. Such discrepancies could be caused by differences in input data on network structures and freight shipment demand between the proposed model and the research by Schmitt et al. [30]. Note that from a high-level perspective, the freight flow patterns obtained from the proposed model and the empirical data generally match.





**Figure 4.** Observed truck traffic flow on the U.S. highway system (adapted from Schmitt et al. [30]).

#### 4.4. Comparison between Truck and Rail Freight Shipment Costs

To illustrate the difference in shipment costs by truck and by rail for the same O-D pair, one data record that has both truck and rail freight shipment demand in 2007 was randomly selected. This record has “Remainder of Kentucky” as its origin and “Remainder of Georgia” as its destination. Truck freight demand was 60.06 vehicles per hour, or 384.38 tons per hour, and rail freight demand was 14.67 trains per day, or 49,900.13 tons per day. The total shipment cost by truck is obtained as 583.36 veh-h/h using Equation (6). For rail shipments, the equation for total shipment cost can be found in Hwang and Ouyang [21] and was computed at 512.88 train-h/day. Finally, the average shipment costs for both transportation modes can be defined as follows:

$$\text{Average shipment cost} = \text{Total shipment cost} / \text{Total freight demand}. \quad (7)$$

Since the units for total costs of truck and rail are different, average shipment cost was used as a normalized metric. In this example, the average shipment cost by truck is 9.71 h or 1.52 vehicle hours per ton, and by rail, it is 34.97 h or 0.01 train hours per ton, since the capacity of a train is much larger than that of a truck. This implies that a truck is a suitable mode for delivering time-sensitive or higher-value commodities, whereas rail is preferred for transporting heavy or bulk goods that are not sensitive to delivery times. The results and implications are consistent with the results derived by Hwang and Ouyang [31].

## 5. Conclusions

With the ever-increasing demand for freight shipments, transportation planners need to estimate nationwide freight movement between geographical regions by freight trucks, since they provide the largest portion of total freight movements in the United States. Efficient freight truck logistics systems are essential for sustainable growth in the U.S. economy, since they comprise most of the hardware and software for transporting raw materials, as well as end products, in every entity in the supply chain.

In this paper, the procedures for freight truck shipment demand network assignment considering traffic congestion are discussed, and the results are explained in detail with illustrations. A fundamental traffic assignment model with the convex combinations algorithm is proposed to solve the freight truck shipment assignment problem under the user equilibrium principle. The BPR link cost function was modified to capture the effect on link travel time for background traffic volumes that already exist on the U.S. highway network. An empirical case study was conducted using big data that contain the entire U.S. highway network and national freight shipment information in 2007. Convergence was

reached within a short computation time, and the optimal truck freight flow and congestion patterns were obtained. It was found that some of the highway links in Washington, Montana, California, Nevada, Kansas, Texas, Florida, the mid-west states near Chicago, and the northeastern areas of the U.S. are loaded with large amounts of freight shipment traffic. Since the link cost function is assumed to be monotonically increasing, we can expect severe traffic congestion in those regions. Model validations were conducted, and the congestion patterns resulting from the proposed model are found to be very close to those observed in the real world from a high-level perspective. Lastly, total and average freight shipment costs between truck and rail for the same O-D sample pair were computed to compare the characteristics of the two major freight transportation modes in the United States. The result implies that truck is preferred for delivering time-sensitive or high-value commodities and rail transport has its advantages for shipping heavy or bulk goods not sensitive to delivery times.

Future research is suggested as follows. First, background traffic flows on the highway network are assumed to be fixed in this study and not affected by route choices made by freight truck drivers. If general highway users represented by background traffic volumes are also able to determine the most efficient routes considering congestion patterns incurred by freight trucks, the results will reflect the impact of traffic congestion on the given highway network more precisely. Second, the results from the proposed model include a variety of information such as total traffic volumes on each link which includes background traffic as well as assigned truck traffic flows on the link, link travel time in hours, average vehicle speed, and freight ton-miles traveled on the link. Such information could be used to forecast freight flows and congestion patterns on the U.S. highway network assuming future freight shipment demand data are available. Furthermore, a long-term strategic infrastructure development plan such as highway capacity expansion scheduling and highway traffic sensor location design to enhance traffic safety could be possible using such information. Third, reduction in vehicle emissions and subsequent enhancement in human health could be achieved since it is well known that traffic congestion significantly affects the amount of vehicle emissions and the national air quality. Such problems could be alleviated by improvements in nationwide freight truck delivery systems. Lastly, model validation based on statistical analysis could be performed once real-world traffic flow data on each network link become available. Then, pairwise *t*-tests can be conducted to verify if there is any statistical difference at the link level between the results from the proposed model and the observed shipment flows.

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