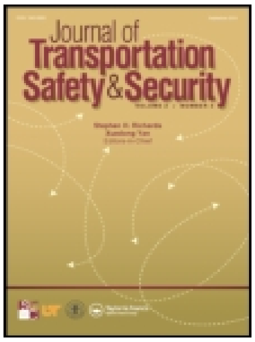

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Direct transportation economic impacts of highway networks disruptions using public data from the United States

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ABSTRACT

This article presents a sequential method to estimate the direct transportation economic impacts (DTEI) related to transportation due to disruptions in highway networks used by trucks and cars. The main input is the Freight Analysis Framework version 3, best public data for truck movements in the United States. The method considers multicommodity flows in an equilibrium framework, associates monetary values to changes in traffic conditions that are specific to each user type, and links truck flows with commodity flows. This approach can consider transportation analysis zones smaller than those presented in the Freight Analysis Framework. A real-world numerical example is presented to estimate the DTEI due to severe floods that occurred in 2008 and disrupted key segments of the highway network in the northwestern Indiana region.

KEYWORDS

freight analysis framework; disruptions; stochastic traffic assignment; OD estimation; commodity flow; traffic flow; trucks; cars; freight; economic analysis

1. Introduction

The identification and quantification of the economic and social impacts of disruptions is fundamental for sound transportation policy decisions. Network disruptions in their various forms cause direct and indirect affects that include route changes, driver frustration, fatalities, infrastructure destruction, and job and gross domestic product (GDP) losses. Indirect impacts are due to the inability of the network to recover after the disruption, for example, reduction in jobs, property values, commodity prices, and GDP, as well as long-term disruptions in supply chains, and increments in production costs, and so on. This work, however, focuses on analyzing the direct transportation economic impacts (DTEI) or changes in transportation operational costs. These impacts are significant because of the high value and volume of the commodities that has to be rerouted and the increment in

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travel times of rerouted passengers. Because the DTEI affect local and regional economies, quantifying them is important to strengthen transportation systems and develop sound policies for network recovery and mitigation of negative effects.

Although public agencies in the United States have sufficient and detailed information for the highway system and its underlying traffic, this is not the case for freight related data. In the United States the most recent public data for freight transportation is the Freight Analysis Framework version 3 (FAF3) (Batelle, 2011; Freight Management and Operations [FMO], 2012; Southworth et al. 2010, 20110). The FAF3 presents a set of transportation analysis zones (TAZs) that covers the United States, origin-destination (OD) matrices for 42 groups of commodities, and a corresponding highway network with traffic counts for trucks and cars. However, three limitations exist in developing models that quantify DTEI based on the FAF3. First, the demand for the 42 groups of commodities is given between highly aggregated TAZs. This is problematic when quantifying the DTEI of disruptions for more disaggregated TAZs systems. Second, the highway network presented in the FAF3 is quite detailed to be linked properly with the aggregated FAF3 TAZs, that is, FAF3 TAZs are too coarse, even for the level of aggregation of the FAF3 network (interstates, freeways, and some arterials). Finally, the flow of trucks at each link in the highway network is not disaggregated by commodity. The last two limitations impede the appropriate linkage between flows of commodities and vehicles, which is important in quantifying the direct economic impacts related to trucks with respect to the commodities transported.

The framework to estimate DTEI presented in this article incorporates FAF3 data and overcomes the aforementioned limitations (Figure 1). The demand in the study area (vehicles between zones) is used to obtain travel times associated to the base case (without disruption) and estimate total operational costs based on vehicle operational costs (VOC) and values of travel time (VT) for cars and trucks. After building a base case scenario, the network is disrupted based on the predefined disrupted scenario. New travel times and total operational costs are obtained to determine the magnitude of impacts. Indirect transportation-related economic impacts associated to other costs are out of the scope of this work.

This framework is a contribution to the current literature because it (1) integrates commodity and traffic flows in the estimation of DTEI, (2) considers multiple commodities, (3) is based on well-accepted traffic theories, (4) incorporates network effects rather than corridor analyses, and (5) is an alternative approach when regional input-output (I/O) data is not available.

This article is organized as follows: Section 2 presents a literature review of previous works and contrasts the contributions of the article. Section 3 presents a detailed framework that takes the advantage of the data presented in the FAF3 and overcomes their limitations. Section 4 presents a case study to

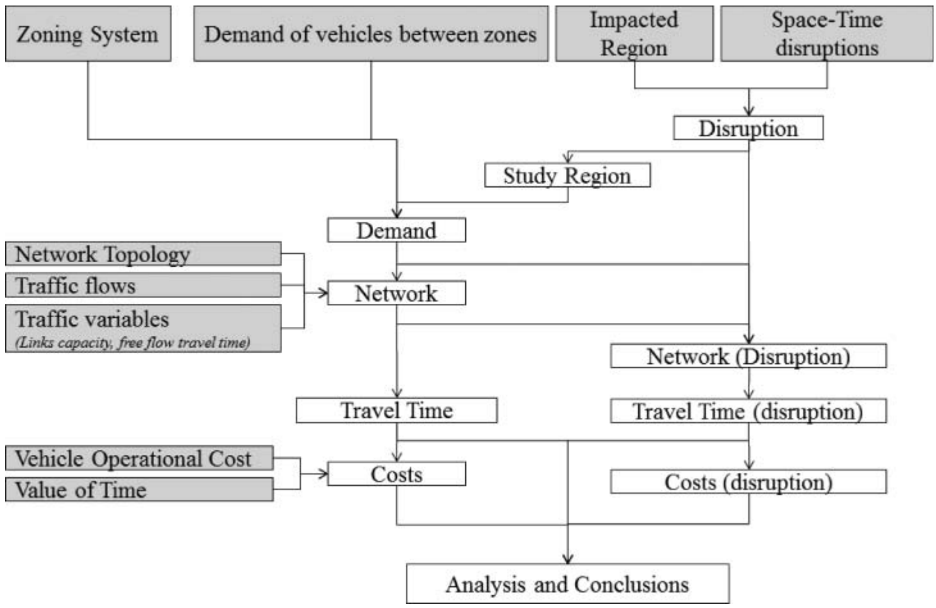


Figure 1. General framework for direct economic impacts.

quantify the direct economic impacts due to the severe 2008 floods in the northwestern Indiana region. Finally, Section 5 presents conclusions and future research directions.

2. Literature review

Several researchers have developed works to understand the effect of disruptions in the traffic network incorporating freight movements. The main ideas and limitations of these works are summarized in Table 1.

After reviewing previous literature, it is observed that network effects are not always considered because several works focus on corridor analyses. This is problematic because highway operations are not isolated, and impacts in the corridor have repercussions over the entire network. Some of the previous works consider only changes in the traffic flows but do not quantify the economic values associated with these changes, which is required for economic analysis. Many of these documents present models specific to truck traffic (vehicle movements) that do not consider commodity flows, which is important because economic impacts are associated to commodities and vehicles. Works that link traffic flows and commodities either make it for one commodity, or for multiple commodities but considering simple traffic-behavior assumptions, that is no user equilibrium or any other sound assumption. Finally, models that use regional IO information are not flexible enough to consider disaggregated TAZs and, with few exceptions, do not consider passenger flows (cars).

Table 1. Literature review summary.

Work	General Idea	Limitations
Adams et al. (2012)	Understating resilience of trucks for a traffic corridor.	Difficult to make conclusions on the economic effect that speed changes have with respect to multiple commodities.
Andreoli et al. (2012)	Using product specific data to estimate the number of trips affected by disruptions and quantify economic impacts.	Their analysis focuses on studying only one commodity (potatoes).
Kersh et al. (2012)	Identify interstate segments where trucks are rerouted due to disruptions and alternative routes.	No traffic equilibrium considered in the rerouting process. Traffic flows are not related to commodity flows.
Park et al. (2011)	Study state-specific and industry-specific economic impacts due to the rerouting of trucks.	Rerouting is simplified using shortest paths without considering congestion effects.
Burgholzer et al. (2013)	Analyze the impact of disruptions in intermodal transportation networks using agent-based simulation.	Competition between modes and users is not considered. Single commodity (containers) approach.
Okuyama et al. (1999); Kim et al. (2002); Sohn et al. (2004); Ham et al. (2005a, 2005b); Gordon et al. (2010)	Multi-regional input-output (IO) multicommodity flow models to assess direct and indirect economic losses of disruptions in transportation networks.	Regional IO information is hard to find for FAF3 TAZs and disaggregated TAZsEstimation trough surveys (Washington State Department of Transportation, 2008) is time consuming and not cost-effective. Integration of passenger trips is not clear.
Cho et al. (2001)	Considers both passengers and freight in an IO framework.	Underestimation of inbound/outbound traffics related to the study area, which is isolated from the rest of the US.

FAF3 = Freight Analysis Framework version 3; TAZ = transportation analysis zones.

This framework overcomes these limitations and hence contributes to the literature in the estimation of DTEI due to disruptions in traffic networks incorporating cars and trucks. The following section clearly presents the methodology of the article and explains the submodules that shape it.

3. Method

This section clearly defines the problem to solve, presents a global vision of the framework, and explains each constituent sub-module.

This work considers DTEI as the increment in VOC and VT of rerouting trucks and cars after network disruptions. Given the FAF3 data, a study area with disaggregated TAZs, and a disruption on the highway network, we are asked to quantify the daily DTEI for the disruption. Table 2 summarizes mathematical notation in the article.

3.1. *Framework*

Figure 2 presents the framework to solve this problem. The main inputs are FAF3, TAZs from planning (PA TAZs), disruption scenarios $\Phi \setminus \{0\}$, (Φ: all scenarios, $\{0\}$: base-case), VOC for cars ω_c and trucks w_t per vehicle-mile, value of time for cars ϑ_c and trucks ϑ_t, and average delay discount rate r^k for shipments of

Table 2. Mathematical notation.

Notation	Description
a	Constant used to scale the result from Equation 4 ensuring that the units of the parameters are consistent.
α_{ij}^k	Fraction of truck-flow associated to empty or commodity-specific loaded trips $(k \in K \cup \{e\})$ from the aggregated flow of trucks traversing arc $(i,j) \in A$.
$\beta_n(D_{ij})$	Truck allocation factor that converts τ_{ij}^k into $\mathrm{T}_{ij}^{k,n}$ according to the classification of D_{ij} into 5 distance ranges (0−50 miles, 50−100 miles, 100−200 miles, 200−500 miles, more than 500 miles). For $n \in \{1,\ldots,5\}$.
$\beta_n^{m,k}$	Truck equivalency factors that converts $T_{ij}^{k,n}$ into $\mathrm{T}_{ij}^{k,n,m}$. For$k \in K, n \in \{1,\ldots,5\}, m \in \{1,\ldots,9\}$
c_{ij}	Traffic flow capacity of arc$(i,j) \in A \cup \overline{A}$ (PCU/hour).
Δc_{ij}	Reduction of capacity for arc $(i,j) \in \Lambda^{\phi}$ because of disruption $\phi \in \Phi$.
C_{ij}	Demand of cars (PCU) from origin i to destination j. $i,j \in \overline{\mathcal{N}}$.
d\subset*ij*	Distance or length of the arc $(i,j) \in A$ (Miles).
D\subset*ij*	Shortest path distance between centroids $i,j \in \mathcal{N}$ (Miles).
e	Identifier representing the flow of empty trucks.
$\epsilon_h^{n,m}$	Empty truck factor that converts $\mathrm{T}_{ij}^{k,n,m}$ into $\mathrm{E}_{ij}^{k,n,m}$. For $n \in \{1,\ldots,5\}, m \in \{1,\ldots,9\}, h \in \{1,2\}$
$E_{ij}^{k,n,m}$	Demand of empty trucks associated to commodity $k \in K$, truck type $n \in \{1,\ldots 5\}$ and body type $m \in \{1,\ldots,9\}$ from origin i to destination j. $i,j \in \mathcal{N}$.
$\overline{\mathcal{E}}$	Set of centroids associated to exterior TAZs in the study area.$\overline{\varepsilon} \subset \overline{\mathcal{N}}$.
Φ	Set of scenarios considered in the analysis, where $\phi = 0 \in \Phi$ correspond to the base case scenario, and $\phi > 0 \in \Phi$ to the disruption scenarios.
G(*N*, *A*)	US highway network available in the FAF3. Composed by a set of nodes *N* and a set of arcs *A*.
$\overline{G}(\overline{N},\overline{A})$	Highway network in the study area. Composed by a set of nodes $\overline{N} \subset N \cup \overline{\mathcal{N}}$ and a set of arcs $\overline{A} \subset A \cup \{(i,j) : i \in \overline{N} \mid j \in \overline{N}\}$ associated to the scenario with no disruption $(\phi = 0 \in \Phi)$
$\overline{G}(\overline{N},\overline{\Lambda}^{\phi})$	Highway network in the study area affected by disruption $\phi \in \Phi \setminus \{0\}$. Composed by a set of nodes $\overline{N} \subset N \cup \overline{\mathcal{N}}$ and a set of arcs $\overline{A} \subset A \cup \{(i,j) : i \in \overline{N} \mid j \in \overline{N}\}$.
$\mathcal{I}$	Set of centroid nodes associated to the TAZs provided by planning agencies in the study area.
$\overline{\mathcal{I}}$	Set of centroids associated to interior TAZs in the study area. $\overline{\mathcal{I}} \subset \overline{\mathcal{N}}$.
K	Set of identifiers for the 42 commodities transported by truck in the FAF3. $K = \{1,\ldots,42\}$.
Λ^{ϕ}	Set of arcs in the highway network affected by the disruption in scenario $\phi \in \Phi$. $\Lambda \in \overline{A}$.
$\mathcal{N}$	Set of centroid nodes associated to the FAF3 TAZs. $\mathcal{N} \subset N$.
$\overline{\mathcal{N}}$	Set of centroid nodes associated to the interior and exterior TAZs in the study area. $\overline{\mathcal{N}} = \overline{\mathcal{E}} \cup \overline{\mathcal{I}}$.
r^k	Average delay discount rate for a shipment associated to commodity $k \in \mathrm{K} \cup \{\mathrm{e}\}$
s_k	Shipping inventory cost associated to the delay faced by commodity $k \in K$ per vehicle mile.
σ_{ij}^k	Value of the flow of commodity $k \in K$ shipped by truck from i to j (2007 US Dollars). $i,j \in \mathcal{N}$.
ζ^k	Average value of a truck shipment associated to commodity $k \in K$
τ_{ij}^k	Flow of commodity $k \in K$ shipped by truck from i to j (Tons). $i,j \in \mathcal{N}$.
T_{ij}^k	Demand of trucks (PCU) associated to empty or commodity-specific loaded trips $(k \in K \cup \{e\})$ from origin i to destination j. $i,j \in \mathcal{N} \cup \overline{\mathcal{N}}$.
$\mathrm{T}_{ij}^{k,n}, \mathrm{T}_{ij}^{k,n,m}$	Demand of trucks associated to commodity $k \in K$, truck type $n \in \{1,\ldots,5\}$ and, when applicable, body type $m \in \{1,\ldots,9\}$ from origin i to destination j. $i,j \in \mathcal{N}$.
$t_{ij}^{\phi}(z_{ij})$	Travel time in arc $(i,j) \in \overline{A} \cup A$ as a function of the flow z_{ij} traversing it in scenario $\phi \in \Phi$.
$\mathcal{T}_{ij}^{\phi}$	Equilibrium travel time from origin i to destination j. $i,j \in \mathcal{N} \cup \overline{\mathcal{N}}$ in scenario $\phi \in \Phi$.
$\Delta\mathcal{T}_{ij}(\phi_1,\phi_2)$	Impact in travel time from origin i to destination j. $i,j \in \overline{\mathcal{N}}$ between scenarios ϕ_2 and ϕ_1.
θ	Error term parameter for stochastic user equilibrium.
u_{ij}	Free flow speed for arc $(i,j) \in A \cup \overline{A}$
ϑ_c, ϑ_t	Value of travel time for cars c and trucks t.
v^k	Average cargo value for a truck shipment associated to commodity $k \in K$
ω_c	Average unit vehicle operational costs for cars c per vehicle mile.
w_t	Average unit fixed vehicle cost (truck VOC excluding shipping inventory) associated to trucks t per vehicle mile.
x_{ij}	Flow of aggregated trucks (PCU) traversing arc $(i,j) \in A \cup \overline{A}$.
x_{ij}^k	Flow of trucks (PCU) associated to empty or commodity-specific loaded trips $(k \in K \cup \{e\})$ traversing arc $(i,j) \in \overline{A} \cup A$.
y_{ij}	Flow of aggregated passenger cars (PCU) traversing arc $(i,j) \in A \cup \overline{A}$.
Ψ^{ϕ}	Total operational costs associated to scenario $\phi \in \Phi$.
$\Delta\Psi(\phi_1,\phi_2)$	Direct economic impact between scenarios ϕ_2 and ϕ_1.
z_{ij}	Flow of aggregated traffic (PCU) $z_{ij} = x_{ij} + y_{ij} = \sum_{k \in K} x_{ij}^k + y_{ij}$ traversing arc $(i,j) \in \overline{A} \cup A$.

FAF3 = Freight Analysis Framework version 3; TAZ = transportation analysis zones; PCU: passenger car units.

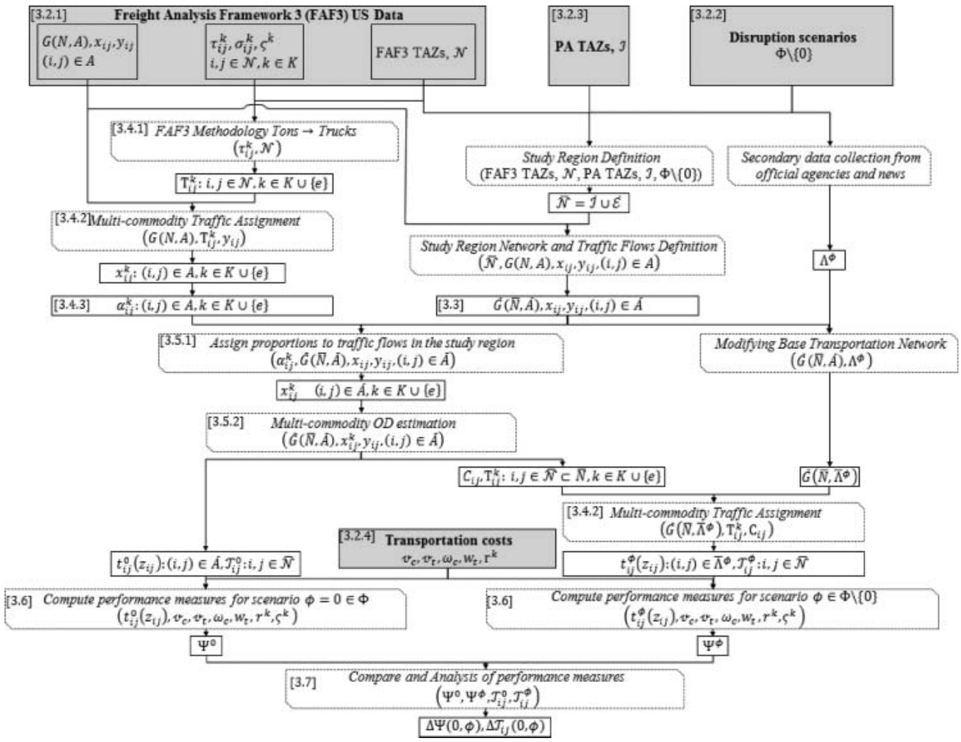


Figure 2. Detailed framework to estimate direct economic impacts of transportation network disruptions.

commodity $k \in K = \{1, \ldots, 42\}$ (commodities in FAF3). FAF3 is the most recent data for freight transportation analysis, but there are three challenges using it: (1) OD truck demand T_{ij}^k is estimated between very aggregated FAF3 TAZs $i,j \in \mathcal{N}$ ($\mathcal{N}$: set of FAF3 TAZs centroids), (2) the FAF3 highway network $G(N,A)$, (N: nodes, A: arcs) is too detailed to be properly linked to the nodes in $\mathcal{N}$, and (3) the flow of trucks x_{ij} at each arc $(i,j) \in A$ is not disaggregated by commodity type k or empty trips e.

This framework integrates methods to determine the proportions of trucks α_{ij}^k, defining a set of study TAZs (represented by centroids $\overline{\mathcal{N}} \subset \overline{N}$) and network $\overline{G}(\overline{N}, \overline{A})$, and assigning α_{ij}^k to available truck traffic counts x_{ij}, $(i,j) \in \overline{A}$. This allows the modeler to determine multicommodity flows x_{ij}^k, $(i,j) \in \overline{A}, k \in K \cup \{e\}$ useful to estimate base truck T_{ij}^k, $i,j \in \overline{\mathcal{N}}, k \in K \cup \{e\}$ and car C_{ij}, $i,j \in \overline{\mathcal{N}}$ OD matrixes, with their corresponding base operational costs Ψ^0 and OD travel times $\mathcal{T}_{ij}^0$, $i,j \in \overline{\mathcal{N}}$. Then, capacity reductions Δc_{ij} are applied to the arcs $(i,j) \in \Lambda^\phi$ ($\Lambda^\phi \subset \overline{A}$: disrupted arcs in scenario $\phi \in \Phi \setminus \{0\}$) to define the disrupted network $\overline{G}(\overline{N}, \overline{\Lambda}^\phi)$. Subsequently, T_{ij}^k and C_{ij} is assigned to $\overline{G}(\overline{N}, \overline{\Lambda}^\phi)$ to obtain the corresponding Ψ^ϕ and $\mathcal{T}_{ij}^\phi$. Ψ^0 and Ψ^ϕ are used to compute the DTEI ($\Delta\Psi(0,\phi) = \Psi^\phi - \Psi^0$). Likewise, $\mathcal{T}_{ij}^0$ and $\mathcal{T}_{ij}^\phi$ are used to determine impacts in travel time between TAZs.

The following subsections present details for the sub-modules that articulate this framework.

3.2. Inputs

The following subsections describe the main inputs of the framework.

3.2.1. Freight analysis framework version 3 (FAF3)

FAF3 presents data for eight modes, but only truck shipments are considered (given the scope of the article). The following data are available in the website of the office of freight management and operations (FMO, 2012): FAF3 TAZs, highway network $G(N, A)$ (with arc capacities c_{ij}, free flow speeds u_{ij}, truck x_{ij} and car y_{ij} flows), and OD matrices by volume of tons τ_{ij}^{k} and monetary value σ_{ij}^{k}, $k \in K = \{1, \ldots, 42\}, i, j \in \mathcal{N}$.

Figure 3 illustrates the FAF3 TAZs and $G(N, A)$ and highlights three difficulties for transportation modeling: (1) The level of aggregation between FAF3 TAZs and $G(N, A)$ makes unclear the assignment of vehicles resulting from τ_{ij}^{k}, $i, j \in \mathcal{N}$ to $G(N, A)$, (2) some states are represented by only one FAF3 TAZs (too coarse for disaggregated analysis), (3) for some states represented by several FAF3 TAZs, they are disconnected or the corresponding centroids fall inside different FAF3 TAZs. This primary addresses aggregation issues (1 and 2). Issue 3 is out of scope and requires further attention by FAF3 developers.

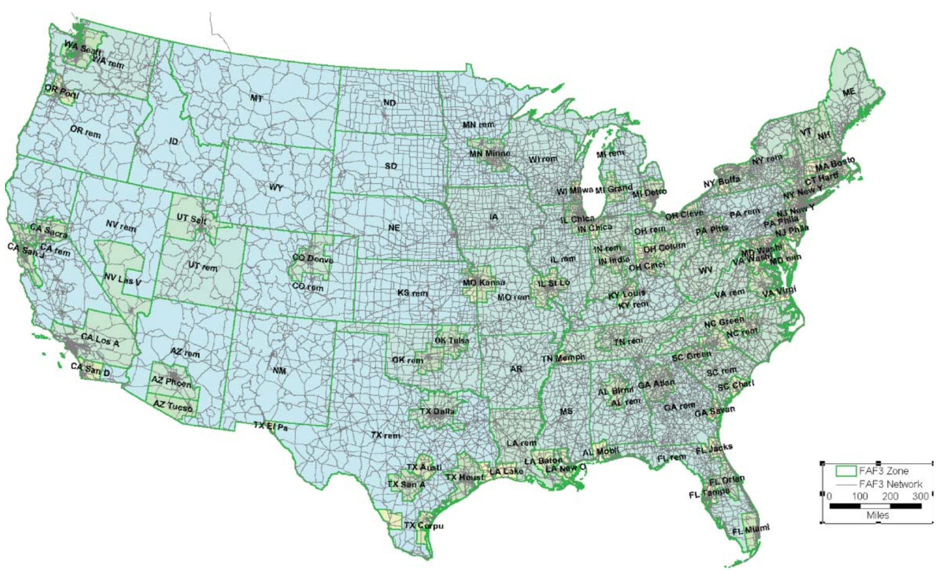


Figure 3. Freight Analysis Framework version 3 Transportation Analysis Zones and highway network $G(N, A)$. Developed with public data from the Freight Management and Operations (2012) website.

The ideal case for estimating DTEI in disaggregated areas is having traffic flows (cars and trucks by commodity type) in a detailed network because the VT and VOC (shipping inventory cost when applicable) are differ between user types. However, this cannot be obtained directly from FAF3 data and motivates the development of this framework.

3.2.2. *Disruption scenario*

A clear definition of the disruption scenarios $\Phi \setminus \{0\}$ is required for DTEI estimation, which are associated to different factors, for example, natural disasters, traffic accidents, or planned attacks. A disruption $\phi \in \Phi \setminus \{0\}$ is related to capacity reductions $\Delta c_{ij},\ (i,j) \in \Lambda^{\phi}$ over a subset of arcs in the highway network (Λ^{ϕ}) over a time period (modeling period).

The locations of the disruptions define the extent of the study area, and corresponding TAZs (represented by centroids $\overline{\mathcal{N}}$) and transportation network $\overline{G}(\overline{N}, \overline{A})$.

3.2.3. *Transportation analysis zones from planning agencies in the region*

Disrupted arcs $(i,j) \in \Lambda^{\phi}$ are easily associated to FAF3 TAZs. However, additional TAZs are required for disaggregated analysis. They can be provided by planning agencies (PA) in the study area. These PA TAZs are related to centroids $\mathcal{I}$ for analysis and used to define the study area, that is, $\overline{\mathcal{N}}$ and $\overline{G}\left(\overline{N}, \overline{A}\right)$.

3.2.4. *Vehicle operation costs and value of time*

Computing DTEI requires converting traffic flow delays into monetary values. Traffic operation costs for cars c and trucks t are affected by the value of user's time ϑ_c, ϑ_t, vehicle operational costs ω_c, w_t and shipping inventory cost r^k associated to commodity $k \in K \cup \ \{e\}$.

Values of time (VT) (tradeoffs that different users are willing to make for their travel time) are captured by ϑ_c and ϑ_t. They are obtained from secondary sources, for example, Forkenbrock and Weisbrod (2001), and properly updated using inflation factors.

Vehicle operational costs (VOC) consist of fixed vehicle costs (e.g., fuel, tires, maintenance, repairs, and mileage-dependent depreciation) and shipping inventory in freight transportation. Fix costs for cars and trucks are captured by ω_c and w_t. These values are obtained from secondary sources, for example, Sinha and Labi (2007), and properly updated using inflation factors. The shipping inventory cost incurred by delays of commodity $k \in K \cup \ \{e\}$ is captured by the average delay discount rate r^k obtained from secondary sources, for example, Winston and Chad (2004).

3.3. *Network and traffic flow in the study area*

The coverage of the study area is defined by (1) the area affected in each scenario $\Phi \setminus \{0\}$, (2) surrounding FAF3 TAZs, (3) PA TAZs in the region (represented by centroids $\mathcal{I}$), and (4) proper connectivity between the FAF3 network $G(N, A)$ and $\mathcal{I}$.

Internal (affected area and corresponding FAF3 TAZ) and external (surroundings) TAZs are defined using these criteria. They are associated to centroids $\overline{\mathcal{N}} = \overline{\mathcal{I}} \cup \overline{\mathcal{E}}$ ($\overline{\mathcal{I}}$: internal, $\overline{\mathcal{E}}$: external).

Internal TAZs (related to $\overline{\mathcal{I}}$) are created aggregating PA TAZs such that (1) similar socioeconomic characteristics are maintained; (2) TAZs are continuous, ideally convex, and not too elongated; (3) direct connectivity to $G(N, A)$ is guaranteed; and (4) natural and political boundaries are maintained.

External TAZs (related to $\overline{\mathcal{E}}$) are defined outside the boundary of the study area to represent outbound, inbound, and crossing flows. They allow traffic to deviate from the affected study area if this is a better option.

The corresponding centroids $\overline{\mathcal{N}}$ are connected to the highway network $\overline{G}(\overline{N}, \overline{A})$ (a subnetwork of $G(N, A)$) covering the impacted area and surrounding environment such that $\overline{N} \subset N \cup \overline{\mathcal{N}}$, $\overline{\mathcal{N}} \subset \overline{N}$, $\overline{A} \subset A \cup \{(i,j) : \ i \in \overline{\mathcal{N}} \mid j \in \overline{\mathcal{N}}\}$, $\left\{(i,j) : i \in \overline{\mathcal{N}} \mid j \in \overline{\mathcal{N}}\right\} \subset \overline{A}$ (centroid connectors). Arcs $(i,j) \in \overline{A} \subset A$ inherit the corresponding attributes $c_{ij}, u_{ij}, x_{ij}, y_{ij}$. For centroid connectors $(i,j) \in \left\{(i,j) : i \in \overline{\mathcal{N}} \mid j \in \overline{\mathcal{N}}\right\} \subset \overline{A}$, $c_{ij} \leftarrow M, u_{ij} \leftarrow M, x_{ij} \leftarrow 0, y_i j \leftarrow 0$ where M is a sufficiently large number.

3.4. *Proportion of trucks in each link per commodity*

Having the flow of trucks x_{ij}^k disaggregated per commodity type $k \in K \cup \{e\}$ in each link $(i,j) \in \overline{A}$ is ideal to compute the multicommodity DTEI. However, this is not available in the FAF3. Estimating x_{ij}^k requires to transform the OD flow of tons τ_{ij}^k (given in the FAF3) into OD flow of trucks for each commodity T_{ij}^k $(i,j \in \mathcal{N}, \ k \in K \cup \{e\})$, performing a multicommodity traffic assignment over $G(N, A)$ to estimate the proportion of trucks α_{ij}^k per commodity $k \in K \cup \{e\}$ in each link $(i,j) \in A$, multiplying α_{ij}^k and the known flow of trucks x_{ij}, $(i,j) \in \overline{A}$ to obtain multicommodity flows, i.e., $x_{ij}^k \leftarrow \alpha_{ij}^k x_{ij}$, $\forall (i,j) \in \overline{A}$, $\forall k \in K \cup \{e\}$.

3.4.1. *Conversion of tons into trucks (FAF3 Methodology)*

The conversion of tons τ_{ij}^k into trucks T_{ij}^k between FAF3 TAZs $(i,j \in \mathcal{N})$ is performed following the methodology presented in the FAF3 (see Battelle, 2011, for details). Table 3 summarizes the conversion steps. Step 1 computes a distance matrix D_{ij} between centroids $i,j \in \mathcal{N}$ based on arc distances d_{ij}, $(i,j) \in A \cup \mathcal{N}$. For each commodity $k \in K$, each OD pair $i,j \in \mathcal{N}$, and five truck types $n \in \{1, \ldots, 5\}$, Step 2 converts τ_{ij}^k into OD flows of trucks $\mathrm{T}_{ij}^{k,n}$ using truck allocation factors $\beta_n(D_{ij})$ that vary according to five distance ranges. Additionally, for nine truck body types $m \in \{1, \ldots, 9\}$, Step 3 converts $\mathrm{T}_{ij}^{k,n}$ into OD flows of trucks $\mathrm{T}_{ij}^{k,n,m}$ using truck equivalency factors $\beta_n^{m,k}$. Furthermore, for two types of operation $h \in \{1, 2\}$, Step 4 finds the empty trips $\mathrm{E}_{ij}^{k,n,m}$ corresponfing to $\mathrm{T}_{ij}^{k,n,m}$ using empty truck factors $\varepsilon_h^{n,m}$. Step 5 aggregates $\mathrm{T}_{ij}^{k,n,m}$ for each $i,j \in \mathcal{N}$ and $k \in K$ to obtain T_{ij}^k

Table 3. Pseudo-code for conversion of tons into trucks.

Step	Operation
1	$D_{ij} \leftarrow$ Shortest path matrix $\forall i,j \in \mathcal{N}$
2	$\mathrm{T}_{ij}^{k,n} \leftarrow \tau_{ij}^{k} \times \beta_n(D_{ij}), \forall i,j \in \mathcal{N}, \forall k \in K, \forall n \in \{1,\ldots,5\}$
3	$\mathrm{T}_{ij}^{k,n,m} \leftarrow \mathrm{T}_{ij}^{k,n} \times \beta_n^{m,k}, \forall i,j \in \mathcal{N}, \forall k \in K, \forall n \in \{1,\ldots,5\}, \forall m \in \{1,\ldots,9\}$
4	$\mathrm{E}_{ij}^{k,n,m} \leftarrow \mathrm{T}_{ij}^{k,n,m} \times \varepsilon_h^{n,m}, \forall i,j \in \mathcal{N}, \forall k \in K, \forall n \in \{1,\ldots,5\}, \forall m \in \{1,\ldots,9\}, \forall h \in \{1,2\}$
5	$\mathrm{T}_{ij}^{k} \leftarrow \theta\left(\sum_{n\in\{1\ldots5\}} \sum_{m\in\{1\ldots9\}} \mathrm{T}_{ij}^{k,n,m}\right) \forall k \in K, \forall i,j \in \mathcal{N}$
6	$\mathrm{T}_{ij}^{e} \leftarrow \theta\left(\sum_{n\in\{1\ldots5\}} \sum_{m\in\{1\ldots9\}} \sum_{k\in K} \mathrm{E}_{ij}^{k,n,m}\right) \forall i,j \in \mathcal{N}$
7	Return $\mathrm{T}_{ij}^{k}, \ \forall k \in K \cup \{e\}, \forall i,j \in \mathcal{N}$

and Step 6 aggregates $\mathrm{E}_{ij}^{k,n,m}$ for each $i,j \in \mathcal{N}$ to obtain T_{ij}^{e}. Notice that a conversion factor θ is used to transform trucks into PCU. The output of this procedure is $\mathrm{T}_{ij}^{k}, \ \forall k \in K \cup \{e\}, \forall i,j \in \mathcal{N}$.

3.4.2. *Multicommodity traffic assignment*

Multi-commodity traffic assignment is used to estimate flows of trucks x_{ij}^{k} in each link $(i,j) \in A$ for commodity $k \in K \cup \{e\}$ based on two inputs: $\mathrm{T}_{ij}^{k}, \ \forall k \in K \cup \{e\}, \forall i,j \in \mathcal{N} \subset N$ and $G(N,A)$. Because the flow of cars $y_{ij}, \ \forall (i,j) \in A$ is given, it is used as preload traffic in the assignment. Multicommodity traffic assignment is a common procedure available in commercial software and approached by several researchers in the past (Caliper Corporation, 2007; Cascetta, 2001; Partriksson, 1994; Sheffi, 1985).

Notice that the total flow from this assignment might not be equal to the total flows given in the FAF3 data, that is, $\exists (i,j) \in A : \sum_{k \in K \cup \{e\}} x_{ij}^{k} \neq x_{ij}$, because x_{ij} are obtained from an ad hoc procedure (Battelle, 2011) that is proprietary information of the FAF3 developers and is not available to the public. However, this is the best possible approximation sufficient to continue with the next steps.

Notice that a more detailed multicommodity traffic assignment is performed for each scenario $\phi \in \Phi \setminus \{0\}$ in subsequent steps. In this case the network used is $\overline{G}(\overline{N}, \overline{\Lambda}^{\phi})$, the demand is given by $\mathrm{T}_{ij}^{k}, \ \mathrm{C}_{ij}, \ \forall k \in K \cup \{e\}, \forall i,j \in \mathcal{N} \subset N$ and there is no preload y_{ij} because the flow of cars is reassigned according to the disruption ϕ. This step associates each arc $(i,j) \in \overline{\Lambda}^{\phi}$ with a traversing travel time $t_{ij}^{\phi}(z_{ij})$ which is a function of the total traffic flow $z_{ij} = \sum_{k \in K} x_{ij}^{k} + y_{ij}$ and can be used to compute VT and VOC for the scenarios with disruptions $\phi \in \Phi \setminus \{0\}$. Another important output is the corresponding OD equilibrium travel times $\mathcal{T}_{ij}^{\phi}, \ i,j \in \overline{\mathcal{N}}$, which are useful to understand the impact in accessibility between different TAZs.

3.4.3. *Proportion of trucks in each link per commodity*

The output of the previous step, i.e., $x_{ij}^k,\ \forall k \in K \cup \{e\}, \forall (i,j) \in A$, is used to compute the proportion $\alpha_{ij}^k,\ \forall k \in K \cup \{e\}, \forall (i,j) \in A$ as presented in Equation 1.

$$\alpha_{ij}^k \leftarrow \frac{x_{ij}^k}{\sum_{h \in K \cup \{e\}} x_{ij}^h},\quad \forall (i,j) \in A,\ k \in K \tag{1}$$

For arcs $(i,j) \in A$ where $\sum_{h \in K \cup \{e\}} x_{ij}^h = 0$ α_{ij}^k cannot be directly computed. If $(i,j) \in A \setminus \overline{A}$, this is not a problem because they are not considered in the analysis. Else, for arcs $(i,j) \in \overline{A}$ a special procedure to obtain α_{ij}^k is required and described below.

3.5. *Multicommodity OD estimation in the study region*

This subsection estimates the OD matrices per commodity type (and empty trips) in the study region $\mathrm{T}_{ij}^k,\ i,j \in \overline{\mathcal{N}}, k \in K \cup \{e\}$ by properly assigning α_{ij}^k to obtain $x_{ij}^k,\ (i,j) \in \overline{A}$, using these flows and the flows of cars $y_{ij},\ (i,j) \in \overline{A}$ in a multicommodity OD estimation between centroids $\overline{\mathcal{N}}$, and finally obtain vehicle OD matrices per vehicle type, i.e., cars C_{ij} and trucks T_{ij}^k for $i,j \in \overline{\mathcal{N}}, k \in K \cup \{e\}$.

3.5.1. *Assign proportions α_{ij}^k to the traffic flows in the study region*

For arcs $(i,j) \in A$ where $\sum_{k \in K \cup \{e\}} x_{ij}^k = 0$, Equation 1 cannot be estimated. Therefore, the proportions for these links are assigned following the modeler's criteria and giving continuity to the values of α_{ij}^k in the adjacent links. Then, Equation 2 is used to compute the corresponding $x_{ij}^k,\ k \in K \cup \{e\}, (i,j) \in \overline{A}$.

$$x_{ij}^k \leftarrow \alpha_{ij}^k x_{ij},\quad \forall (i,j) \in \overline{A}, k \in K \cup \{e\} \tag{2}$$

3.5.2. *Multicommodity OD estimation*

5w?>Multicommodity OD estimation is a common procedure available in commercial transportation software and approached by several researchers in the past (Caliper Corporation, 2007; Nielsen 1993, 1998). The outputs of this procedure are OD matrices for cars C_{ij} and trucks $\mathrm{T}_{ij}^k,\ k \in K \cup \{e\}$ between internal and external zones $i,j \in \overline{\mathcal{N}}$. Likewise, this step associates each arc $(i,j) \in \overline{A}$ with a traversing travel time $t_{ij}^0(z_{ij})$ which is a function of the total traffic flow $z_{ij} = \sum_{k \in K} x_{ij}^k + y_{ij}$ and can be used to compute the total VT and total VOC in the base case $\phi = 0 \in \Phi$. Other important outputs are the OD equilibrium travel times $\mathcal{T}_{ij}^0,\ i,j \in \overline{\mathcal{N}}$ useful to understand accessibility impacts.

3.6. Computation of performance measures for scenario $\phi \in \Phi$

This step is performed after multicommodity OD estimation for $\phi = 0 \in \Phi$ and after multicommodity traffic assignment for $\phi \in \Phi \setminus \{0\}$. The main input required from these procedures are $t_{ij}^{\phi}(z_{ij}),\ \ \forall \phi \in \Phi,\ \forall (\mathrm{i,j}) \in \overline{\mathcal{A}} \subset \overline{A}$, where $\overline{\mathcal{A}}$ is the set of arcs covered by internal TAZs in the study area (related to $\overline{\mathcal{I}}$). Other inputs are $\vartheta_c, \vartheta_t, \omega_c, w_t, r^k$ (previously defined), and average value of a truck shipment ζ^k for $k \in$ K. Notice that for empty trips $r^e = \zeta^e = 0$. Average values of ζ^k can be obtained from the FAF3 inputs as $\zeta^k = \sum_{i,j \in \overline{\mathcal{N}}} \sigma_{ij}^k / \sum_{i,j \in \overline{\mathcal{N}}} \tau_{ij}^k,\ \ k \in K$.

For the estimation of total VT and VOC the methodology discussed by Sinha and Labi (2007) in chapters 5 and 7 is followed. The total VT for scenario $\phi \in \Phi$ is given by Equation 3.

$$VT = \sum_{(i,j) \in \overline{\mathcal{A}}} \left[\left(\vartheta_c y_{ij} + \vartheta_t \sum_{k \in K \cup \{e\}} x_{ij}^k \right) \times t_{ij}^{\phi}(z_{ij}) \right] \tag{3}$$

The total VOC combines fixed costs (cars and trucks) and shipping inventory cost (trucks). The estimation of per vehicle mile shipping inventory costs s_k are based on American Association of State Highway and Transportation Officials (2003), which considers the shipment value ζ^k, the discount rate for commodity r^k, and the link travel speed $d_{ij} \ / \ t_{ij}^{\phi}(z_{ij})$ (Equation 4).

$$s_k = a \cdot r^k \cdot \zeta^k \cdot [d_{ij} / t_{ij}^{\phi}(z_{ij})]^{-1} \tag{4}$$

A proper daily discount rate (based on Winston & Chad, 2004) is related to each commodity and applied in Equation 4. The constant a is used to scale the results ensuring that the units of the parameters are consistent in the computation. Equation 5 estimates the total VOC for a scenario $\phi \in \Phi$.

$$VOC = \sum_{(i,j) \in \overline{\mathcal{A}}} \left(\omega_c y_{ij} + \sum_{k \in K \cup \{e\}} w_t x_{ij}^k \right) \cdot d_{ij} + \mathrm{C} \cdot \left(\sum_{k \in K \cup \{e\}} r^k \zeta^k \right) \cdot x_{ij}^k t_{ij}^{\phi}(z_{ij}) \tag{5}$$

Finally, total operational cost associated to scenario $\phi \in \Phi$ is computed in Equation 6.

$$\Psi^{\phi} = VT + VOC \tag{6}$$

3.7. Comparison and analysis of performance measures

At this point the total transportation cost Ψ^0 associated to the base scenario $\{0\} \in \Phi$ and the total transportation cost Ψ^{ϕ} associated to the disrupted scenario $\phi \in \Phi \setminus \{0\}$ are estimated. The DTEI due to the disruption $\phi \in \Phi \setminus \{0\}$ is presented in Equation 7.

$$\Delta\Psi(0,\phi) = \Psi^{\phi} - \Psi^{0} \tag{7}$$

As a subproduct, accessibility impacts $\Delta\mathcal{T}_{ij}(0,\phi)$ related to the disruption $\phi \in \Phi \setminus \{0\}$ can be estimated using Equation 8, where $\mathcal{T}_{ij}^{\phi}$ is the equilibrium travel time from origin $i \in \overline{\mathcal{N}}$ to destination $j \in \overline{\mathcal{N}}$ in scenario $\phi \in \Phi$.

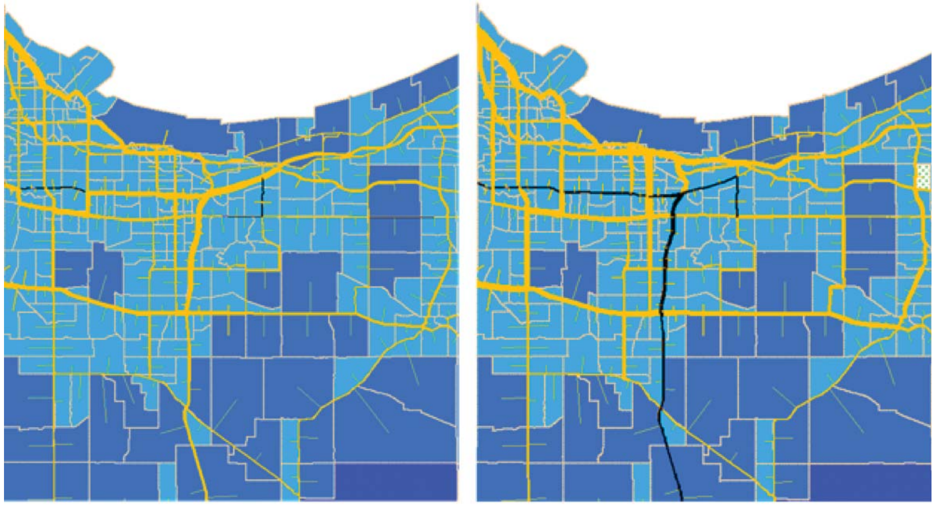
$$\Delta\mathcal{T}_{ij}(0,\phi) = \mathcal{T}_{ij}^{\phi} - \mathcal{T}_{ij}^{0} \tag{8}$$

4. Case study and results

In this section a study case is used to demonstrate the proposed framework. From 15 to 18 September 2008, a major flood forced close several highway segments in the northwestern Indiana region, including the important corridor Borman Expressway. The closure lasted 4 days, and freight and passenger traffic suffered serious disruptions. The proposed framework is applied here to estimate the DTEI due to this disruption.

The FAF3 commodity data ($\tau_{ij}^{k}, \sigma_{ij}^{k}, \zeta^{k}$), TAZs ($\mathcal{N}$), and highway network $G(N,A)$ can be downloaded from the FMO website (FMO, 2012) in TransCAD format. TransCAD is used for the case study, because it can perform several tasks presented in the framework, that is, manipulation of geographic information system (GIS) files, multicommodity traffic assignment, and multicommodity OD estimation. The disruption scenario associated to road closures is constructed by collecting records from the Indiana Department of Transportation (INDOT) and news articles from various local media. All roads closed by the disruption are identified (Λ^{ϕ}). Two disruption scenarios $\phi = 1, 2$ are prepared, because some segments of roads are closed in different time periods during the 4-day flood. Figure 4 illustrates these scenarios, where Scenario I ($\phi = 1$) shows the highways closed in the first day (black lines in Figure 4a) and Scenario II ($\phi = 2$) shows the highways closed in the other 3 days (black lines in Figure 4b). Detailed information about the road closures is presented in Table 4.

The PA TAZs used to construct the study area are provided by the Northwestern Indiana Regional Planning Commission (NIRPC). The final zoning system is defined after appropriate modification of the PA TAZs (Figure 5). The highway network $\overline{G}(\overline{N},\overline{A})$ (Figure 5), a subnetwork of $G(N,A)$, is used to perform traffic assignment and OD estimation. Multicommodity OD estimation described in subsection 0 is performed using TransCAD. Tests are performed to compare different configurations of the OD estimation. The results concluded that including the non-truck flow as a new commodity, and using stochastic user equilibrium (SUE) rather than user equilibrium (UE) achieves a better performance as the frequency of links



(a) Scenario I (b) Scenario II

Figure 4. Disruption scenarios (closed roads in black).

with small relative error is considerably high (Figure 6). The use of SUE is also consistent with Battelle (2011) that replicates the effect of imperfect information when drivers reroute to unfamiliar paths under disruptions.

For the base scenario ($\phi = 0$), high traffic volume is observed on the Borman Corridor (I-80, I-94, US 6, and part of US 41). Likewise, I-65 (northbound), I-90 close to Chicago, and U30 present high traffic volumes. Speeds in the study area range between 60 and 65 mph, and it is slightly higher in the southern part of I-65 and east side of I-94 and I-80 because of higher speed limit.

For the disruption in Scenario I ($\phi = 1$) the affected users of the closed segment of the Borman Corridor, that is I-80, have to reroute to adjacent roads to reach their destinations. Thus, considerable increment of traffic is observed on the segment of U6 adjacent to the closed segment, and its average speed decreases to 40 mph to 50 mph in the most congested segment, and 50 mph to 60 mph in the adjacent links. Out of these disruptions, the conditions of the rest of the network remain similar to the base case.

Table 4. Road closures for disruption scenarios.

Disruption Scenarios	Road Closures (Λ^{ϕ})	Length (miles)
Scenario I ($\phi = 1$)	I-80/94 between U.S. 41 and SR 912, Lake County	4.87
	SR 51 between U.S. 6 and Fairview in Lake Station, Lake County	2.59
	U.S. 6 between Wisconsin St. and SR 51 in Lake County	3.40
	U.S. 6 between SR 149 and Meridian Road in Porter County	4.84
Scenario II ($\phi = 2$)	I-80/94 (Borman Expressway) between SR 51 and Indianapolis Boulevard	15.47
	Northbound I-65 between SR 24 and I-80/94	65.52
	SR 51 between U.S. 6 and Fairview in Lake Station, Lake County	2.59
	SR 2 between I-65 and U.S. 231 in Lake County	5.23

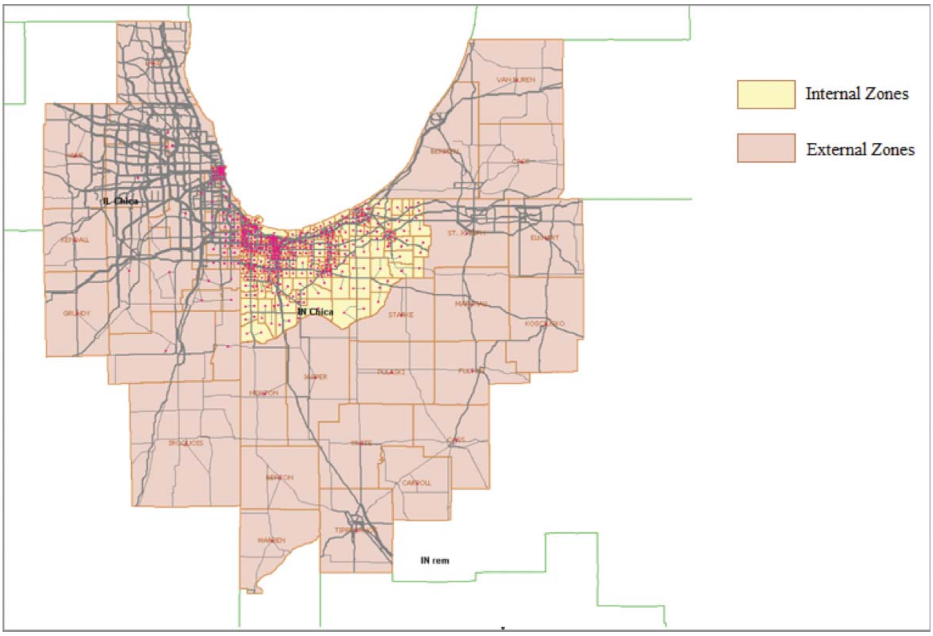


Figure 5. Transportation Analysis Zones and network for the study area.

In Scenario II ($\phi = 2$), a large number of segments are closed and significant changes in the flow patterns are observed. Due to the large closure on I-80, a considerable amount of flow reroutes to I-90. Additionally, the utilization of U6 and U30 increases. Closing the northbound direction of I-65 results in full utilization of several northbound links, for example, S49, S53, and S55. Speed reductions are significant in the surroundings of the affected area. Several most affected sections on the east part of U6, have their average speed decrease to 50 mph to 60 mph.

The VT and VOC (subsection 0) are computed considering the following cost values and properly updated using inflation factors: $\vartheta_c = \$21.344\ /\ vehicle{\cdot}mile$, $\vartheta_t = \$37.296\ /\ vehicle{\cdot}mile$, $\omega_c = ¢21.86\ /\ vehicle{\cdot}mile$, $w_t = ¢47.39\ /\ vehicle{\cdot}mile$, $r^k = 0.15\ /\ day$ for perishable commodities, $r^k = 0.05\ /\ day$ for bulk commodities, and $r^k = 0.10\ /\ day$ for other commodities.

The DTEI $\Delta\Psi(0, \phi)$ are calculated to quantify the effect of the disruption (subsection 0). Table 5 shows the cost composition for passenger cars and trucks within the internal zones in the study region. Under normal conditions, the total transportation costs is $\Psi^0 = \$62.797$ million. Disruptions in the first and subsequent 3 days increased this amount to $\Psi^{\{1\} \cup \{2\}} = \$87.420$ million, resulting in a total DTEI of $\Delta\Psi(0, \{1\} \cup \{2\}) = \$24.623$ million, which represents about a 40% cost increment of Ψ^0. Although the number of trips is higher for passenger cars than trucks, the impacts are higher for the latter due to the shipping inventory costs. The freight shipping inventory costs contributes to more than 60% of the total VOC.

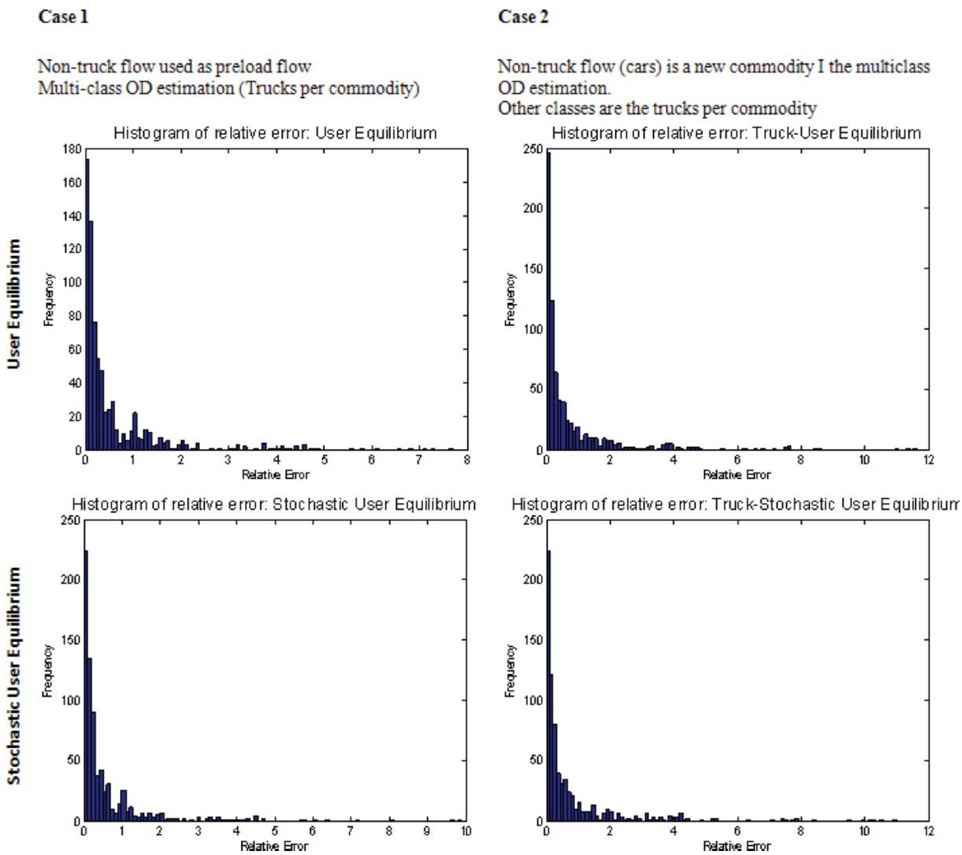


Figure 6. Multiclass origin-destinations estimation validation.

Table 5. Estimated direct cost for the internal zones in the study area (million dollars).

			Vehicle Operational Costs (VOC)			
Scenario	Vehicle Type	*VT*	Inventory	Fixed[(a)]	ψ_ϕ	$\Delta\psi(0,\phi)$
Base Case[b] $\phi = 0$	Passenger Car	$17.181	$—	$11.153	$28.334	$—
	Truck	$5.855	$23.807	$4.802	$34.464	$—
	Total	$23.036	$23.807	$15.955	$62.797	$—
Scenario I[c] $\phi = 1$	Passenger Car	$4.862	$—	$3.121	$7.983	$0.90
	Truck	$1.778	$7.191	$1.432	$10.401	$1.79
	Total	$6.640	$7.191	$4.553	$18.384	$2.68
Scenario II[d] $\phi = 2$	Passenger Car	$17.238	$—	$10.875	$28.113	$6.86
	Truck	$7.073	$28.281	$5.568	$40.923	$15.07
	Total	$24.312	$28.281	$16.443	$69.036	$21.94
Scenarios I & II[b] $\{\phi = 1\} \cup \{\phi = 2\}$	Passenger Car	$22.100	$—	$13.996	$36.096	$7.763
	Truck	$8.851	$35.473	$7.000	$51.324	$16.860
	Total	$30.951	$35.473	$20.996	$87.420	$24.623

[a]Total VOC excluding shipping inventory cost.
[b]Values for 4-day disruption.
[c]Values for 1-day disruption.
[d]Values for 3-day disruption.

One benefit of this study is that the inventory VOC allows quantifying the DTEI for different commodities transported in the study area. Table 6 presents the increment in inventory VOC due to the disruption for each commodity. The inventory VOC significantly increases for perishable commodities, (alcoholic beverages, other agriculture products, other foodstuffs, meat/seafood), high-value commodities (precision instruments, electronics, pharmaceuticals), energy-related commodities (crude petroleum, coals and fuel oils). On the other hand, bulk low-price commodities (nonmetallic minerals, wood products, gravel, natural sands, etc.) are

Table 6. Total inventory vehicle operational costs for internal zones in the study area by commodity (million dollars).

	Total Cost		
Commodity	Base Case	Scenarios I & II	% Increments
Alcoholic beverages	$0.159	$0.505	217.00
Waste/scrap	$0.139	$0.326	134.99
Precision instruments	$0.242	$0.514	112.87
Other agriculture products	$0.466	$0.952	104.36
Textiles/leather	$0.386	$0.768	99.05
Electronics	$1.535	$2.721	77.18
Other foodstuffs	$1.454	$2.567	76.63
Crude petroleum	$0.048	$0.082	72.70
Furniture	$0.381	$0.639	67.55
Pharmaceuticals	$1.307	$2.172	66.12
Fertilizers	$0.126	$0.204	61.15
Meat/seafood	$0.821	$1.303	58.71
Coal-n.e.c.	$0.358	$0.548	53.27
Mixed freight	$0.725	$1.097	51.39
Fuel oils	$0.054	$0.082	50.99
Milled grain prods.	$0.889	$1.336	50.38
Transport equip.	$0.159	$0.238	49.93
Motorized vehicles	$2.508	$3.706	47.76
Animal feed	$0.124	$0.183	47.59
Plastics/rubber	$1.230	$1.783	44.96
Articles-base metal	$0.484	$0.696	43.93
Machinery	$1.954	$2.806	43.64
Chemical prods.	$0.849	$1.204	41.85
Nonmetal mineral products	$0.179	$0.253	41.25
Printed products	$0.388	$0.527	35.76
Miscellaneousmanufacturing products	$0.958	$1.293	34.92
Paper articles	$0.356	$0.475	33.71
Gasoline	$0.382	$0.505	32.12
Nonmetallic minerals	$0.113	$0.149	31.40
Wood products.	$0.201	$0.261	29.72
Coal	$0.306	$0.392	27.83
Newsprint/paper	$0.541	$0.663	22.56
Gravel	$0.039	$0.047	20.36
Natural sands	$0.012	$0.015	19.00
Cereal grains	$0.228	$0.271	18.40
Basic chemicals	$0.672	$0.795	18.28
Base metals	$2.589	$2.917	12.68
Metallic ores	$0.220	$0.241	9.50
Building stone	$0.031	$0.034	8.85
Logs	$0.014	$0.015	6.27
Live animals/fish	$0.095	$0.101	6.20
Tobacco products	$0.083	$0.086	3.34

n.e.c. = Not elsewhere classified.

affected at a lower level. As shown in the results, the new methodology enables tracking the impact for each commodity sectors, such that a better understanding of the actual impact in freight transportation can be drawn.

5. Conclusions

This article presents a framework to quantify the DTEI of transportation network disruptions. It is important for decision makers to quantify the direct transportation operation costs due to natural disasters or planned attacks impacting the transportation network. This article models impacts for trucks and cars, because DTEI are different for cars and trucks and also different between commodities carried on trucks.

The framework developed in this article is based on the FAF3 data, which is the most recent and publicly available freight transportation data in US. As the level of aggregation in the FAF3 is too coarse for regional analysis. This framework transform multicommodity OD flows at the national level to multicommodity traffic flows and OD matrices at the regional level. The development of this disaggregation is achieved by sequentially execution of stochastic traffic assignment and OD estimation, which is essential to model multicommodity traffic flows. By modeling the redistribution of traffic flows in an equilibrium framework, the increments in travel time for each type of user due to rerouting and congestion are computed and associated to the corresponding values of time and vehicle operational costs.

This article contributes to the literature by considering the following features in a jointed methodology: (1) multicommodity flows in an equilibrium framework that incorporates network effects, (2) monetary values specific to each user type that are associated with the disruption, (3) linkage between truck and commodity flows. Additionally this work shows the potential of using FAF3 data in comprehensive freight transportation analyses. To conclude, we identify some limitations of this work and future directions. Currently, the internal and external zones in the study region are defined using data from planning agencies that based on sociodemographic characteristics. It is possible to improve the accuracy of the framework by using a regional zoning system that is consistent with the economic activities of the commodities. Additionally, the multicommodity traffic assignment and OD estimation models used in this work convert the flow of trucks to passenger car equivalents. This assumption can be improved by considering more realistic traffic flow models. The framework can be further improved if data for truck flows by commodity type is available to validate the multicommodity flows (currently only the total truck flow is available). Other direct impacts related to disruptions in supply chains, and logistics operations, for example, Wilson (2007), can be considered, which is more challenging given the multiplicity of actors, interactions, and objectives in supply chain networks. Finally, considering freight behavioral components can improve the accuracy of this modeling output, for example, competition among FAF3 modes, impact of disruptions in transshipment facilities, changes in user behavior, and activities resulting from the disaster (activity-based modeling). These topics are covered in future work.

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