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ORIGINAL PAPER

Highway freight transportation disruptions under an extreme environmental event: the case of Hurricane Katrina

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Abstract A safe, resilient, and sustainable transportation system for efficient freight flow is critically important to a nation's economy. A major disruption to the transportation system due to extreme natural or human disasters can significantly affect the freight movement in the system. The purpose of this research was to develop a general framework to study disruptions to freight flows under an extreme event and apply the framework to retro-analyze the impact of 2005 Hurricane Katrina to the freight movement on the US highway network using a geographical information system, assignment models, and performance measures. Freight movement dynamics prior to and after the disaster are analyzed using aggregated measures such as vehicle mile traveled and vehicle time traveled for different types of roads in urban and rural areas in the USA. This research shows that when a disaster occurs to a part of the highway transportation network, the freight flow changes are not only local, but also regional and national, indicating that applying solely distance-based methods to modeling flow disruption effects may not capture the whole picture. The research provides some insights for pre- and post-disaster decision makings that help lead to a resilient freight highway transportation system.

Keywords Freight transportation · Highway · Assignment · Disruption · GIS · Katrina

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Introduction

Highway transportation network is the dominant means for freight movement in the USA. Any disruption caused by a disaster to the freight movement on the US highway transportation network would generate negative impacts, including emergent evacuation of people, temporary closure of businesses due to delayed shipments of materials and merchandises, or postponed delivery of basic goods, such as food, water, medicine, or fuel, to the disaster-affected regions. This paper studies the disruptive impact of Hurricane Katrina on the US highway freight flow movement using an extreme event framework, aggregated flow measures, common assignment methods, and damage–recover scenarios for Katrina-affected regions and the entire USA. In this research, the disruptive impact is regarded as the changes of state-wide highway network freight flow vehicle miles traveled (VMT) and vehicle hours traveled (VHT) before and after Hurricane Katrina.

Hurricane Katrina, one of the costliest disasters in the US history, had serious negative impacts on the American highway system. In Louisiana, Mississippi, and Alabama, 45 bridges and extensive roadways were damaged (DesRoches 2006). The flooding from Katrina covered 80 % of New Orleans, the bull's eye of Katrina. New Orleans' unique geography and the City's collapsed levees and floodwalls all contributed to the severe damages to its highway networks and properties. In addition to these physical damages, Katrina also caused 1,836 direct and indirect deaths in Louisiana (1,577), Mississippi (238), and other states (21) and 135 missing in Louisiana alone (Beven et al. 2008). The total estimated economic loss caused by Katrina is estimated at $108 billion dollars (Blake et al. 2011).

Since freight flow interactions with the Katrina-affected areas are spread throughout the USA, this research is not only on highway networks in Louisiana, Mississippi, and Alabama, but also on the entire US highway transportation network. Origins and destinations (O–D) or network links located outside the Katrina-affected regions were assumed to have no supply–demand or capacity changes; otherwise, they would have partial or full supply–demand values or capacities corresponding to the damage/recovery scenarios—one for pre-disaster condition, two for bridge and roadway closures caused by floods, and four for recovery schedules at first, third, sixth months, and after 6 months. The New Orleans Metropolitan Statistics Area (MSA) node was closed with zero or reopened with full O–D production–attraction in freight flow assignment.

A major effort of this research is to develop a framework to study the impact of pre- and post-Katrina freight flows through the US highway network. At the core of the framework are flow assignments using the All-or-Nothing (AON) and User Equilibrium (UE) (Sheffi 1985) methods. These assignments are based on O–D centroids of MSAs or states and executed in TransCAD (Caliper 2010). In addition, aggregate performance measures—truck VMT and VHT—are designed to quantify total flow changes before and after Katrina.

This research shows that the largest freight flow disruptions occurred to network segments at the disaster locales. However, significant regional and national ripple effects can also be seen in the distribution of the freight flow over the entire US highway transportation network. For example, most southern parts of the USA took more than 6 months to recover, whereas the northeast regions recovered much faster. Hence, the major contribution of this research is its modeling scale, which helps reveal that the flow disruptive impact caused by a disaster is not restricted to the local disaster area only, as modeled in most existing publications on freight. Therefore, making decisions on pre-disaster preparation and post-disaster rescue freight shipping by just focusing on a local highway network would result in sub-optimal decisions. Another contribution of this paper is the general framework for transportation interruption assessment using aggregated performance measures (VHT and VMT) and recovery scenarios.

This paper starts with the "Introduction" section, which is followed by the "Materials and methods" section summarizing the relevant literature, modeling framework, freight databases, and the Hurricane Katrina. The freight flow dynamics and scenarios at the national and state levels are discussed in the "Results and discussion" section. Highlights of findings and some remarks conclude this paper. This research was conducted from 2010 to 2013 in Oklahoma, USA. It was a part of a series studies on state and national freight flow movement started in 2003.

Materials and methods

Literature review

The literature on the impact of extreme events (often disasters) on transportation systems is extensive. However, the publication on the effect of freight disruption caused by an extreme event in the highway transportation network is sparse. This situation is true even if in recent decades there is an upward trend of natural disaster occurrences (Haghani and Afshar 2009; Vos et al 2010), such as the 1994 Northridge earthquake in the USA, 1995 Kobe earthquake in Japan, 2005 May tornado in Oklahoma City, 2005 Hurricane Katrina in New Orleans, and various man-made disasters, such as the September 11, 2001 world trade center bombing in New York City and 2002 I-40 bridge collapse in Oklahoma.

One class of the current literature focuses more on the direct physical damages and reconstruction to the transport network or human casualty in the disaster-affected areas rather than on the network's flow disruptions and its effects at different scales. Another group of the existing research emphasizes on better estimations of social and economic impacts and losses (indirect costs) caused by disaster disruptions to the transportation system. The third category of available publications is on efficient delivery and re-routing to and from the disaster regions during and after a disaster. The fourth type of research is more on system-wide modeling endeavors, impact assessments, and policy strategies for a resilient transportation system, including the freight logistics component at local, regional, and national levels. Each of these broad categories will be briefly reviewed.

Damage and reconstruction

DesRoches (2006), in an edited report to American Society of Civil Engineers, provided extensive information on the transportation system's physical damage in Louisiana, Mississippi, and Alabama. The report lists the damaged 45 bridges and the damage levels on railroads and roadways, besides the detours. The bridge damage costs and engineering repair expenses from Hurricane Katrina were also reported by Padget et al. (2008). The authors observed the damage patterns to bridges and developed a relationship between storm surge elevation, damage level, and repair cost. They concluded that the damage to bridges in hurricane events occur due to storm surges, and designing on higher elevations or using simple design improvements could help mitigate damage and costs.

Reconstruction of the disrupted transportation network is critical due to its vital role in restoration of other lifelines. In reconstruction after an extreme event, which is different than retrofit management since the vulnerability of the network link is known, the disrupted link attributes, such as capacity, traffic volume, spatial location, as well as the attributes of rescue and freight trucks, need to be considered. Traffic demand often changes during and after the extreme event, in which situations may vary in time and scale, i.e., right after the event where only emergency vehicles might be allowed, at times when disrupted links are being recovered, and during occasions when only certain kinds of emergency vehicles or goods are allowed (Chang and Nojima 1998).

Reconstruction operations on transportation networks after an extreme event can be prioritized with different perspectives such as network connectivity (Basoz and Kiremidjian 1997), network reliability and traffic flow (Wakabayashi and Kameda 1992), travel delays (Nojima and Sugito 2000), accessibility based on distance decay functions or traffic volumes (Sohn 2006), and social criteria with travel times (Chang 2003).

Economic impact and loss

Transportation-related economic loss or impact caused by the 1994 Northridge earthquake is estimated by Gordon et al. (1998). The study concludes that about \$1.5 billion of the \$6.5 billion business interruption losses could be attributed to transportation, more specifically to bridge collapses and highway damages caused by the earthquake. Similar works can also be found in Cochrane (1997), Boarnet (1998), and Willson (1998). The 1995 Kobe earthquake in Japan generated a loss of about \$178 billion, equivalent to 0.7 percent of global gross production (Papadakis 2006).

Cho et al (2001) integrated a highway model with an Input–Output (IO) model for Los Angeles, Kim et al. (2002) developed a combined transportation network with a multi-regional IO model, and Okuyama et al (2004) originated a closed interregional IO model emphasizing distributional effects, which may be applicable to extreme events incurring drastic quarter-to-quarter changes like earthquakes. Recently, Haggerty et al (2008) developed a transportation-based IO framework enabling the examination of interdependencies among economic sectors and the effects of an extreme event on freight transport.

Levinson and Xie (2008) evaluated the effect of the I-35W Bridge (Minnesota, Mississippi) collapse using a gravity model and concluded that the collapsed bridge caused an sizable economic loss depending on the flexibility of travelers in adjusting their trip destinations.

Delivery and rerouting

Freight transportation plays an important role by delivering needed supplies and goods to disaster regions prior to, during, or after a disaster. In the case of Hurricane Katrina, the Department of Transportation marshaled more than 1,639 trucks to support the delivery of more than 3,731 truckloads of goods, including more than 25 million meals ready to eat, 31 million liters of water, 56,400 tarps, more than 19 million pounds of ice and 215,000 blankets. Transporting these goods from distribution centers through the disrupted transportation network in addition to the normal traffic load was obviously a challenge; hence, efficient and effective re-routing of freight trucks to the most suitable alternative routes during and immediately after extreme events requires in-depth studies of freight movements under normal and extreme conditions (Chin et al 2006). In addition, Chin et al (2006) showed a 10 % improvement in average travel time for all travelers when different routing strategies are used considering both passenger vehicles and freight trucks.

In particular, after hurricanes Katrina and Rita, the inadequate response to extreme events attracted attention from the researchers and urged the academic community to study emergency logistics and disaster response strategies from the transportation planning perspective (Litman 2006). Haghani and Afshar (2009) developed a comprehensive model that describes the integrated supply chain operations in response to disasters, as well as finding optimal location for temporary facilities considering the capacity constraints. The model can provide delays and assign limited resources ensuring the optimality for the entire system.

During or immediately after the disaster, humanitarian efforts must quickly move large amounts of different kinds of goods and relief personnel to the disaster area to minimize casualty and damage. Freight services by local businesses might be the most agile options as suggested by (Haghani and Afshar 2009). More research on disaster response and commercial logistics can be found in Beamon (2004), Beamon and Kotleba (2006), Van Wassenhove (2006), and Oloruntoba and Gray (2006).

Chang (2000), in making the distinction of local hinterland cargo, from-to flow (to the rest of Japan), and through flow (foreign transportation cargo), concluded that after the Kobe earthquake, from-to and through flows suffered the most, resulting in both short-term revenue and long-term competitive position for the Kobe port. The study demonstrates the importance of local hinterland cargo, through freight flow, and port transshipment cargo, hence showing the port's vulnerability.

System effect, vulnerability, and resilience

Aydin and Shen (2012) tackled the impact of the 2002 I-40 bridge collapse in Oklahoma on freight flow movement. Due to the bridge's critical location on I-40, a major US east–west corridor, the bridge collapse impacted not only Oklahoma, but also many other states from the west to east coasts. The authors highlighted the local, regional, and national freight flow changes prior to and after the collapse. The research finds that some conventional impact models, which more or less rely on gravity-based spatial distance decay effects, often overestimate the near-by but underestimate the further-out freight flow changes in the network.

Rodrigue et al. (2009) pointed out that a disruption at a much high scale can impact the security of a whole region or nation. Increased mobility, infrastructure and economic interdependency, concentration of distribution, or urbanization each are regarded as having a significant impact to the threat and risk level of disasters on transportation systems. They argue that with the increasing reliance on distribution systems, a major disaster to the transportation system can have very disruptive consequences to transportation supply (i.e., modes, routes, and terminals); transportation readiness (i.e., under time-sensitive needs); and transportation vulnerability. Therefore, good transportation disaster planning should have considered risk assessment, preparedness, mitigation, response, and recovery.

Some recent studies on extreme event on transportation and supply chain systems are on network risk, vulnerability, security, efficiency, and resilience. For example, Latora and Marchiori (2005) proposed a network efficiency measure. Nagurney and Qiang (2008, 2009) incorporated flows, costs, and behaviors for supply chain network vulnerability and resilience. World Economic forum (2012) has proposed comprehensive risk assessment to supply chain, including supply–demand and operational risks. Similar studies in this direction include Berdica (2002), Okasaki (2003), Litman (2006), and Manuj and Mentzer (2008).

The majority of the existing research reviewed focus on a specific type of extreme event (i.e., hurricane, earthquake, or bridge collapse) and its disruption on transportation networks using different models (i.e., IO, gravity, optimization and econometric) and various assumptions. These studies mostly focus on physical damage and reconstruction of transportation components or humanitarian logistics and distribution of goods to the disaster areas. In addition, the reviewed literature does not provide a general framework to study the impact of an extreme event to a transportation system at the regional or national levels, thus limited in spatial scope and weak in system perspective. Finally, no previous research has retro-analyzed freight flow disruptions caused by the deadliest hurricane Katrina to the entire US highway transportation network.

It would be beneficial to have a generic model that can be applied to various extreme events to a transportation network so that their impacts can be cross-compared. In this research, we present a framework that can be applied to any extreme event affecting a transportation system with slight contextual modifications. Publicly available databases and details on extreme events are the only information necessary, and the application of the framework is straightforward. The framework, consequently, will guide transportation planners as well as emergency managers in strategic decision making under extreme event conditions to handle pre-disaster planning, during-disaster relief endeavors, and post-disaster recovery freight movement.

An extreme event framework

The research framework is summarized in Fig. 1. From a network analysis point of view, extreme events (natural or man-made) can be analyzed in four types in terms of the resulting damage on the network, namely node, link, area (sub-network), and hybrid scenarios. For example, an earthquake's damage to the transportation network can be represented as a series of broken links, whereas a flood would result in an inaccessible area, which possibly includes link(s) and node(s).

The framework requires a *transportation network prior or after an extreme event*, a *freight Origin–Destination (O–D) matrix*, and a flow assignment method. These databases are either publicly available or can be created. *An Extreme Event* often results in a change to the network configuration. The *Transportation Network* is preferable in a geographical information system (GIS) format and corresponds to pre- and post-disaster scenarios. The *O–D Matrix* should consider freight type, OD scale (i.e., traffic analysis zone, county, MSA, and state), time unit, and interval (i.e., day, month, and year). The *Traffic Assignment* method, such as the All-or-Nothing, User Equilibrium, and System Optimum (Sheffi 1985) in transportation planning, can best be implemented in a GIS system.

The *Assignment Results* are used at the *Comparative Analysis* step to calculate the performance measures designed by the user, such as total flow change (increase or decrease), vehicle hours traveled (VHT), vehicle miles traveled (VMT), and link congestion measure volume-capacity ratio (VCR).

Flow increases on links can be calculated as differences for post-disaster and pre-disaster conditions. Routes with higher or lower flows after the disaster can be highlighted.

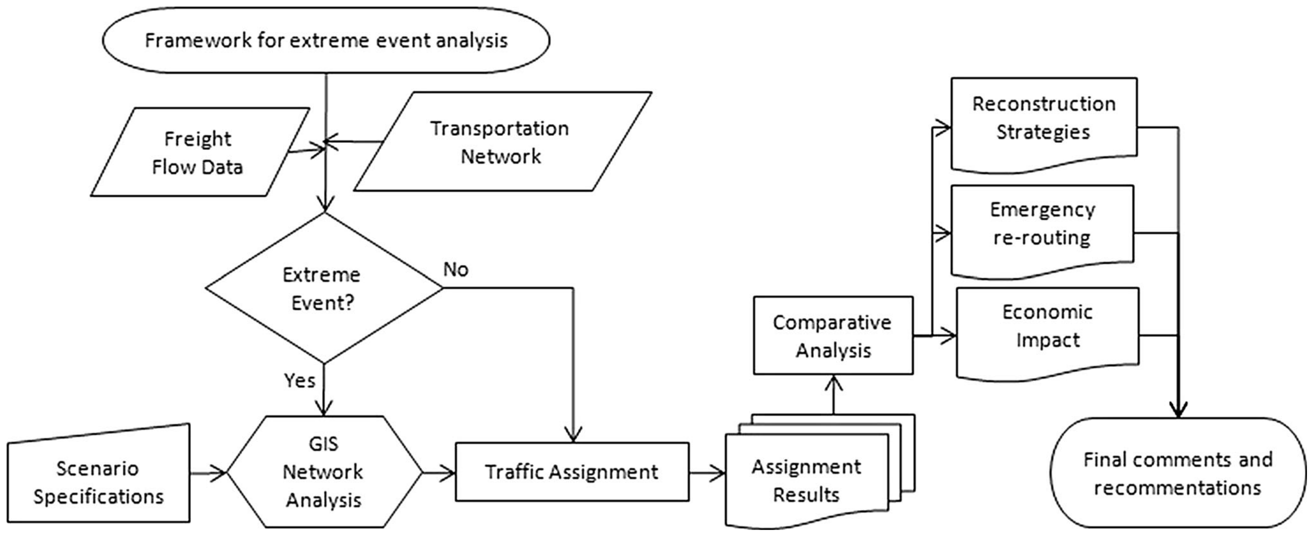

Fig. 1 A general framework for extreme event impact analysis

VMT or VHT demonstrates the increased or decreased miles or hours traveled, and as a consequence, increased or decreased costs. VMT and VHT can be calculated as the sum of all link distances or hours by flows from origins to destinations:

$$\mathrm{VMT} = \sum_{l} v^{l} d^{l} \quad (1)$$

where v^l is the link flow volume and d^l is the length of link l of the network.

Vehicle hours traveled is calculated as the sum of all link times from origin to destination for all OD pairs.

$$\mathrm{VHT} = \sum_{l} v^{l} t^{l} \quad (2)$$

where v^l is the link flow volume and t^l is the travel time on link l of the network.

The link VMT or VHT differences before and after a disaster will likely be increased, decreased, or no change due to flow interruptions. If the VMT (post-disaster) − VMT (pre-disaster) for link l >0, then the link has an increased flow; =0, the link has the same flow; <0, the link has a decreased flow after the disaster. Similarly, the VHT (post-disaster) − VHT (pre-disaster) for link l >0; then, the link travel time is increased; =0, the link travel time is the same; <0, the link travel time is decreased after the disaster. Furthermore, if VMT (post-disaster) − VMT (pre-disaster) and/or VHT (post-disaster) − VHT (pre-disaster) for the entire network of a state (i.e., Louisiana) is >0, then the state network is negatively affected; = 0, the network is not affected; <0, the state network is positively affected after the disaster. We analyze and summarize the state-level VMT and VHT differences between a damage/recovery scenario and the pre-disaster situation (base scenario) in the "Results and discussion" section.

The *Comparative Analysis* compares the differences of pre- and post-disaster situations for various scenarios. The analysis can provide useful inputs to *Emergency Re-routing*, *Reconstruction Strategies,* and *Economic Impact* estimations. The last step *Final Suggestions and Recommendations* is developed by combining all the outputs of the framework with the interpretations of the performance measures and policy- or scenario-specific concerns.

Most widely used flow assignment models in transportation planning are All-or-Nothing (AON) and User Equilibrium (UE) (Sheffi 1985). AON is an un-capacitated assignment and ignores the fact that link travel times are dependent on link capacity and link flow. It also assumes that the travelers have precise knowledge of the travel time on the links. It uses the shortest path algorithm in assigning the flow to the shortest path for each origin and destination pair. The shortcoming of the AON assignment is that it does not account for the link capacity. So, travel time is purely based on distance and does not depend on the link volume. However, there is an argument in favor of the AON method that says knowing the traffic on links helps determine the capacity to be supplied to or removed from that route to meet the desired level of service, which is the ultimate goal of transportation planning.

In contrast to AON, UE assignment takes account of the link volume and capacity. The deterministic UE assumes that the drivers have perfect knowledge about travel costs on a network and so they choose the best route for them. Equilibrium flow algorithms require iterative procedures between flow assignments and loaded travel times. UE is a nonlinear and capacitated assignment model, and the basic assumption is that no driver can unilaterally reduce his/her travel costs by shifting to another route (Wardrop 1952; Sheffi 1985).

$$\text{Min} \sum_l \int_0^{v^l} S_l(x)\mathrm{d}x \tag{3}$$

$$\text{St. } v^l = \sum_i \sum_j \sum_r \delta_{ij}^{rl} x_{ij}^{rl} \tag{4}$$

$$\sum_r x_{ij}^{rl} = F_{ij} \tag{5}$$

$$v^l \geq 0, x_{ij}^{rl} \geq 0 \tag{6}$$

where parameter $\delta_{ij}^{lr} = 0{,}1, = 1$ if link l is on path r from i to $j = 0$; otherwise, x_{ij}^{rl} = flow on link l of path r from i to j; $S_l(x)$ = a function of flow x_{ij}^{rl} on link l; F_{ij} = total freight flow from origin i to destination j; v_l = total flow volume on link l. The objective function is to minimize the total travel time on links. Constraint (4) specifies that flow volume on link l is the sum of all flows from all paths and all origins and destinations using that link. Constraint (5) requires that each OD flow must be assigned. Constraint (6) ensures non-negativity for link or path volume.

The damage caused by Katrina to highway transportation networks in the disaster region was heavy and extensive. Because damage repairs and debris cleaning of the affected areas took days, months, and in some cases, years (DesRoches 2006), freight flow movement was interrupted accordingly. As a result, neither the shipments from, nor the shipments to the disaster regions could be realized in normal ways due to the affected highway components such as damaged bridges and closed road segments. The physical damages to the transportation system and the relocation of some people and businesses inevitably changed the freight supply and demand balances. Specifically in this research, the O–D flows in the disaster-affected areas and the link capacities of damaged highway segments were adjusted according to the damage levels and recovery schedules.

Freight databases and processing

The freight flow data were gathered from the Freight Analysis Framework (FAF) database developed by Federal Highway Administration (FHWA). FAF provides a comprehensive national database of freight flows and integrates data from a variety of sources, such as Commodity Flow Survey (CFS) developed by the Census Bureau of the Department of Commerce and the Bureau of Transportation Statistics (BTS) of the US Department of Transportation (USDOT), the For-Hire Trucking (Commodity Origin and Destination) Survey by Statistics Canada, and GeoFreight by BTS and the Federal Highway Administration[1] (FHWA) of the USDOT.

FAF has estimates of commodity freight flows at 5-year intervals using Standard Classification of Transported Goods (SCTG[2]) coding system. FAF1 provides freight estimates for 1998 and forecasts for 2010–2020. FAF2 contains freight estimates for 2002 plus forecasts through 2035. The newest version FAF3 has freight estimates for 2007 and forecasts for 2015–2040. All FAF databases provide freight flows in tonnage and value by commodity and mode at state, MSA, and world regional levels (Shen and Aydin 2012).

The highway network databases available for this study include the National Transportation Atlas Database[3] (NTAD), Oak Ridge National Lab[4] (ORNL) intermodal highway network, and FAF3. The final highway network used for this research consists of 170,772 links with various attributes, such as length, speed, capacity, in TransCAD™ format (Center for Transportation Analysis 2010). TransCAD™ is a GIS designed mainly for traffic engineering, transportation planning, supply chain management, and facility location studies (Caliper 2010). In this research, necessary data manipulations, such as link free-flow speed, travel time, VCR, VHT, VMT; GIS operations, such as generation of MSA centroids and connection of flow data table to network origins and destinations; flow computations, such as flow assignments in AON and UE; and results visualizations, such as flow maps, were mostly done in TransCAD.

FAF3 database provides the freight data by tonnage and value by state or Metropolitan Statistic Area (MSA) and the remaining part of the state (or non-MSA). For example, Oklahoma freight data are provided for two MSAs—Oklahoma MSA and Tulsa MSA—and the remainder of the state, with total 3 origins and destinations. Together, FAF3 provides freight flows for 123 US MSAs and state reminders, plus major ports, border crossings, and freight ports. In this research, TransCAD was used to generate 123 MSA/Reminder centroids as O–Ds to which freight production and attraction table was linked. A total od 123 centroid connectors were generated to connect centroids to the highway network. Therefore, the integrated database has all US highway roads, including road functional classifications and urban and rural locations.

1 http://www.fhwa.dot.gov/.

2 http://www.bts.gov/programs/commodity_flow_survey/methods_and_limitations/commodity_classification_in_1997/classification.html.

3 http://www.bts.gov/publications/national_transportation_atlas_database/2007/.

4 http://www.ornl.gov/.

Code mapping is a methodology that establishes a bridge between SCTG and North American Industry Classification System (NAICS) codes so that the state or MSA employment involved in producing each of the commodities can be acquired. County business pattern (CBP) provides employment data for each industry at the state, MSA, and county levels by NAICS codes. State and MSA population data were obtained from the Census Bureau. Using the employment and population data, we were able to econometrically link freight flows for possible forecasts and split state-/MSA-level production and attraction data into smaller spatial-level production and attraction data, such as at the county, census track, and block levels (Wang et al. 2012).

The commonly available freight data, such as the data provided by FAF, are either in tonnage or in dollar values. Even though for the AON assignment the freight unit is not important, for the UE assignment, the unit needs to be number of trucks, which is the same as the capacity information for the network. The Freight Analysis Framework Highway Capacity Analysis Methodology Report (FHWA 2002) provides a chart of average payload factors by commodity types (STCC) and truck types (single unit truck, semi trailer, double trailer, and triples). The conversion of STCC and SCTG is prepared by DRI "Commodity Flow Forecast Update Report" (Bingham 2002). An average payload factor is used to convert the total freight, and the tonnage is divided by the payload factors to find the number of trucks between each OD pair, which is used for assignments (Ojha 2008).

Hurricane Katrina case study

On August 23, 2005, Katrina formed near the Bahamas. While crossing Florida, it was a Category 1 storm. In the Gulf of Mexico, Katrina rapidly strengthened and became a Category 5 storm with wind levels up to 175 mph. Even though Hurricane Katrina was a Category 3 storm when it made the landfall in Louisiana, it caused damage far from the eye, which had a radius of 100–120 miles. As a result, a widespread devastation occurred in Louisiana, Mississippi, and Alabama as shown in Fig. 3. Many areas were under water, and slight to severe damage was observed in residential, non-residential homes, government buildings, and infrastructure.

Geographical conditions in Louisiana are such that low performance of levees and floodwalls worsened the conditions in the city. In Louisiana alone, 33 bridges were damaged; 12 significant, 13 moderate, and 8 slight. According to Louisiana Department of Transportation (LADOT), debris removal, emergency, and permanent repair cost over $12 million. The major problem was caused by those failed bridges, and by the extensive amount of debris on the roadways. Hurricane Katrina then hit Mississippi. In total, 7 bridges were damaged; 4 significant and 3 moderate. Damage was due to storm surges or impact from barges. The majority of the damage occurred on US-90 and on routes connecting I-10 to US-90.

Alabama was not affected as much as the other two states. Still, Hurricane Katrina caused more than $20 million of damage to the roadways of Alabama (DesRoches 2006). In total, 4 bridges were damaged; 2 moderate and 2 major. There was congestion and delays on main routes, but because US-90 and I-10 run parallel and the abundance of available alternative routes, the problem was resolved.

Roadway damage and the flood data for September 5 and 21 were retrieved from the FEMA[5] Web site. In total, there were 45 bridges and roadway sections that were damaged due to the hurricane. Incorporating the data into the highway network, 23 of the bridges as well as the road closure at I-90 in Mississippi were selected for scenarios based on the damage/recovery level and the spatial location (Fig. 2). Table 1, structured from a modification from Padget et al. (2008), shows the damaged bridges, roadways, floods, repairs considered in this study.

We constructed 7 scenarios for Hurricane Katrina using the flood data and the report by DesRoches (2006), covering 7 different damage/recovery time intervals in Table 2. The damaged bridges and roads were grouped into G1 through G4 according to their re-functioning or reopening dates or recovery lengths (i.e., 1, 3, 6 months, or over 6 months).

Scenario 0.0 simulated the condition right before Katrina without any bridge/road closure or damage caused by the Hurricane. Scenario 1.0 reflected the situation of September 5, 2005 flood, which damaged bridges and closed roads in G1 through G4. In Scenario 1.1, the flood on September 21, 2005 further extended the damages and recoveries of the affected bridges and roadways in G1 through G4. In Scenarios 1.0 and 1.1, the New Orleans MSA node was modeled as a completely damaged node with zero freight production and attraction values. Scenario 1.2 had the same bridge damages and roadway closures in G1 through G4, but New Orleans MSA node was assumed back to its full production and attraction. Scenario 1.3 was a month later, when 10 of the damaged bridges in G1 were open for freight movement while the bridges/roads in G2, G3, and G4 were still not functioning. Scenario 1.4 was 3 months after the event, when 3 more of the damaged bridges were open for traffic while G3 and G4 bridges/roads were yet to reopen. Scenario 1.5 was 6 months after

[5] http://www.gismaps.fema.gov/2005pages/rsdrkatrina.shtm.

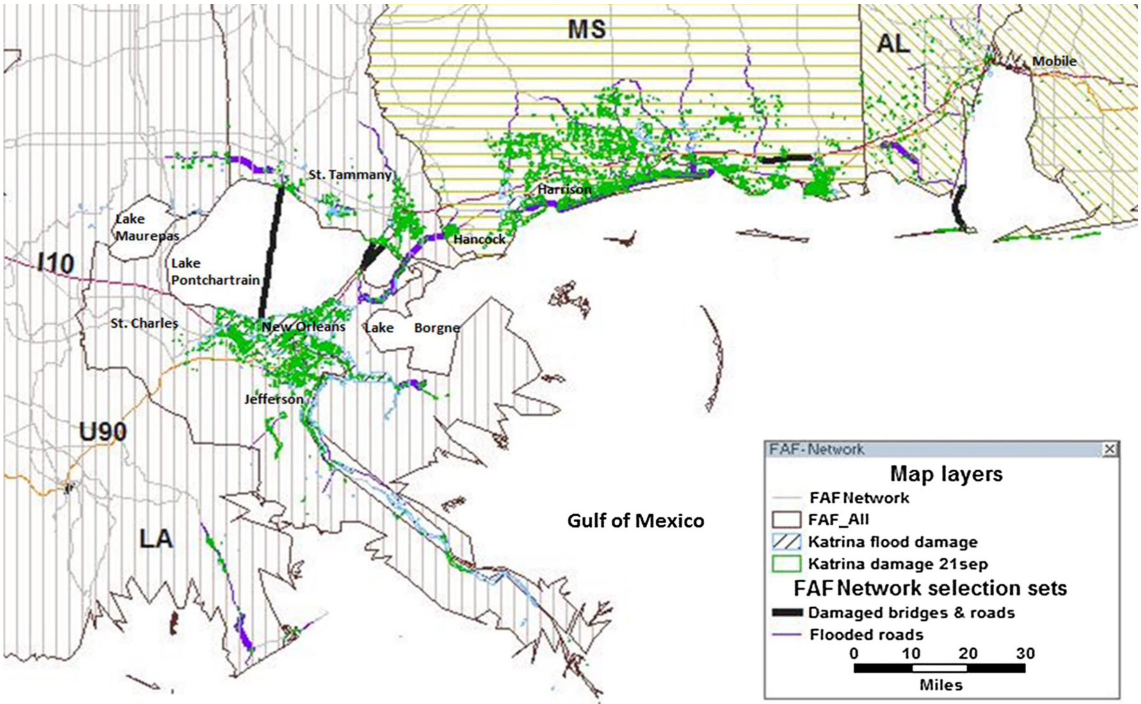

Fig. 2 Damage to highway network in Louisiana, Mississippi, and Alabama

the event and 4 more of the damaged bridges and the closed road sections were open for traffic, yet there were still 5 damaged bridges in G4 that were not open for traffic, which took longer than a year to repair.

Results and discussion

National flow dynamics and scenarios

Total freight flow on a link is the amount of flow a link carries on its lanes in each direction. If a road is used more compared to pre-disaster conditions after the event, it may result in congestion depending on the capacity of the road, and as the usage of the road increases, the maintenance and repair costs are assumed to increase. Congestion results in delays and hence wastes of time, energy, and money.

Due to Hurricane Katrina, bridges and roadways were closed resulting in changes in the shortest path between several OD pairs. For example, Scenario 1.0, the flood on September 5 impacted the coming in, out, within, and through freight flows in LA drastically. The changes under AON can be observed in Fig. 3; the blue lines indicate the roads that carried less from and to flow after the disaster for LA, due mainly to the temporal closure of the New Orleans MSA node, hence its freight supply and demand; and the orange lines indicate the detour roads that were not or less used prior to Katrina. The OD pairs trading with LA and AL (i.e., FL, GA, TX, and TN) were at the top of the list to use detours. In addition to that, due to the damage on I-10 and U-90, their freight flows shifted north to parallel roads. The increased or detoured freight flows were on roads located around the disaster region except the interstate reaching up to Pennsylvania. As expected, highways I-20, I-90, and I-10 in the south experienced the highest flow fluctuations.

When link capacity was incorporated into the scenarios, the VMT and VHT value changes under UE were spread out on more links in the entire US highway network, again with blue color indicating those links carrying reduced flows and orange color showing links shipping increased flows, as shown in Fig. 3. For example, of all the links which experienced a change after the September 5 flood in Scenario 1.0, 36 % increased and 64 % decreased. Decreased flows were largely concentrated on I-10, US-90, while large portions of the increased flows were carried on I-80, I-40, and I-75.

Total percentage VMT and VHT changes on US highway network by Scenario and assignment are summarized in Table 3. Under the AON assignment, the VMT and VHT decreased from the pre-disaster condition (or Scenario 0.0) to Scenario 1.0 and Scenario 1.1. Here, the decreases were primarily due to the closure of New Orleans MSA with zero nodal freight production and attraction even though the

Table 1 Damaged bridges and roadways by recovery time (in month) and link group

Damaged bridge or roadway name by state	Interstate or state highway	Damage level	Repair Time	Link group	State
Bayou La Batre bridge	Hwy 188	Moderate	≤1	G1	Alabama
Cochrane Africatown USA bridge	US-90	Moderate	>6	G4	
Mobile Delta Causeway	I-10, US-90/98	Moderate	≤6	G3	
Bayou Lafourche @ Leeville	LA-1	Extensive	≤1	G1	Louisiana
Bonfouca	LA-433	Extensive	≤6	G3	
Caminada Bay	LA-1	Extensive	≤1	G1	
Chef Menteur	US-90	Extensive	≤3	G2	
Claiborne	LA-39	Moderate	≤3	G2	
East Pearl River	US-90	Moderate	≤1	G1	
Inner harbor navigation channel	Florida Ave.	Extensive	>6	G4	
Lake Pontchartrain	I-10	Complete	≤6	G3	
Pontchartrain Causeway	LA Causeway	Complete	≤1	G1	
Rigolets Pass	US-90	Extensive	≤1	G1	
Tchefuncte River Madisonville bridge	LA-22	Moderate	≤1	G1	
US-11@ Lake Ponchartrain	US-11	Extensive	≤1	G1	
West Pearl River	US-90	Moderate	≤1	G1	
Yscloskey	LA-46	Extensive	>6	G4	
Biloxi Back Bay bridge	I-110	Extensive	≤3	G2	Mississippi
Biloxi-Ocean Springs bridge	US-90	Complete	>6	G4	
I-10 Pascagoula River bridge	I-10	Extensive	≤1	G1	
US-90 Bay St. Louis bridge	US-90	Complete	>6	G4	
US-90 Henderson point bridges	US-90	Complete	≤6	G3	
US-90 roadway (between Pass Christian and Biloxi-Ocean Springs Bridge)	US-90	Extensive	≤6	G3	

Table 2 Seven constructed scenarios

Scenarios and flood dates			Bridges/roadways conditions at the end of			
Scenario	September 5, 2005	September 21, 2005	First month	Third month	Sixth month	Over 6 months
SC0.0	No flood	No flood	G1 open	G2 open	G3 open	G4 open
SC1.0	Flood	*	G1 closed	G2 closed	G3 closed	G4 closed
SC1.1	*	Flood	G1 closed	G2 closed	G3 closed	G4 closed
SC1.2	No flood	No flood	G1 closed	G2 closed	G3 closed	G4 closed
SC1.3	No flood	No flood	G1 open	G2 closed	G3 closed	G4 closed
SC1.4	No flood	No flood	G1 open	G2 open	G3 closed	G4 closed
SC1.5	No flood	No flood	G1 open	G2 open	G3 open	G4 closed

* Indicates that Scenario 1.0 and Scenario 1.1 only applies to the flood on September 5, 2005 or September 21, 2005 respectively

damaged bridges and roads actually caused higher VMT and VHT. However, after the floods, with the reopened New Orleans MSA node, and with the damaged bridges and roads yet to recover as in Scenario 1.2, the VMT and VHT increased over their pre-disaster levels. Here, the small portions over the Scenario 0.0 can be regarded as caused by the 23 damaged bridges and roads in the affected areas of LA, MS, and AL. Moving to Scenario 1.3 and then to Scenario 1.4 with more bridges and roads reopened, the increased portions of VMT and VHT in Scenario 1.2 dropped slightly with almost no drop from between Scenario 1.3 and Scenario 1.4. However, after all bridges and

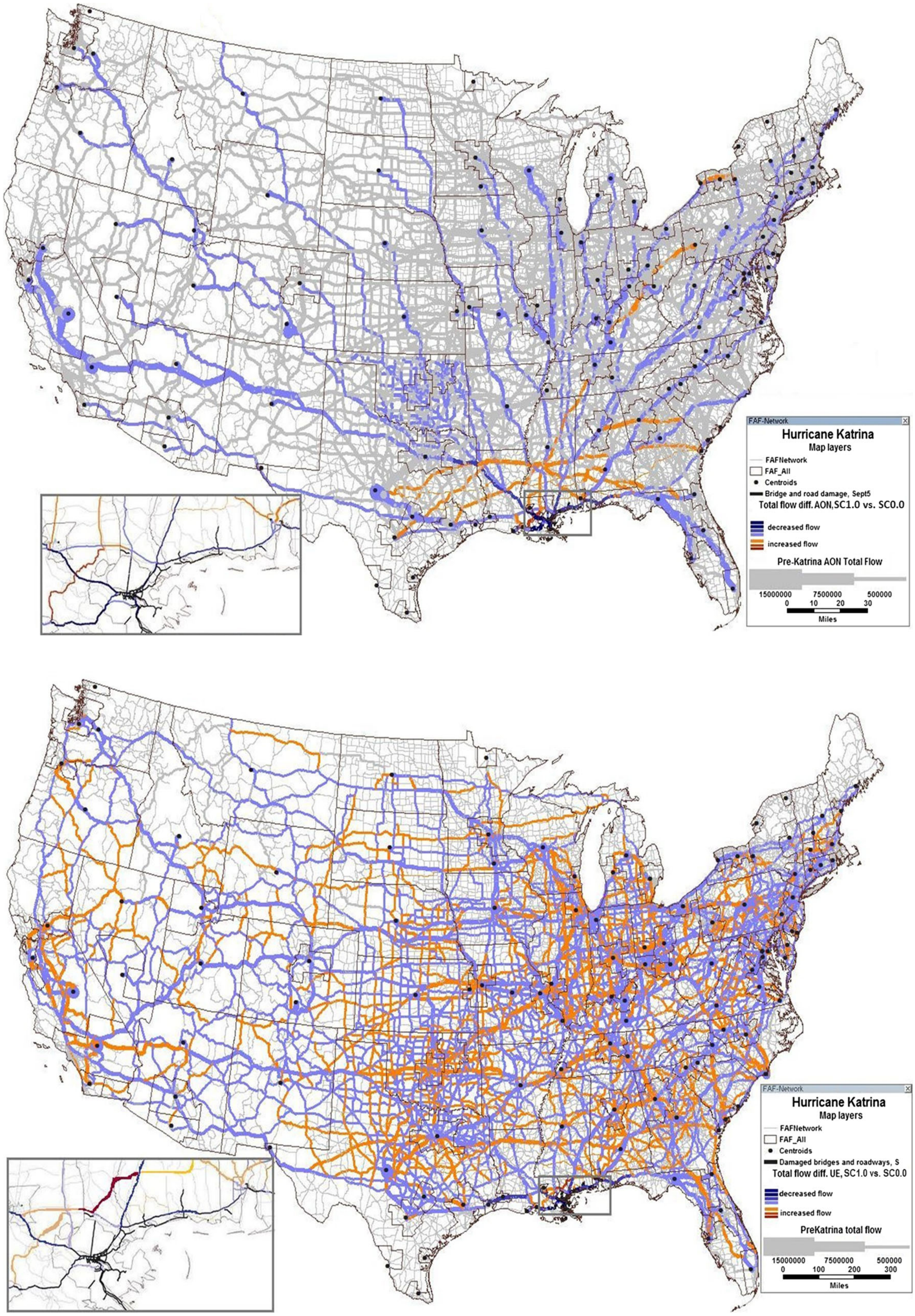

Fig. 3 US freight on highway for SC1.0 under AON (*top*) and UE (*bottom*)

Table 3 Total VMT and VHT percentage changes by scenario and assignment

Assignment/measure	SC0.0–SC0.0	SC1.0–SC0.0	SC1.1–SC0.0	SC1.2–SC0.0	SC1.3[a]–SC0.0	SC1.4–SC0.0	SC1.5[b]–SC0.0
VMT–AON	0.00	−2.18247	−2.18247	0.05883	0.01572	0.01572	0.00
VHT–AON	0.00	−2.18238	−2.18238	0.05880	0.01538	0.01538	0.00
VMT–UE	0.00	−2.15883	−2.15890	0.06364	0.01534	0.01534	0.00
VHT–UE	0.00	−1.17590	−1.17616	0.03040	0.00507	0.00505	0.00

[a] $(VHT_{SC1.3}–VHT_{SC0.0})/VHT_{SC0.0}*100$

[b] Scenario 1.5 with all the bridges and roadways reopened

roads fully recovered in Scenario 1.5, the VMT and VHT also resumed back to their normal pre-disaster levels.

It is interesting to see that under AON, the total VMT and VHT changes, with respect to the base scenario, were almost identical for all scenarios. This similarity suggests that (1) the Katrina and its flood on September 5 flood caused the most damage while the flood on September 21 did not and (2) the reopened bridges and roads starting on Scenario 1.3 only generated slight VMT and VHT changes. The similar patterns of total US VMT and VHT percentage changes from one scenario to another can also be observed for the UE assignment. However, VMT and VHT percentage changes under UE for the same scenario (i.e., −2.15883 vs. −1.17590 under Scenario 1.0) are somewhat different. This difference is primarily due to the link capacity consideration in UE, which uses more roadway links of wider varieties of lengths, capacities, and travel times to carry the O–D flows.

Interestingly, Table 3 shows that across the scenarios, the VMT percentage changes under UE are always larger than their corresponding VHT percentage changes. Also, UE models result in less disruption percentage differences in terms of absolute value than AON models do for most scenarios. The main reason perhaps lies in the modeling focuses of AON and UE. AON only considers the shortest link/path distance in assigning O–D flows without considering link/path capacity. However, UE considers the shortest travel time through a link performance function in which link capacity is considered. The impact of distance may be greater in AON while the flow movement may be more efficient in UE, which assumes that all the information is available to make a cost-effective decision to pick a route from origin to destination. Although the algorithms and objectives of the two models are quite different, detailed comparisons of their performance measures call for further studies.

State flow dynamics and scenarios

Figure 4 shows the average VMT percentage changes under AON for all scenarios against the pre-Katrina under UE assignment for the USA and the three states (LA, MS, and LA) affected most by Katrina. Prior to Katrina, the average VMT changes were zero for all. Under Scenario 1.0, the VMT changes all went down significantly, with the most drop for Louisiana, where the major supply and demand at New Orleans MSA node were stopped alongside with damaged roads and bridges due mainly to the flood on September 5. The VMT change under Scenarios 1.1 was almost identical to that of Scenario 1.0 with the same closed roads and bridges, though the second flood in New Orleans happened on September 21. By Scenario 1.2, when New Orleans MSA was reopened with pre-Katrina production and demand, the VMT changes all increased, with LA, MS, and AL having more increases than the US average. From Scenario 1.2 to Scenario 1.4, all VMT changes gradually dropped corresponding to reopens of more damaged roads and bridges. However, the relatively large drops in VMT in Scenario 1.3 imply that roads and bridges reopened in Scenario 1.3 affected freight flows more than those recovered in Scenario 1.4. All VMT values resumed to pre-Katrina conditions after Scenario 1.5 when

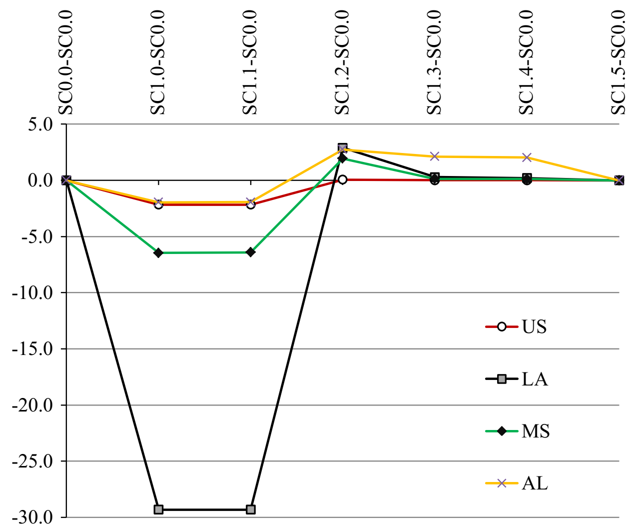

Fig. 4 VMT percentage changes under SC0.0–1.5 for LA, MS, and AL under AON

Table 4 Significant VMT and VHT percentage changes by state under UE

State	SC1.0–SC0.0	State	SC1.1–SC0.0	State	SC1.2–SC0.0	State	SC1.3–SC0.0	State	SC1.4*–SC0.0
VMT percentage changes by scenario under UE for top twenty states and US[a]									
LA	−29.3271	LA	−29.3379	LA	2.8951	AL	2.0149	AL	2.0292
MT	−11.3157	MT	−11.3158	MS	1.9492	FL	1.1570	MT	0.1849
VT	−8.3133	VT	−8.3133	AL	0.7524	LA	0.1905	WY	0.1736
NM	−7.2989	NM	−7.3217	AR	0.3857	MT	0.1850	SD	0.1729
MS	−6.4721	MS	−6.4127	MT	0.3040	WY	0.1735	AR	0.1689
SD	−6.3326	SD	−6.3339	SD	0.2461	SD	0.1728	KS	0.1269
TX	−5.4820	TX	−5.4853	IL	0.2278	AR	0.1653	MS	0.1133
KS	−3.9091	KS	−3.8873	TN	0.1924	TX	0.1616	GA	0.1091
WA	−3.8913	WA	−3.8754	NV	0.1854	MS	0.1274	NV	0.0989
AZ	−3.8528	AZ	−3.8687	WY	0.1723	KS	0.1268	TN	0.0723
ID	−3.6122	ID	−3.6122	KS	0.1335	GA	0.1087	OK	0.0548
AR	−2.8377	AR	−2.8466	WV	0.0997	NV	0.0988	CA	−0.0441
WY	−2.7015	WY	−2.7015	VT	0.0871	NM	0.0736	CO	−0.0496
CO	−2.5700	CO	−2.5497	OR	−0.0789	AZ	0.0719	OR	−0.0546
UT	−2.5005	UT	−2.4753	AZ	−0.0829	TN	0.0712	UT	−0.0573
FL	−2.1372	FL	−2.1389	DC	−0.0943	UT	0.0573	AZ	−0.0719
AL	−1.9563	AL	−1.9985	NC	−0.1285	OR	0.0546	NM	−0.0737
VA	−1.7439	VA	−1.7438	SC	−0.1640	OK	0.0530	TX	−0.1626
OR	−1.4120	OR	−1.4217	TX	−0.2052	CO	0.0496	LA	−0.2000
MO	−1.3707	MO	−1.3756	FL	−1.2740	CA	0.0440	FL	−1.1570
USA	−2.1588	USA	−2.1589	USA	0.0636	USA	0.0153	USA	0.0157
VHT percentage changes by scenario under UE for top twenty states and the USA[b]									
LA	−30.2375	LA	−30.2288	LA	3.1346	AL	2.2418	AL	2.2580
MT	−11.1505	MT	−11.1506	MS	2.4761	LA	0.2861	LA	0.2605
VT	−8.5375	VT	−8.5375	AL	0.7543	WY	0.2052	WY	0.2053
NM	−8.2693	NM	−8.3008	AR	0.4081	AR	0.1884	AR	0.1940
SD	−6.3408	SD	−6.3420	MT	0.3059	MT	0.1875	SD	0.1876
MS	−6.1219	MS	−6.0523	SD	0.2650	SD	0.1875	MT	0.1874
AZ	−4.7754	AZ	−4.7951	WY	0.2081	KS	0.1237	KS	0.1238
TX	−4.5732	TX	−4.5750	NV	0.1803	MS	0.1001	NV	0.0928
WA	−3.9530	WA	−3.9514	IL	0.1497	NV	0.0928	MS	0.0877
KS	−3.7737	KS	−3.7539	KS	0.1391	MO	0.0816	MO	0.0808
ID	−3.5005	ID	−3.5005	TN	0.1078	GA	0.0789	GA	0.0794
AR	−3.0767	AR	−3.0888	WV	0.0923	OK	0.0603	OK	0.0625
WY	−2.8333	WY	−2.8334	VT	0.0910	NM	−0.0568	NM	−0.0569
UT	−2.7947	UT	−2.7640	AZ	−0.0619	AZ	−0.0580	AZ	−0.0580
AL	−2.3588	AL	−2.4013	OR	−0.0810	OR	−0.0603	OR	−0.0604
CO	−2.2488	CO	−2.2318	TX	−0.0962	OH	−0.0749	OH	−0.0752
FL	−1.9803	FL	−1.9817	NC	−0.1038	TX	−0.0891	KY	−0.0870
VA	−1.7263	VA	−1.7259	KY	−0.1652	KY	−0.0904	TX	−0.0897
MO	−1.3839	MO	−1.3866	SC	−0.1740	IL	−0.1060	IL	−0.1076
DC	−1.3065	DC	−1.3067	FL	−1.0900	FL	−0.9781	FL	−0.9780
USA	−1.1759	USA	−1.1762	USA	0.0304	USA	0.0051	USA	0.0051

[a] $(VMT_{SC1.4}–VMT_{SC0.0})/VMT_{SC0.0}*100$

[b] $(VHT_{SC1.4}–VHT_{SC0.0})/VHT_{SC0.0}*100$

all roads and bridges were fully functional. The average VHT percentages showed the similar variation patterns for US, LA, MS, and AL.

The freight VMT and VHT percentage changes at the state level were dynamic with decreased or increased percentage values under various scenarios. The dynamics were similar for both AON and UE with Scenario 0.0 and Scenario 1.5 showing the same pre-disaster and recovered post-disaster conditions, Scenario 1.0 and Scenario 1.1 having the largest decreases for all states, Scenario 1.2 showing the largest changes for almost all states after the New Orleans MSA node was reopened, and Scenario 1.3 and Scenario 1.4 having small but steady variations for almost all states.

The VMT and VHT percentage changes (increase or decrease) by scenario under UE for top twenty states and the USA are summarized in Table 4. The two tables show several important features. First of all, LA, MS, and AL were among the top twenty for both VMT and VHT changes across all the scenarios, with LA being on the top for Scenario 1.0 to Scenario 1.2 and AL on the top for the Scenario 1.3 and Scenario 1.4, meaning the closed New Orleans MSA node and damaged bridges/roads in LA, MS, and AL affected these three states more than they did to most other states. Second, VMT and VHT changes were virtually the same for Scenario 1.0 and Scenario 1.1, though those for Scenario 1.1 are slightly larger, indicating that the September 21 flood only generated marginal impact with respect to the September 5 flood after Katrina. Third, from Scenario 1.0 to Scenario 1.4, especially from Scenario 1.2 with New Orleans MSA node and some bridges/roads reopened, VMT and VHT changes dropped gradually for the USA on the average and for most states, but not for some states. Fourth, VMT values were consistently higher than VHT values under all scenarios at the US level, but not so at the state level. Finally, most of the top twenty states were located in the south; however, some northern states, such as MT, VT, WY, SD, and IL also had quite large VMT and VHT changes for some scenarios.

Figure 5 shows the changes in VMT by state, Scenario 1.0 versus base Scenario 0.0. Expectedly, the highest decrease was observed at the southern part of the USA. The main reason is the decreased attraction and production of New Orleans port shutdown, followed by the first flood immediately after Katrina. Some small northern states, such as MT, ND, VT, though far away from LA, MS, and AL, had big VMT decreases as well. These big decreases perhaps could be attributed to these northern states relative small VMTs, but relative high freight interactions with the Katrina-affected states. These general patterns also hold for VHT value ups and downs in Scenario 1.0. Figure 5 also illustrates the VHT percentage changes by state under Scenario 1.2 and Scenario 1.4. While the Scenario 1.2 had more VHT increases concentrated in LA, MS, and AL, the Scenario 1.4 had more states with increased VHT values spread out, including some northern states (MT, WY, SD), Midwest states (i.e.,

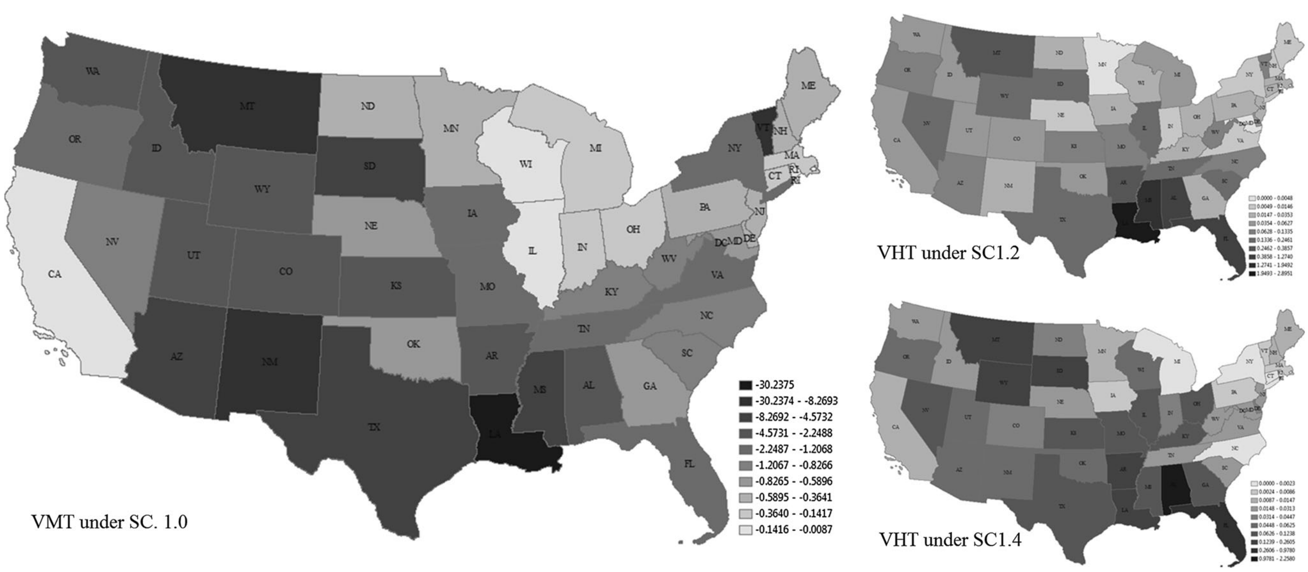

Fig. 5 VMT and VHT percentage change under UE and for Sc1.0, SC1.2, and SC1.4

KS, MO, IL, and OH), and southern states around AL. Again, these general patterns were also observed for VMT under Scenarios 1.2 and 1.4. Six months after the disaster, VMT and VHT values of all states resumed from their Scenario 1.0–Scenario 1.4 increases or decreases to pre-Katrina levels.

Conclusion

This research develops a generic framework to model the highway freight movement under an extreme event. The important parts of the framework are the assignment models, constructed scenarios, OD matrix, performance measures, and integration of various databases. Using the entire US highway network to study an extreme event on such a magnitude as Hurricane Katrina provides an opportunity to see the event's effect at local, state, and national scales. The sole focus on freight transportation disruptions, the framework, the approach, and scale of this research makes this research distinct from the existing literature, in which the gravity model applications are often used with a main focus on local networks, less on state, and much less on national effects. Gravity-type models use the distances between OD pairs as multiplier factors and operate with a distance decay function, which may underestimate the regional and national flow dynamics and impacts. This research shows that distance dependency may not be significant as previous research has indicated, since an extreme event in a locale can affect freight movement in remote areas.

AL, LA, MS, TX, and GA are the states highly impacted by the disaster. Altered production and attraction flows at some origins (i.e., New Orleans) and the failures of network links (i.e., bridges) caused flow increases and decreases on many links in the highway transportation, hence the ups and downs of VMT and VHT measures at the local and state level. Flood scenarios differed from other scenarios in that a flood-affected multiple links and nodes in an area; hence, there were more significant VMT and VHT variations with some decreases of around 2 % under both AON and UE. The increased flows are observed at the parallel interstates to the north and decrease with the trading partners of LA, AL, and MS on all transportation networks. After the flood, the performance measures increased about 2–3 %. Flow changes mainly occurred on major interstate and arterial highways. The disaster seemed to have shifted flows from major interstates to major arterials and minor arterials.

Results indicate that the transportation network damage impacted not only the surrounding region but other states as well. In spite of the fact the disaster regions had the highest impact; the freight flow at any part of the network might have had the possibility of being affected significantly, which indicates that the distances from the disaster area are not a key variable in measuring the flow changes and impacts. We are confident to say that the impact factors consist of at least the following network failures, the network itself, trading partners of the disaster region, and attraction and production of the disaster region. It is also dependent on the location of the disaster, network properties, network details, and data used in the analysis.

Nevertheless, there are some limitations of this study. Other than floods, bridge, and roadway damages, the behaviors of freight operators and regulators were not considered. In terms of data, Louisiana was only represented with 5 MSAs, Mississippi with 1 MSA, and Alabama with 3 MSAs. To make this study more accurate, the MSAs used in the study can further be divided into counties or finer spatial units, which will make more highway segments carry freight flows, hence closer to the reality. Of course, more or better performance measures could be designed in addition to VHT and VMT. More detailed spatial comparisons of flows under both pre- and post-disaster conditions, for example, at the MSA level, can be made. Looking into freight types, such as specific goods, may also be interesting.

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