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Simulating Impacts of Disruptions to Liquid Fuels Infrastructure

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Simulating Impacts of Disruptions to Liquid Fuels Infrastructure

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Abstract

This report presents a methodology for estimating the impacts of events that damage or disrupt liquid fuels infrastructure. The impact of a disruption depends on which components of the infrastructure are damaged, the time required for repairs, and the position of the disrupted components in the fuels supply network. Impacts are estimated for seven stressing events in regions of the United States, which were selected to represent a range of disruption types. For most of these events the analysis is carried out using the National Transportation Fuels Model (NTFM) to simulate the system-level liquid fuels sector response. Results are presented for each event, and a brief cross comparison of event simulation results is provided.

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This report presents a methodology for estimating the impacts of events that damage or disrupt liquid fuels infrastructure. The impact of a disruption depends on which components of the infrastructure are damaged, the time required for repairs, and the position of the disrupted components in the fuels supply network. Impacts are estimated for seven stressing events in different regions of the United States: a Gulf Coast hurricane, a Mid-Atlantic hurricane, a Boston Harbor oil spill, a Denver refinery explosion, a New Madrid earthquake, a Southern California earthquake, and a Northern California earthquake. These regions were selected to represent a range of disruption types and liquid fuels infrastructure systems configurations.

The analysis for six of these events is carried out using the National Transportation Fuels Model (NTFM) to simulate the system-level response of the liquid fuels sector. The NTFM was not used for the Boston Harbor oil spill because the NTFM is not applicable at the local scale of this event.

The impact estimates have two fundamental steps: defining the stressing event and estimating the event's impact in terms of a performance metric. The event definition includes the event's location and estimates of damage to infrastructure facilities and recovery times, including damage to supporting infrastructure such as electric power.

The metric used to evaluate the level of impact is how well the liquid fuels sector performs its mission of providing fuel to consumers during and after a stressing event: specifically, the decrease in fuel consumed during both the event and the period until recovery to normal operations. Measures of decrease in fuel consumption include duration, magnitude, and geographic extent of fuel shortages.

The seven stressing events differ with respect to the infrastructure components disrupted, the durations of the disruptions, and the magnitude, duration, and spatial extent of fuel shortages. For each individual event, the level of impact depends on which system-level adaptive responses are available to mitigate fuel shortages. That is, what options are there to receive fuels by alternative transportation routes, make use of surge capacities, or draw down inventories? It is the role of the NTFM to discover and simulate these adaptive responses in order to guide intuition about the impact severity of a specific stressing event.

For the most part, the liquid fuels system responded well to each stressing event, though the size and duration of fuel shortage impacts for specific regions and cities varied widely. From a broad regional perspective, the Gulf Coast hurricane and New Madrid and Southern California earthquakes tended to have the most severe effects, due to the larger portions of the supply chain (upstream, downstream and transportation) and regions affected. On the same basis, while the Boston Harbor oil spill event had consequential effects, it was the least severe of the seven stressing events examined.

ACRONYMS

CICLOPS	Cyclone-Induced Commercial Loss of Power Simulator
CY	Calendar Year
DOE	U.S. Department of Energy
EIA	Energy Information Administration
GIS	Geographical Information System
LNG	Liquefied Natural Gas
MMI	Modified Mercalli Intensity
NISAC	National Infrastructure Simulation and Analysis Center
NMSZ	New Madrid Seismic Zone
NTFM	National Transportation Fuels Model
SLOSH	Sea, Lake, and Overland Surges from Hurricanes model
U.S.	United States
USGS	U.S. Geological Survey

1 INTRODUCTION

This report presents a methodology for estimating the impacts of events that damage or disrupt liquid fuels infrastructure. The impact of a disruption depends on which components of the infrastructure are damaged, the time required for repairs, and the position of the disrupted components in the fuels supply network. Impacts are estimated for seven stressing events, which were selected to represent a range of disruption types.

The impact estimates have two fundamental steps: defining the disruptive event and estimating the event's impact in terms of a performance metric. The event definition includes the event's location and magnitude and estimates of damage to infrastructure facilities and recovery times, including damage to supporting infrastructure such as electric power.

The metric used to evaluate the level of impact is how well the liquid fuels sector performs its mission of providing fuel to consumers during and after a stressing event: specifically, the decrease in fuel consumed during both the event and the period until recovery to normal operations. Measures of decrease in fuel consumption include duration, magnitude, and geographic extent of fuel shortages.

The system-level performance of the liquid fuels sector during a disruptive event is a result of complex interactions involving market dynamics and operational decisions at individual facilities. These interactions are sufficiently complex that forecasting performance is difficult without computer models that represent the most important aspects of sector operations. This analysis employed the National Transportation Fuels Model (NTFM) to simulate the response of the liquid fuels sector to most of the stressing events. The NTFM estimates the availability of liquid fuels in the event any component of the national fuel supply chain is damaged or disrupted. NTFM calculates flows of crude oil and refined products on the transportation network and storage levels at tank farms assuming adaptive responses that include:

- Drawing down inventories at storage and distribution terminals,
- Increasing output at unaffected refineries to compensate for damaged refineries,
- Rerouting flows on the pipeline system, and
- Decreasing consumption of fuels, not only in directly affected areas but also in neighboring areas.

These adaptive responses are market-driven and the model algorithms include a simplified representation of market dynamics and the resulting decisions made by consumers and facility operators, as well as the physical constraints imposed by the capacities and connectivity of individual infrastructure facilities (e.g. pipelines, refineries, terminals). The actions of individual operators during disruptive events depend on many factors such as contractual obligations, laws and regulations, and operator-specific business strategies. A computer model cannot predict these individual actions. Instead, the NTFM algorithms assume that markets and operators act to utilize excess capacity and available storage across the entire model network to provide fuels to distribution terminals experiencing shortages. In this sense, NTFM biases results toward the best possible outcome with respect to minimizing fuel shortages.

2 MODEL DESCRIPTION AND LIMITATIONS

The NTFM is a network model of the transportation of crude oil and refined products in the lower 48 states and the portions of Canada that supply crude oil to the United States. The fuel supply infrastructure represented by the NTFM spans from oil fields to fuel distribution terminals. Infrastructure is represented as a network consisting of oil fields, refineries, tank farms, and terminals (the nodes of the network), and the pipelines, rail lines, and waterways that connect the nodes (the edges of the network). Simulated flows on the network are constrained by the capacities of the individual infrastructure elements that form the network edges. The NTFM includes a simplified model of market-based allocation that reroutes fuel through the network to areas where it is most needed. Fuel consumption decreases as supplies at distribution terminals fall below normal levels. This dependence of consumption rate on supply in the model is a proxy for the effect of price on consumption in the real world. This simplified representation of the market does not include knowledge of the future. For example, consumer behavior does not account for expectations of how long it will take to repair a damaged facility.

The NTFM uses data from a variety of sources. The model network was updated recently to represent the state of infrastructure at the end of 2013, the most recent time period for which sufficient information is available. This update includes information provided by INTEK Inc. for recent pipeline changes and rail loading/unloading capacities of crude, and information provided by the Energy Information Administration (EIA) on recent rates of crude-oil production at model nodes that represent producing regions. Import and export data at various ports and amounts of petroleum transportation on rivers are taken from calendar year (CY) 2012 data collected by the U.S. Army Corps of Engineers Waterborne Commerce Statistics Center. Crude production, refinery capacities, and storage are from CY 2013 data provided by the EIA. The service areas for the aggregated distribution terminals, as well as the amount of demand for each area, are estimated from 2012 U.S. Census Bureau and 2013 EIA data. Information on pipeline capacities came from a wide variety of sources, including geographical information system (GIS) databases, company reports, web sites, news articles, and a 1989 study by the National Petroleum Council.[1]

The NTFM has a high level of spatial resolution, but it does not represent every petroleum facility as a separate model element. Nodes and edges of the model network often represent individual facilities and pipelines, but if multiple facilities of the same type are near to each other, they may be aggregated into a single network element. For example, four refineries in the Philadelphia area are aggregated into one network node and consequently share the same connections to other nodes. Simulating the disruption of one of these refineries is accomplished by reducing the aggregate capacity of the node by the amount contributed by the disrupted refinery.

The model does not include contractual and operational restrictions; the lack of such restrictions renders the model more flexible in responding to a disruption than the real system. The model does not distinguish between different grades of crude oil or different types of refined products, which also renders model response more flexible than the real system.

The timing of shortages in the model—that is, how long it takes before shortages develop and how quickly shortages are resolved after a disruption—depends on the amount of storage of

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[1] National Petroleum Council, *Petroleum Storage and Transportation*, 5 volumes, 1989.

refined products throughout the area at the beginning of the disruption. Based on EIA data, terminal nodes in the model have about five days of product storage and refinery nodes have about nine days of product storage before disruptions. These storage amounts are national averages, rather than data for specific facilities. Also, storage levels at any given facility fluctuate up and down continually, so the level at the time of a stressing event cannot be known precisely. Because the model does not differentiate between types of refined products, it does not include separate storage of different fuel types. It is possible that shortage timing or patterns could be different for different types of refined products.

As with all models, the results of individual simulations depend on an analyst's judgment in specifying values for model parameters and on model assumptions, level of spatial resolution, and availability of data. Consequently, judgment on the part of an analyst is required to interpret simulation results and express the level of confidence in those results.

3 STRESSING EVENTS

3.1 Gulf Coast Hurricane

This analysis assesses the availability of liquid fuels after a hypothetical Category 5 hurricane makes landfall in the Houston, Texas, area.[2] The area of the Gulf Coast affected by the scenario hurricane is home to significant petroleum production and refining capabilities. Gulf Coast hurricanes affect fuel supplies by shutting down offshore production, refineries, ports, and transmission pipelines for durations that depend on the level of damage suffered and the availability of electric power. The Gulf Coast area experiences hurricanes with some regularity and hurricane response measures are in place to minimize impacts. The large amount of inventory and highly connected pipeline network in the area give the liquid fuels sector flexibility to respond to such disruptions.

3.1.1 Event Definition

The trajectory, category, and storm size of the hypothetical hurricane in this analysis are based on a scenario previously developed from historical data by the National Infrastructure Simulation and Analysis Center (NISAC).[3] The hypothetical hurricane makes landfall on Galveston Island, Texas, just south of Galveston Bay. The storm proceeds inland through Houston, northwest to Dallas-Ft. Worth, Texas, north to Tulsa, Oklahoma, and northeast to Columbia, Missouri.

Hurricanes damage infrastructure through high winds and flooding. Storm-surge depth generally increases as the hurricane strength category increases. Storm surge can flood industrial facilities, businesses, and residences, and cause damage to critical infrastructure systems that supply services to those entities. High-speed winds primarily knock over trees, especially when the ground is already saturated. Falling trees can take down nearby distribution power lines, resulting in power outages. As the wind speed in an area increases, the extent of power outages also increases.

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[2] A Category 5 hurricane has sustained winds of 157 miles per hour or higher, according to the National Weather Service, "The Saffir-Simpson Hurricane Wind Scale Summary Table," www.nhc.noaa.gov/sshws_table.shtml?large, accessed November 13, 2014.

[3] *Houston, Texas, Hurricane Scenario Analysis Report, April 2014*, draft report, Office of Cyber and Infrastructure Analysis, National Protection and Programs Directorate, U.S. Department of Homeland Security, 2014.

For this hypothetical hurricane, storm-surge inundation depths were modeled using the National Hurricane Center's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model. Of most importance to the petroleum infrastructure, four refineries in Beaumont and Port Arthur, Texas, with a total capacity of 1.5 million barrels per day, are in the region projected to be inundated by storm surge. Table 1 presents further detail about these refineries.

Table 1. Refineries located in the expected storm-surge inundation area.

Refiner	City	State	Capacity (barrels/day)	Storm-Surge Depth (ft.)
ExxonMobil	Beaumont	Texas	344,600	>8
Total Petrochemicals	Port Arthur	Texas	225,500	>8
Premcor Refining	Port Arthur	Texas	330,000	4–6
Motiva Enterprises	Port Arthur	Texas	600,250	4–6

Analysts employed the NISAC Cyclone-induced Commercial Loss of Power Simulator (CICLOPS) to estimate maximum sustained wind speeds and damage to the electric-power distribution system throughout the affected area. Percent damage to the distribution system directly correlates to percent customer outages. The model results are presented in 25-percent outage increments:

- Sustained winds of 25–40 mph produce up to 25 percent damage or customer outages (0- to 25-percent outage area).
- Sustained winds of 40–50 mph produce up to 50 percent damage or customer outages (25- to 50-percent outage area).
- Sustained winds of 50–65 mph produce up to 75 percent damage or customer outages (50- to 75-percent outage area).
- Greater than 65 mph sustained winds produce up to 100 percent damage or customer outages (75- to 100-percent outage area).

Thirty refineries are located in the projected electric-power outage areas: 13 in the 75- to 100-percent outage area, three in the 50- to 75-percent outage area, and 14 in the 0- to 25-percent outage area. Table 2 presents further detail about these refineries. In addition to refineries, the hurricane-caused power outages would affect numerous distribution terminals, pipeline pump stations, and other facilities. Figure 1 provides a map showing the projected power-outage areas.

Table 2. Refineries located in the power outage area.

Refiner	City	State	Capacity (barrels/day)	Power Outage Area (Probability, %)
ExxonMobil	Beaumont	Texas	344,600	75–100
Total Petrochemicals	Port Arthur	Texas	225,500	75–100
Premcor Refining	Port Arthur	Texas	330,000	75–100
Motiva Enterprises	Port Arthur	Texas	600,250	75–100
ExxonMobil	Baytown	Texas	560,500	75–100
Marathon	Galveston Bay	Texas	451,000	75–100
Deer Park Refining	Deer Park	Texas	327,000	75–100
Houston Refining	Houston	Texas	263,776	75–100
Phillips 66	Sweeny	Texas	247,000	75–100
Valero	Texas City	Texas	225,000	75–100
Pasadena Refining	Pasadena	Texas	100,000	75–100
Valero	Houston	Texas	88,000	75–100
Marathon	Texas City	Texas	84,000	75–100
Citgo	Lake Charles	Louisiana	427,800	50–75
Phillips 66	Westlake	Louisiana	239,400	50–75
Calcasieu Refining	Lake Charles	Louisiana	78,000	50–75
Flint Hills Resources	Corpus Christi	Texas	293,000	0–25
Valero	Corpus Christi	Texas	200,000	0–25
Citgo	Corpus Christi	Texas	163,000	0–25
Valero	Three Rivers	Texas	93,000	0–25
Calumet Lubricants	San Antonio	Texas	16,112	0–25
ExxonMobil	Baton Rouge	Louisiana	502,500	0–25
Motiva Enterprises	Convent	Louisiana	235,000	0–25
Alon Refining	Krotz Springs	Louisiana	80,000	0–25
Placid Refining	Port Allen	Louisiana	59,000	0–25
Delek Refining	Tyler	Texas	60,000	0–25
Calumet Shreveport	Shreveport	Louisiana	57,000	0–25
Holly Refining	Tulsa West	Oklahoma	85,000	0–25
Holly Refining	Tulsa East	Oklahoma	70,300	0–25

Refiner	City	State	Capacity (barrels/day)	Power Outage Area (Probability, %)
Coffeyville Resources	Coffeyville	Kansas	115,000	0–25

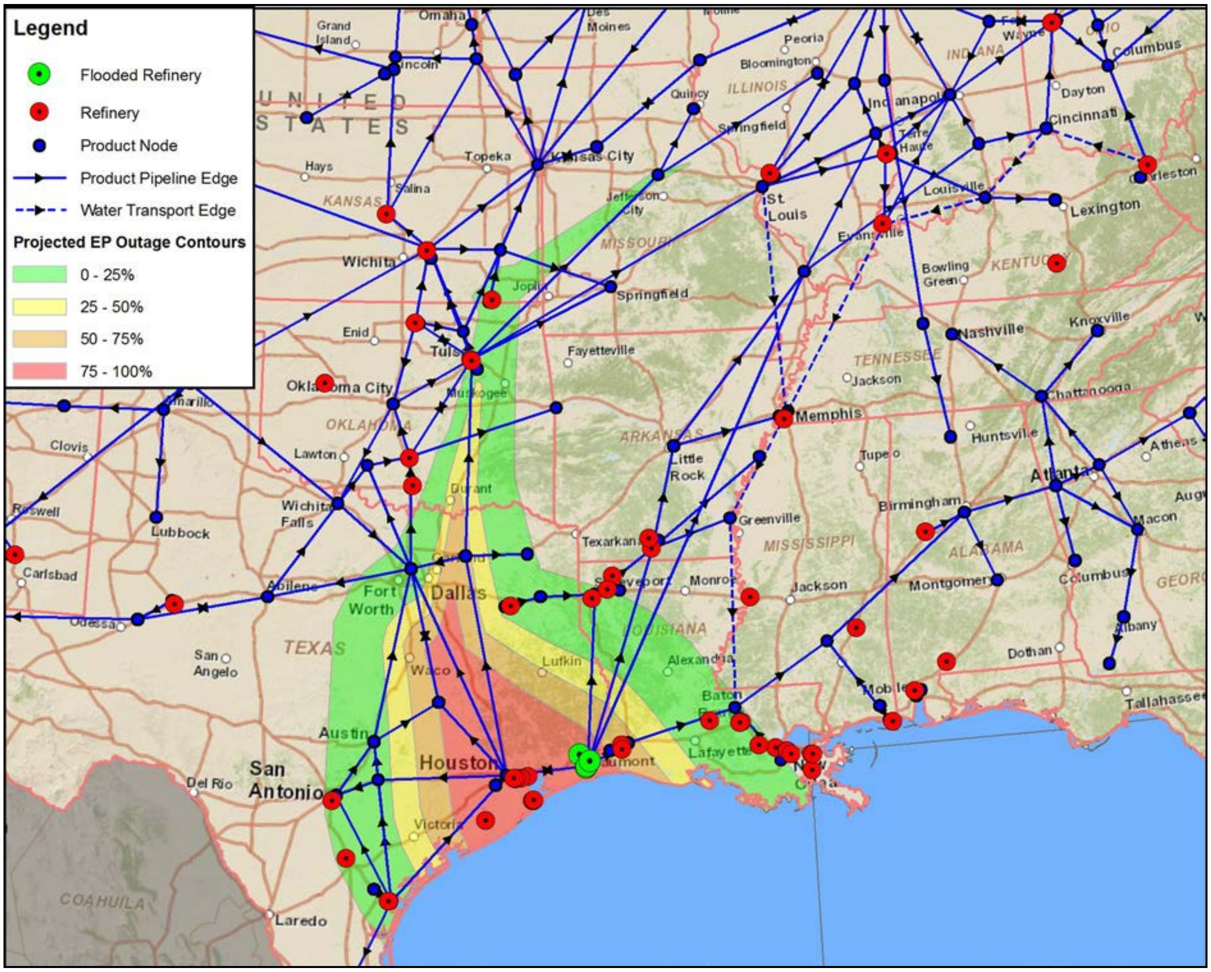

Figure 1. Refineries and product network relative to the projected electric-power outage area.

This analysis based estimates of the duration of closures on information about conditions during Hurricane Rita (2005). Note that offshore production platforms and refineries typically shut down in advance of a storm and come back on line after undergoing inspections and any necessary repairs. To include the pre-hurricane shutdown time in the following list of specific simulation assumptions, Day 0 is the day before landfall.

Offshore production in the Gulf is defined in the scenario as:

Days 0 to 14	100 percent shut in
Days 15 to 21	75 percent shut in

- Days 22 to 28 60 percent shut in
- Days 29 to 42 30 percent shut in

Refineries in the storm-surge inundation area with flooding depth of greater than 8 feet, and in the 75- to 100-percent outage area, are assumed 100 percent shut in for Days 0 to 42 of the simulation. This category includes one refinery in Beaumont and one refinery in Port Arthur.

Refineries in the storm-surge inundation area with flooding depth of 4–6 feet, and in the 75- to 100-percent outage area, are assumed 100 percent shut in for Days 1 to 28 of the simulation. This category includes two refineries in Port Arthur.

Refineries in the 50- to 100-percent outage area, but not in storm-surge inundation areas, are assumed shut in as follows:

- Days 0 to 12 100 percent shut in
- Days 13 to 42 20 percent (one large refinery) shut in

This category includes 12 refineries in the Houston, Texas, and Lake Charles, Louisiana, areas.

Coastal refineries in the 0- to 25-percent outage area are assumed 100 percent shut in for Days 0 to 7 of the simulation. This category includes nine refineries in the Corpus Christi, Texas, and Baton Rouge, Louisiana, areas.

Refineries in the New Orleans, Louisiana, area outside the 0- to 25-percent outage area are assumed 100 percent shut in for Days 0 to 1 of the simulation.

Ports in the 50- to 100-percent outage area are assumed 100 percent shut in for Days 0 to 12 of the simulation. This category includes ports at Houston, Texas City, Freeport, Beaumont, and Port Arthur in Texas, and Lake Charles, Louisiana.

Ports in New Orleans and Baton Rouge in Louisiana, and Corpus Christi, Texas, are assumed 100 percent shut in for Days 0 to 1 of the simulation.

Pipeline segments and distribution terminals in the 50- to 100-percent outage area are assumed 100 percent shut in for Days 1 to 7 of the simulation. This assumption is a simplification of the actual situation, in which power would take longer to be restored in the hardest-hit areas and might be restored in less than 7 days in some areas.

3.1.2 Simulated Impacts

The spatial extent and severity of shortages in the simulation are shown in Figure 2. The areas colored red have severe shortages, while the yellow areas have milder shortages. Shortages are calculated as the total amount of lost consumption over the 60 days after hurricane landfall divided by the normal amount of consumption for those 60 days. As an example, a shortfall fraction of 15 percent could mean no fuel at all for nine days, or no fuel for seven days and then lesser shortages for a while after that, resulting in an average shortfall of 15 percent over 60 days (see Figure 3, below).

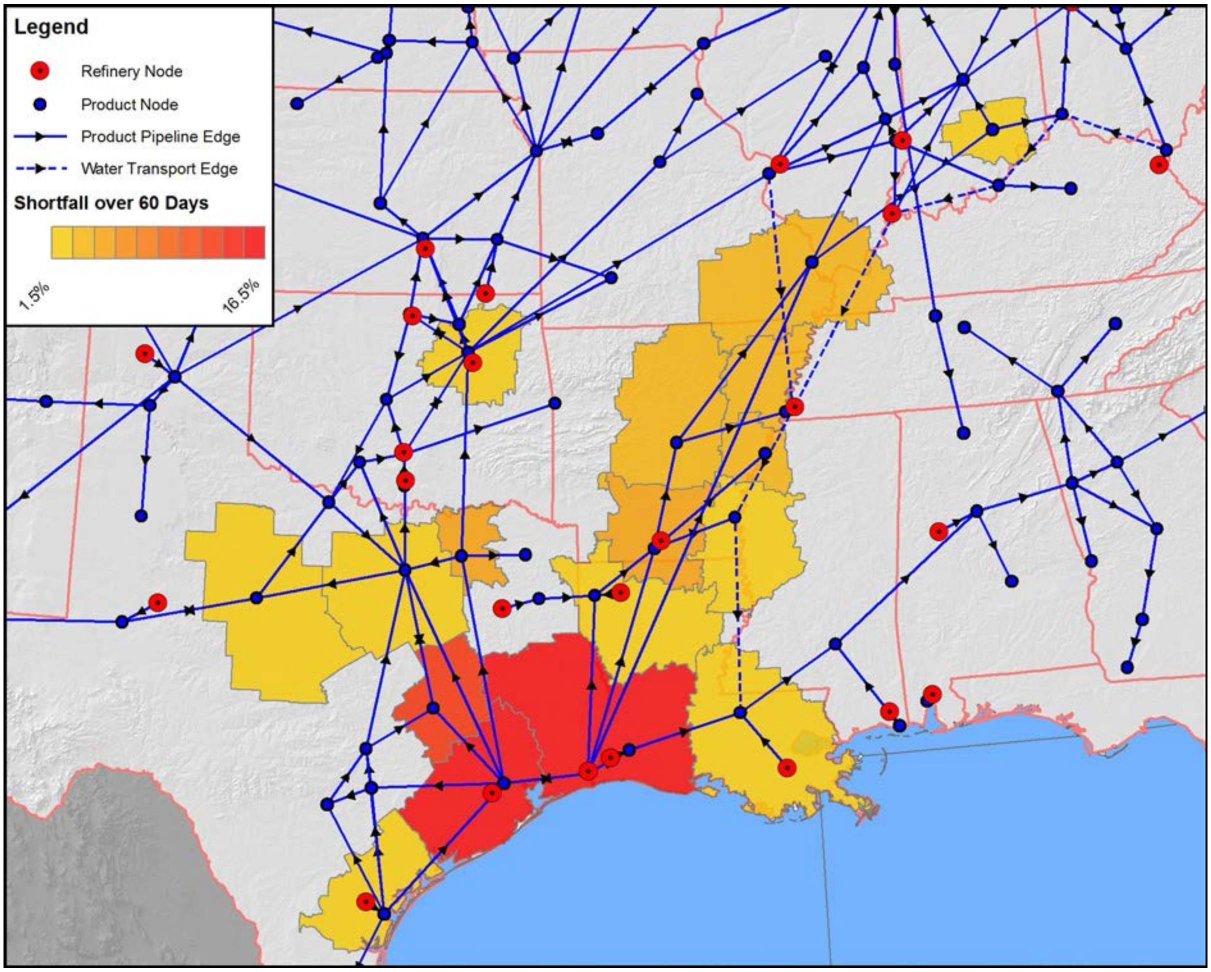

Figure 2. Simulated areas of fuel shortages. Also shown is the NTFM refined-product network.

The fuel shortages in the scenario occur in two stages. In the immediate aftermath of the hurricane, widespread electric-power outages would cause fuel shortages, especially in the Houston–Beaumont–Lake Charles area, because most pipelines and distribution systems require electrical power. Lesser shortages would extend inland to the Dallas-Ft. Worth and Tulsa areas (following the hurricane path after landfall) and along a corridor from eastern Texas and western Louisiana through Arkansas to southern Missouri. After power is restored, refined-product storage in the area would be released to relieve shortages. However, the extended refinery outages, especially in Beaumont and Port Arthur where the refineries are inundated by storm surge, would cause fuel shortages to increase again in the corridor from eastern Texas and western Louisiana to southern Missouri. This area receives much of its refined products from Beaumont through two major pipelines: the 26-inch Centennial pipeline to Martinsville, Illinois, and the 16-inch Enterprise Products pipeline to Seymour, Indiana.

Figure 3 shows that fuel distribution is completely shut down in the Lake Charles area for a week, then recovers, and then much less severe shortages develop later. The graph for the Houston area is very similar. Figure 3 also indicates that the simulated full recovery to normal consumption takes a long time. In this case simulated consumption is still a little over 1 percent below normal 120 days after the storm event. The calculated slow recovery is likely because excess capacity and the drive to refill depleted inventories by acquiring more crude or refined products are slightly underestimated in the model. An assumption of the model is that consumption rate is a function of inventory and consequently consumption will not fully return to normal until inventories do. The slow recovery of the last few percent of consumption is a model artifact and, in an actual event, full normal consumption would be likely to return more quickly after the last refineries return to service at Day 42 in the scenario timeline.

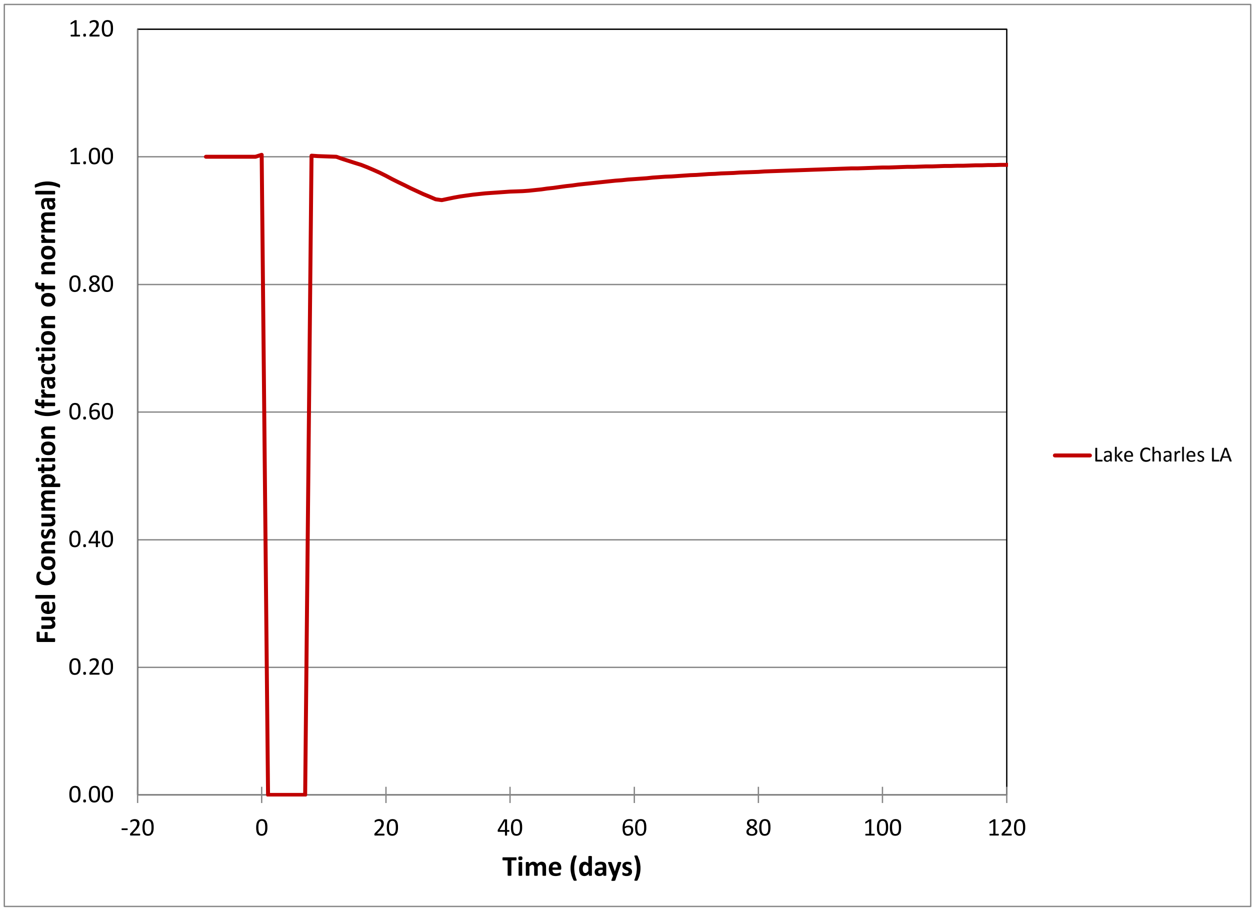

Figure 3. Simulated changes in fuel consumption in the Lake Charles service area.

Figure 4 shows that farther along a pipeline corridor, the severity is less, but the basic timing is similar. The longer-term shortages peak about a month after hurricane landfall, but even at the peak, consumption is less than ten percent below normal rates. Shortages improve after that because two of the Port Arthur refineries come back on line after four weeks. The figure also indicates slight increases (about three-tenths of a percent) in consumption in Lake Charles for a few days before and after the complete shutdown of the distribution terminal there. This increase occurs as both inflows (from refineries) and outflows (water shipments and pipelines) fluctuate rapidly, resulting in a net slight increase in inventory at the terminal for a few days. Although this result is numerically correct for the specified disruption schedule, the small increase in consumption is below the level of resolution of this model and thus not significant. (The same increases are present in Figure 3, but the increases are not evident because the vertical scale of Figure 3 is not exaggerated.)

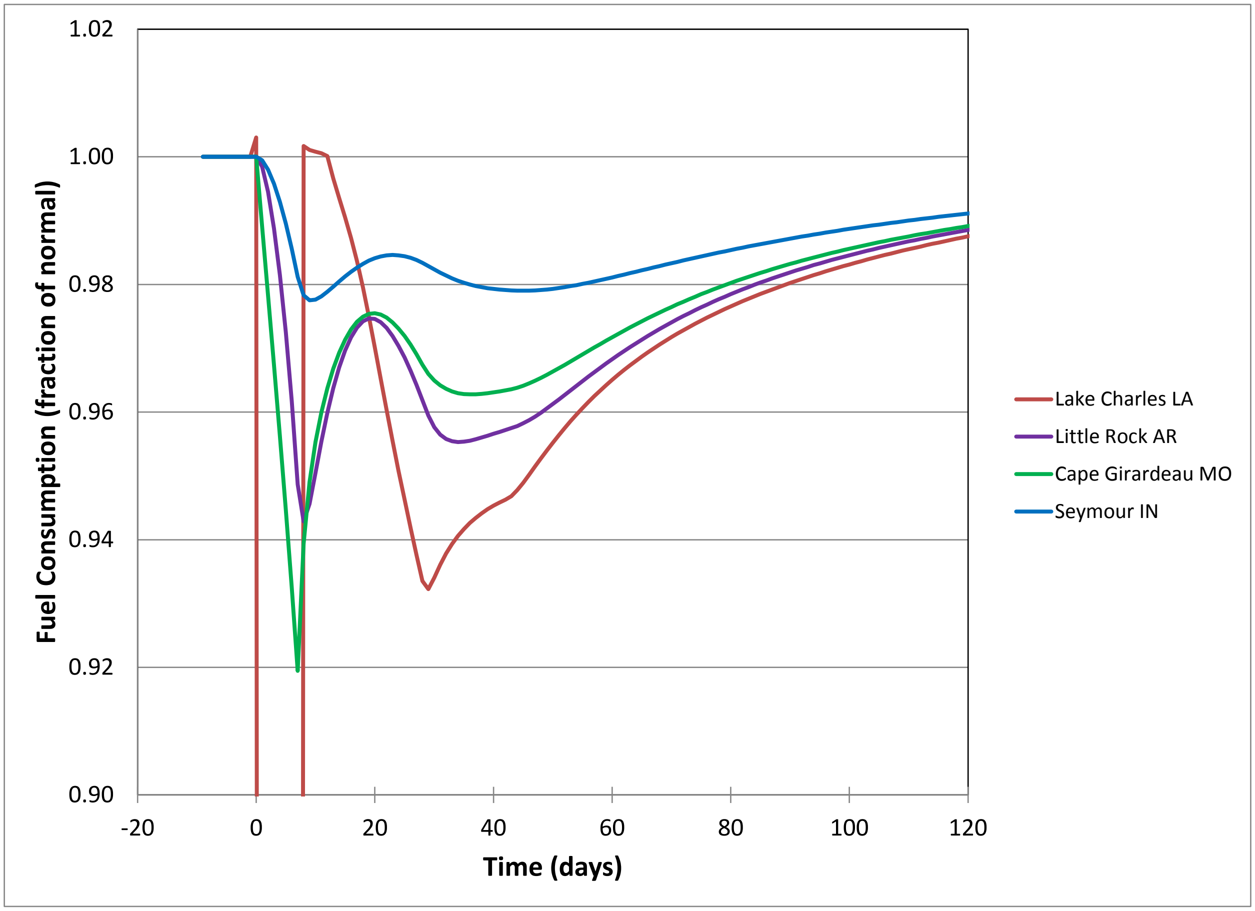

Figure 4. Simulated changes in fuel consumption for areas going north from Lake Charles and Beaumont.

This hurricane scenario results in large decreases—about 50 million barrels—in inventories of refined products in the affected area. While these inventories are recovering, additional stressing events would be more likely to result in fuel shortages.

Shipments of refined products out of the Gulf ports from Corpus Christi to New Orleans also are disrupted (for up to 13 days in the scenario timeline). Most of these shipments are destined for ports in Florida and the U.S. East Coast, so fuel shortages could occur in those areas, too, but any such shortages would likely be insignificant because other sources of supply are available to those areas.

3.2 Mid-Atlantic Hurricane

This analysis assesses the availability of liquid fuels after a hypothetical Category 4 hurricane makes landfall in the Norfolk, Virginia, area.[4] Because the area of the east coast affected by the scenario hurricane is at the downstream end of the liquid fuels supply chain, fuel shortages caused by the storm do not propagate to other areas.

3.2.1 Event Definition

The trajectory, category, and storm size of the hypothetical hurricane in this analysis are based on a scenario previously developed from historical data by NISAC.[5] The hypothetical hurricane was assumed to be a Category 5 storm while in the Atlantic Ocean, decreasing to a strong Category 4 storm at landfall near Norfolk, Virginia. The storm proceeds northward toward Washington, DC, and then central Pennsylvania and western New York.

As for the Gulf hurricane (see Section 3.1.1), storm-surge inundation depths were modeled using the SLOSH model. There is significant flooding from storm surge in Chesapeake Bay and its tributary rivers, including along the Potomac River in Washington, DC. However, no significant petroleum infrastructure is affected by the flooding.

Also as for the Gulf hurricane, the NISAC CICLOPS model was used to estimate maximum sustained wind speeds and damage to the electric-power distribution system throughout the affected area. Six refineries are located in the projected electric-power outage areas: one in the 50- to 75-percent outage area, three in the 25- to 50-percent outage area, and two in the 0- to 25-percent outage area. Table 3 presents further detail about these refineries. In addition to refineries, the hurricane-caused power outages would affect numerous ports, distribution terminals, pipeline pump stations, and other facilities. Figure 5 provides a map showing the projected power-outage areas.

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[4] A Category 4 hurricane has sustained winds from 130 to 156 miles per hour, according to the National Weather Service, "The Saffir-Simpson Hurricane Wind Scale Summary Table," www.nhc.noaa.gov/sshws_table.shtml?large, accessed December 2, 2014.

[5] *Hurricane Scenario Analysis for the Mid-Atlantic Region*, Office of Infrastructure Protection, Infrastructure Analysis and Strategy Division, U.S. Department of Homeland Security, May 2007.

Table 3. Refineries located in the power outage area.

Refiner	City	State	Capacity (barrels/day)	Power Outage Area (Probability, %)
Delaware City Refining	Delaware City	Delaware	182,200	75–100
Philadelphia Energy Solutions	Philadelphia	Pennsylvania	335,000	25–50
Monroe Energy	Trainer	Pennsylvania	185,000	25–50
Paulsboro Refining	Paulsboro	New Jersey	160,000	25–50
Phillips 66	Linden	New Jersey	238,000	0–25
American Refining Group	Bradford	Pennsylvania	11,000	0–25

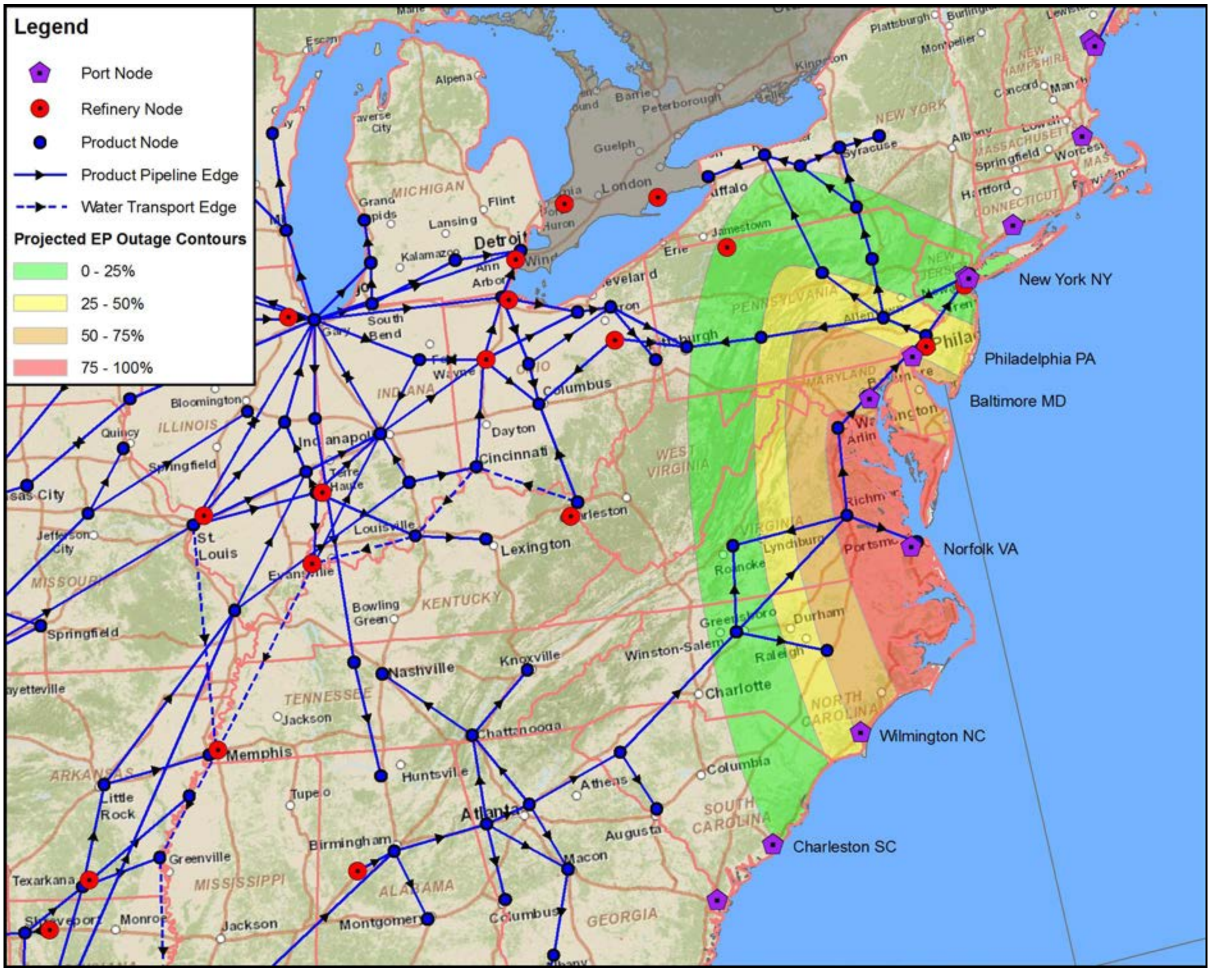

Figure 5. Petroleum refineries, ports, and product network relative to the projected electric-power outage area.

Once again, estimates of the duration of closures are based on information about conditions during Hurricane Rita (2005). Note that refineries typically shut down in advance of a storm and come back on line after undergoing inspections and any necessary repairs. To include the pre-hurricane shutdown time in the following list of specific simulation assumptions, Day 0 is the day before landfall.

Refineries in the 50- to 75-percent outage area are assumed 100-percent shut in for Days 0 to 12 of the simulation. This category includes the refinery in Delaware City, Delaware (near Philadelphia).

Refineries in the 25- to 50-percent outage area are assumed 100-percent shut in for Days 0 to 7 of the simulation. This category includes three other refineries in the Philadelphia area.

Coastal refineries in the 0- to 25-percent outage area are assumed 100-percent shut in for Days 0 to 7 of the simulation. This category includes the refinery in Linden, New Jersey (near New York City).

Ports in the 50- to 100-percent outage area are assumed 100-percent shut in for Days 0 to 12 of the simulation. This category includes ports at Norfolk, Virginia; Wilmington, North Carolina; Baltimore, Maryland; and Philadelphia.

Ports in Charleston, South Carolina, and the New York City area are assumed 100-percent shut in for Days 0 to 1 of the simulation.

Pipeline segments and distribution terminals in the 50- to 100-percent outage area are assumed 100-percent shut in for Days 1 to 7 of the simulation. This assumption is a simplification of the actual situation, in which power would take longer to be restored in the hardest-hit areas and might be restored in less than 7 days in some areas.

3.2.2 Simulated Impacts

While the region affected by the hypothetical hurricane contains a few refineries (see Table 3), most of its fuel is supplied by pipeline from the Gulf Coast (the Colonial and Plantation refined-product pipelines) or by water shipments of imports. Therefore, the severity of shortages depends primarily on how long pipelines, terminals, and ports are out of service because of the storm. In the model simulation, a large area is without fuel supply for a week because of power outages: along the coast from the vicinity of Wilmington, North Carolina, up past Baltimore, Maryland, plus inland for 100 to 200 miles along that strip. Ports are assumed to be out of service longer than pipelines and terminals because they would need repairs and cleanup. Because of this additional delay, the worst shortages are in the area around Wilmington, which receives fuel only by port (no pipelines).

Inventories of refined products are drawn down in the area affected by the hurricane because of lost production at refineries and lost imports at ports while they are shut down. Less-severe fuel shortages persist for some time after power is restored as inventories are restocked.

The spatial extent and severity of fuel shortages in the simulation are shown in Figure 6. The red areas have severe shortages, while the yellow areas have milder shortages. Shortages are calculated as the total amount of lost consumption over the 20 days after hurricane landfall divided by the normal amount of consumption for those 20 days.

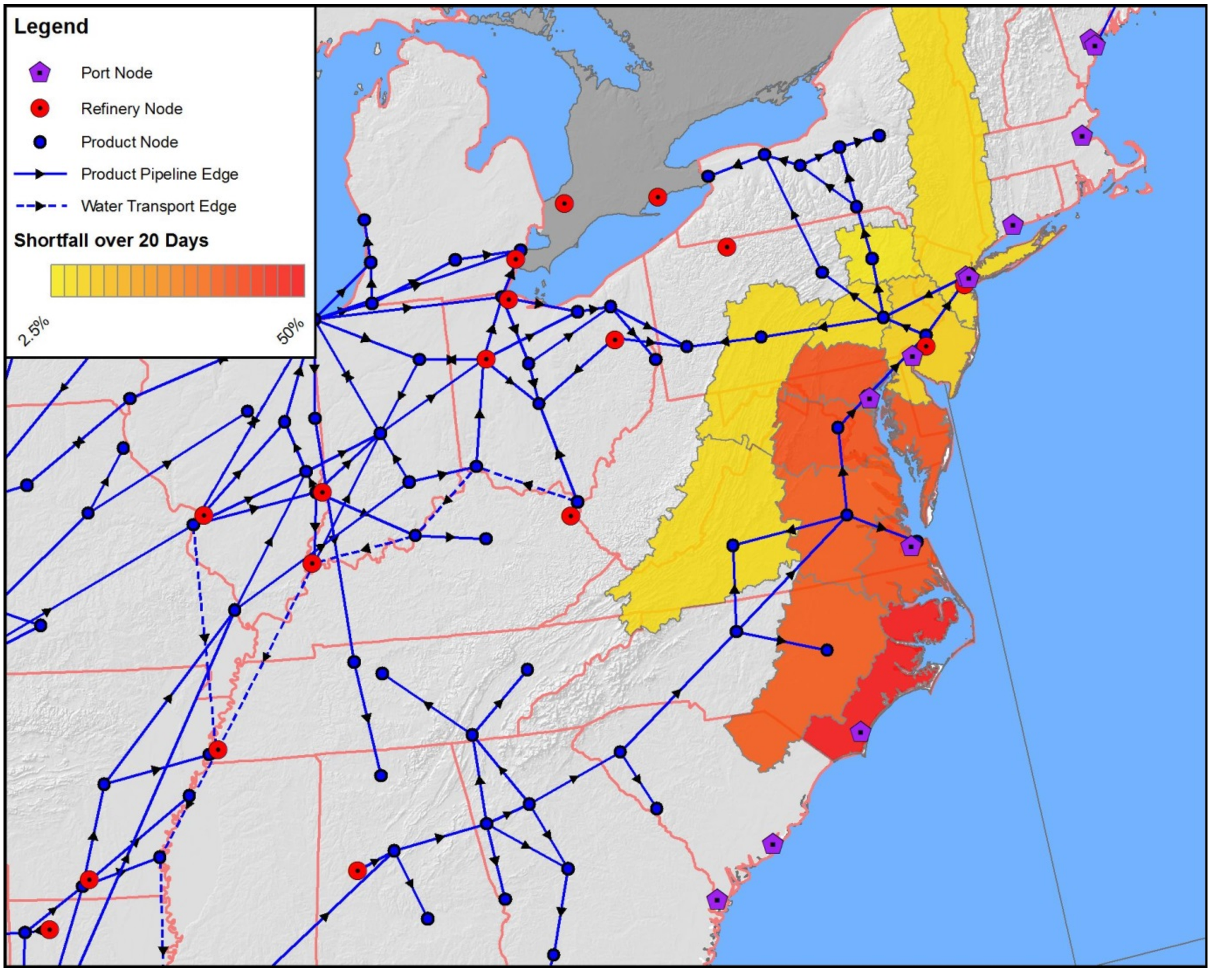

Figure 6. Simulated areas of fuel shortages. Also shown is the NTFM refined-product network.

Figure 7 shows simulation results for two hard-hit coastal areas. Both are assumed to be without fuel supplies for seven days because of power outages, and ports in both areas are assumed to be out of commission for 13 days. The difference between the two is that Norfolk, Virginia, has a pipeline connection in addition to its ports, while Wilmington, North Carolina, is supplied only through the port. The occurrence of a secondary shortage in Wilmington is sensitive to assumptions about fuel demand and the amount of local storage. The distribution terminal is assumed to have approximately a five-day supply of fuels (the national average) at normal consumption rates. Simulated fuel inventories are severely drawn down over the six days between the end of the power outage and the opening of the port but are not completely exhausted because demand is reduced by increased prices. The simulation does not account for a downward pressure on prices that could occur if storm damage reduced the need for fuels (e.g., less driving because roads are blocked). The real-world fuel shortage would be less severe if Wilmington actually has more than five days of local storage. As discussed previously for Figure 3, the slow recovery of the last several percent of consumption is a model artifact and, in an actual event, full normal consumption would be likely to return more quickly after the port returns to service at Day 12 in the scenario timeline.

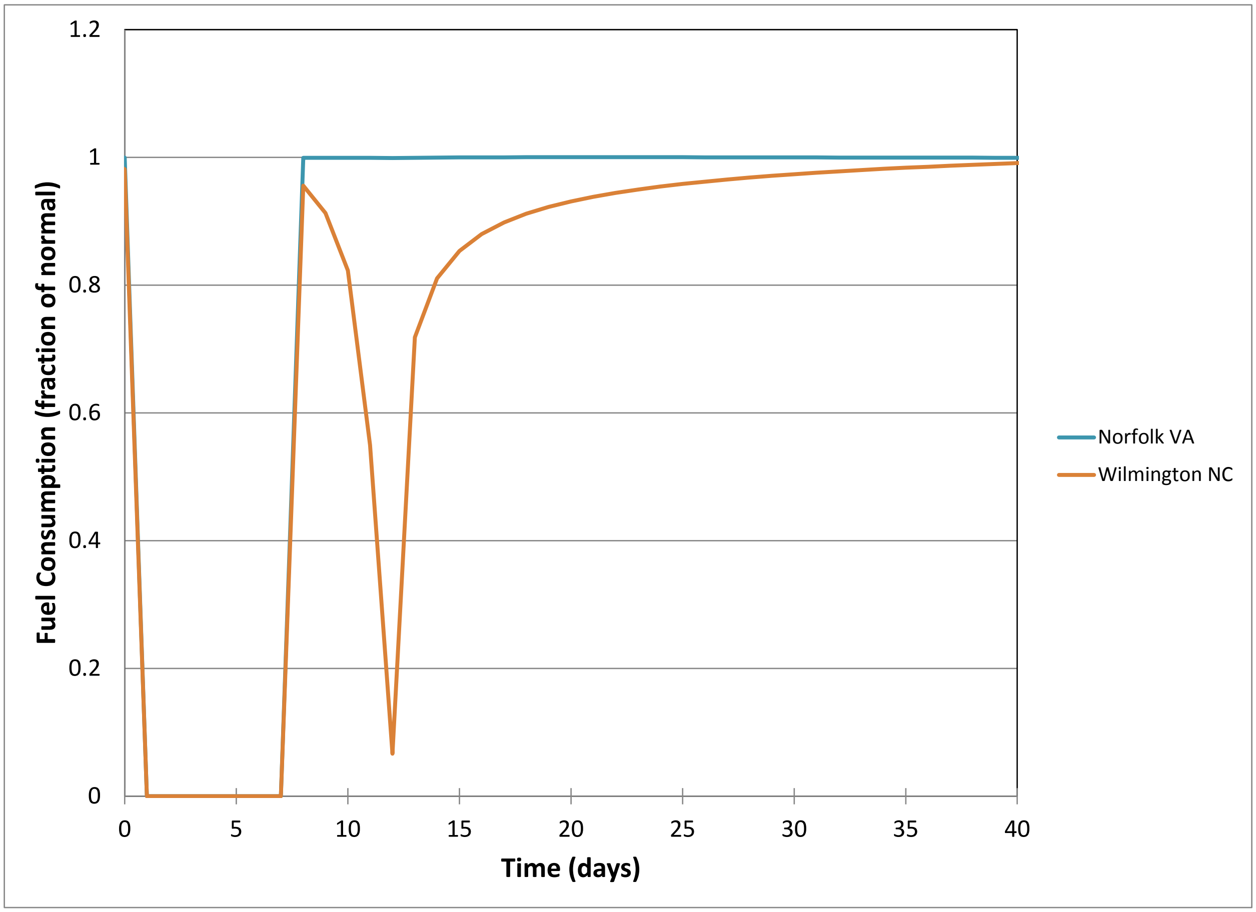

Figure 7. Simulated changes in fuel consumption in the Norfolk and Wilmington service areas.

Figure 8 shows that there are fuel shortages in areas farther from the hurricane landfall, but the severity is less as distance increases. As in Figure 7, the slow recovery of the last several percent of consumption is a model artifact and, in an actual event, full normal consumption would be likely to return more quickly.

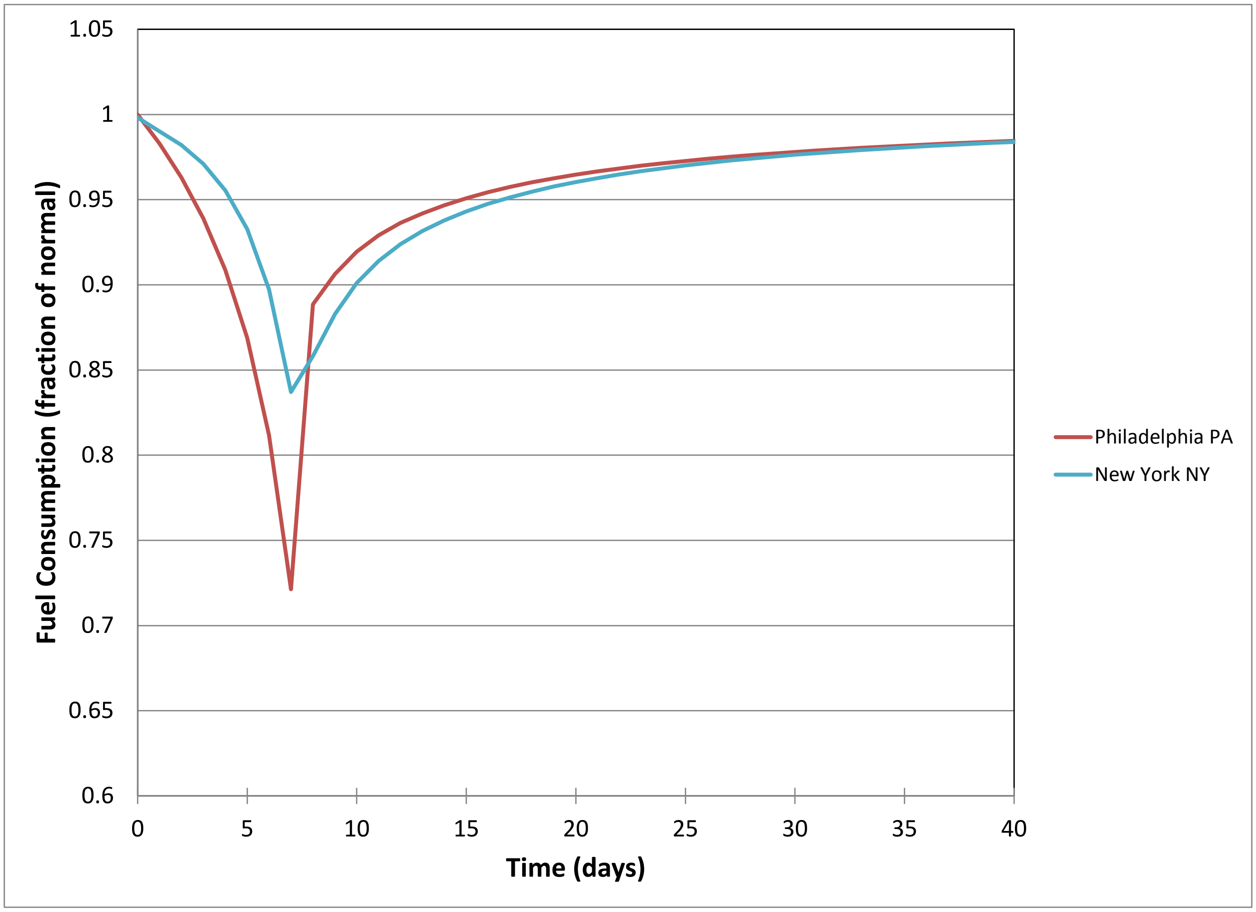

Figure 8. Simulated changes in fuel consumption in the Philadelphia and New York service areas.

3.3 Boston Harbor Oil Spill

3.3.1 Background

Boston Harbor is the largest seaport in New England. It is the home to refined petroleum product import and storage terminals, as well as a liquefied natural gas (LNG) terminal. In 2012[6] Boston Harbor received some 196,000 barrels per day of refined petroleum products, or 27 percent of New England's delivered petroleum consumption.[7]

Figure 9 shows the petroleum facilities in New England and the surrounding area. There are no refineries in New England, though there are refineries in the New York City and greater Philadelphia areas. There also are nearby Canadian refineries in Montreal, St. John, and Halifax. Some of the neighboring ports may have excess capacity in the event of a scenario that disrupts

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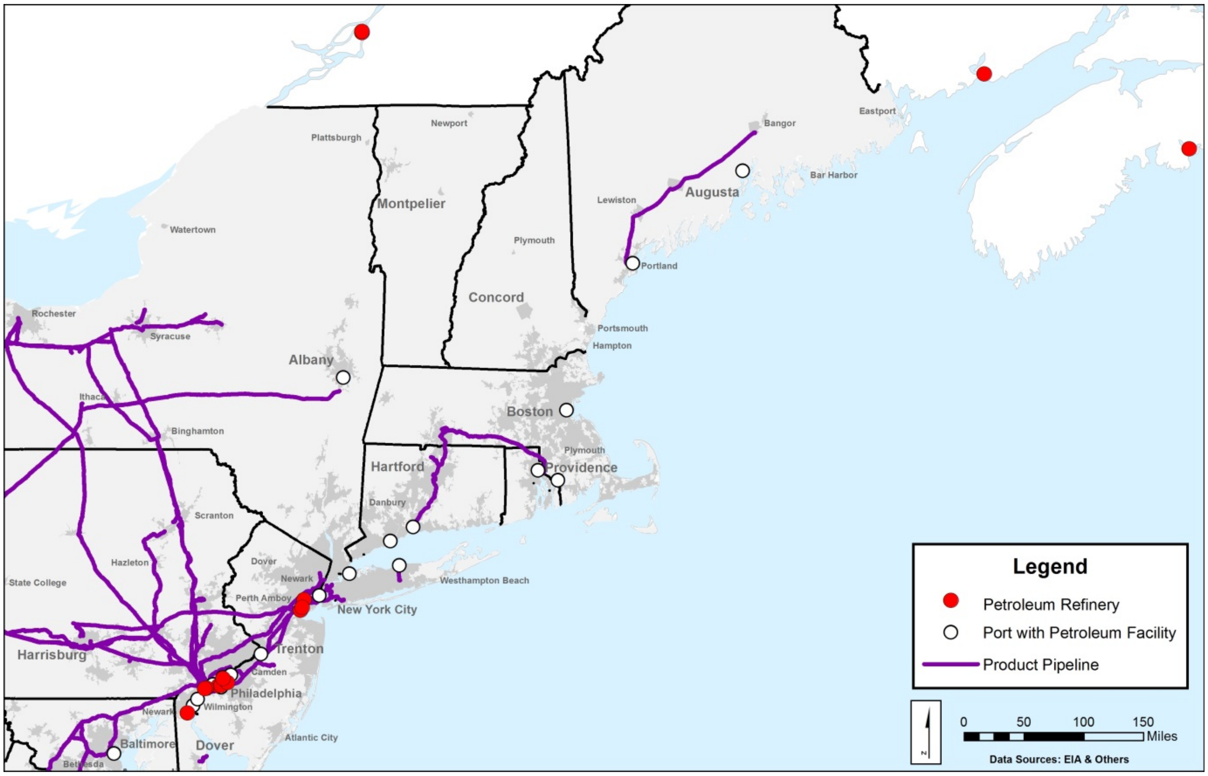
[6] The latest year for which total Boston Harbor petroleum product shipments are available, based on Army Corp of Engineers data.

[7] In 2012, New England consumed some 735,000 barrels per day of petroleum, according to the Energy Information Administration's (EIA's) 2014 Annual Energy Outlook.

Boston Harbor, in particular Providence, Rhode Island; Portland, Maine; and New Haven, Connecticut. While there are a number of petroleum product terminals in New England, there are only two petroleum product pipeline systems—one running between Connecticut and Rhode Island through south central Massachusetts, and one in Maine.



Data Sources: EIA & Others

Figure 9. Petroleum Facilities in New England and Surrounding Area

Figure 10 shows a high-level view of the petroleum facilities in the greater Boston area. As can be seen, most of the terminals and port facilities are clustered in and around the inner harbor, with several in the outer harbor Quincy-Braintree area.

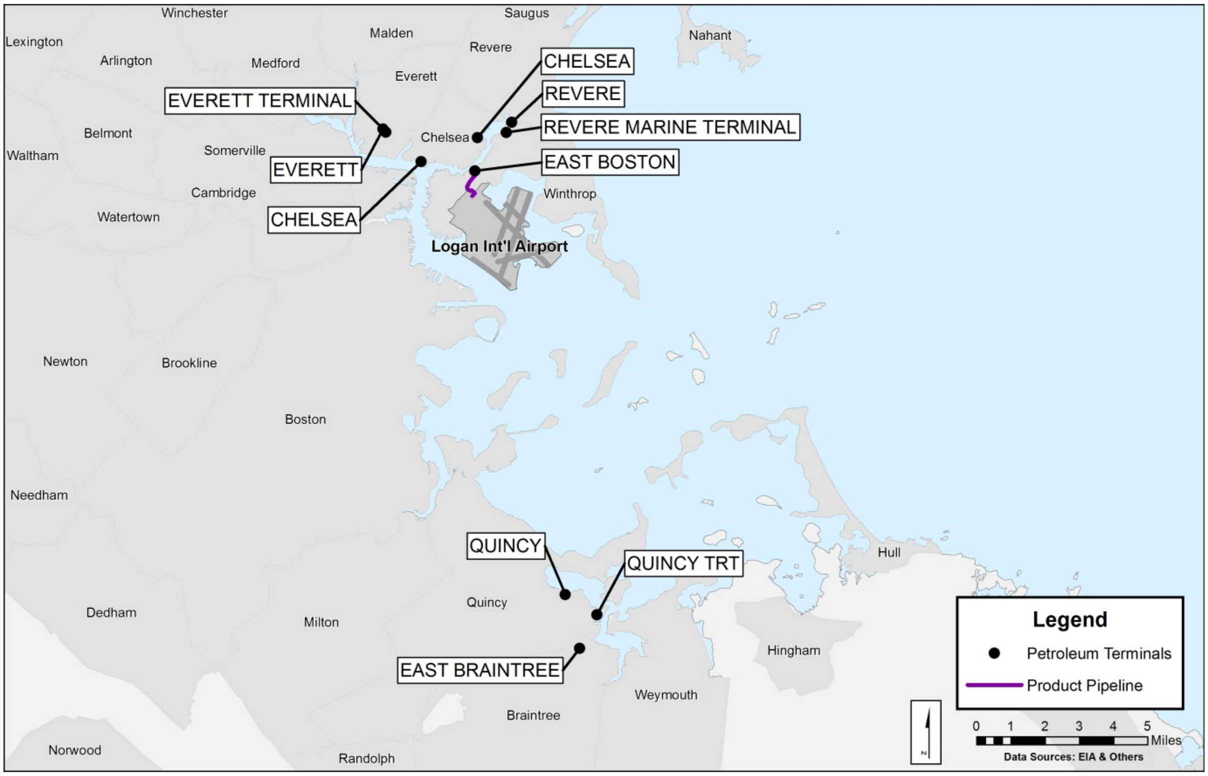


Figure 10. Petroleum Facilities and Terminals in the Greater Boston Area

Figure 11 takes a closer look at the petroleum facilities in the inner harbor area, including the Northeast Home Heating Oil Reserve in Revere. There are seven privately owned petroleum product terminals located in the inner harbor, as well as one LNG terminal. These are listed in Table 4 and Table 5.

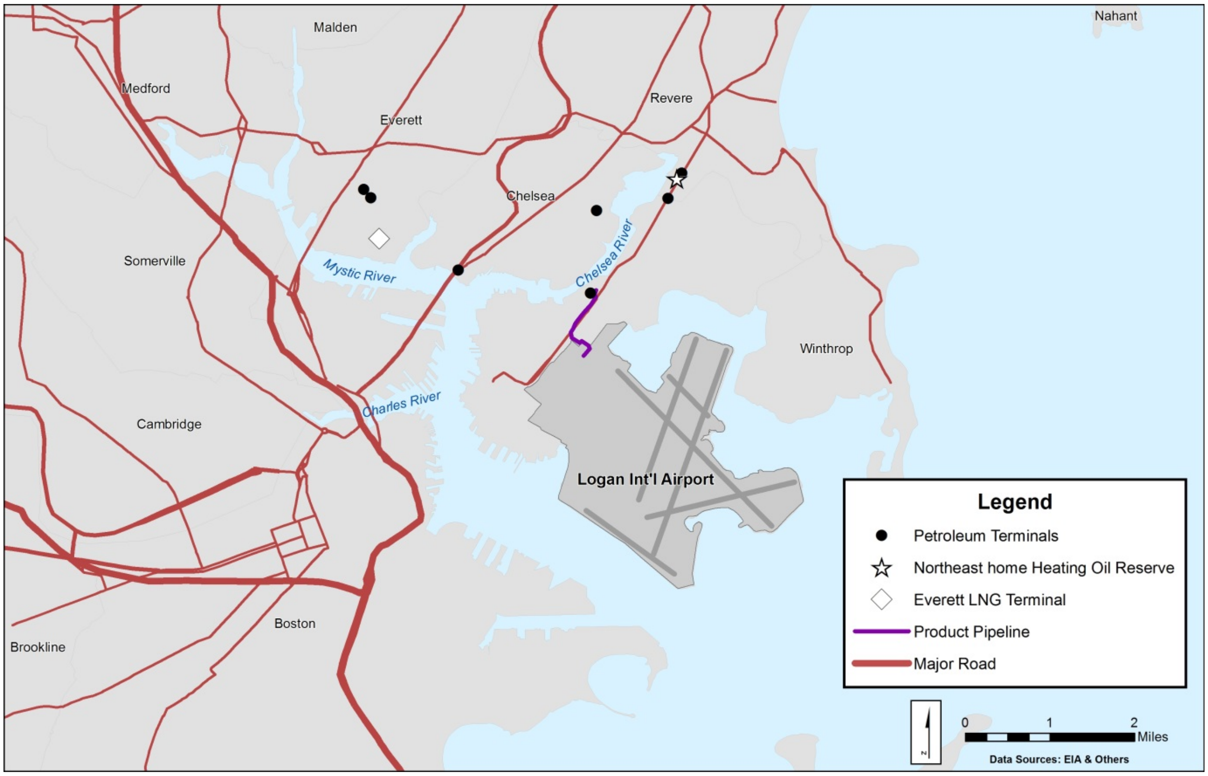


Figure 11. Petroleum Facilities and Terminals in the Inner Harbor Area

Table 4. Petroleum Product Terminal Operators in the inner Boston Harbor.

Petroleum Terminals	City
Sunoco Logistics	East Boston
Global Companies, LLC	Chelsea
Gulf Oil LP	Chelsea
Global Companies, LLC	Revere
Irving Oil Terminals	Revere
Exxon Mobil Pipeline Corp	Everett
Sprague Operating Resources LLC	Everett

Table 5. LNG Terminals Located in Boston Harbor.

Terminal	City	Capacity (billion cubic feet)
Distrigas	Everett	3.4
Northeast	Cape Ann	Not currently operating

Terminal	City	Capacity (billion cubic feet)
Gateway	(Offshore)	
Neptune	Gloucester (Offshore)	0.4 per day, Not currently operating

The Northeast Home Heating Oil Reserve in Revere is just off the Chelsea River and Boston Harbor. This reserve was created in 2000 as the home heating oil component of the Strategic Petroleum Reserve in the Northeast, with the intent of helping the region better cope with a severe winter weather event. The reserve size initially was set at two million barrels, with the expectation that this would provide enough reserve fuel oil for 10 days, providing enough time to route ships from the Gulf of Mexico to New York Harbor. In 2001, this reserve was separated from the Strategic Petroleum Reserve. In 2011, the reserve volume was reduced to 1 million barrels and the reserve's fuel was changed from No. 2 heating oil to ultra-low-sulfur distillate. As of 2012, 500,000 barrels of ultra-low-sulfur distillate are stored at the facility in Revere, and an additional 500,000 barrels are stored at a facility in Groton Connecticut.

In addition, in June 2014 Department of Energy (DOE) Energy Secretary Moniz directed the Office of Petroleum Reserves to establish a one million barrel gasoline component of the Strategic Petroleum Reserve in the Northeast. This was established quickly, and at present, as shown in Table 6, there is one location in Revere (300,000 barrels), one in South Portland, Maine (99,000 barrels), and three locations in New Jersey—Cataret (200,000 barrels), Port Reading (500,000 barrels), and Raritan Bay (zero).

Table 6. Northeast Regional Refined Petroleum Product Reserve.

Terminal Operator	City	Capacity (barrels)
BP Products North America	Carteret, NJ	200,000
Buckeye Terminals LLC	Port Reading, NJ	500,000
Buckeye Terminals LLC	Raritan Bay, NJ	0
Global Companies LLC	Revere, MA	200,000
South Portland Terminal LLC	South Portland, ME	99,000

3.3.2 Analysis

The transportation fuels assets in this region are located at the downstream end of a water transportation system. Because Sandia National Laboratories' National Transportation Fuels Model (NTFM) does not include the transportation (usually by truck) from distribution terminals to gasoline stations and end users, the analysis in this report does not use the NTFM to simulate the impacts of this stressing event.

Typically Boston Harbor has a 5-day heating oil and 7–8 day aviation fuel reserve. Refined product terminals typically have a 5–6 day reserve.

With the current procedures and regulations in place, a major oil spill from a tanker or other cargo vessel in the main area of the harbor appears to be a relatively low probability but high consequence event. If an oil spill were to occur, based on past oil spills it is more likely to occur in the off-loading process at one of the terminals. Nonetheless, a combination of bad weather, the difficulty of navigating portions of the Boston Harbor, and the possibility of mechanical, electronic, and/or human failure suggests that a major oil spill that could close the harbor cannot be ruled out. In this instance, a three-week closure was assumed to help illustrate some of the potential petroleum product consequences for consumers and companies.

The severity of this incident and any shortage will depend on many factors, including how much petroleum product storage and accessible volume is available in and around the shortage area when the event occurs. In addition, expectations will play a key role.

When a hypothetical oil spill in Boston Harbor first occurs, the length of the port closure likely would not be known, but the event would become known to the public. Based on past behavior in perceived shortages, individuals and companies likely would attempt to build petroleum (and other) stocks to be ready for the anticipated shortage. Consumers typically carry about half a tank of gasoline in their vehicles, and with this uncertainty they likely would proceed to top off their tanks. Doing so could create unanticipated shortages at retail gasoline stations and distribution terminals. In turn, these facilities likely would raise their prices to avoid running out. A similar pattern likely would occur for diesel fuel and for heating oil. This process could be expected to take place even while stocks at the Boston Harbor terminals were still available.

The port closure also would affect all other port commerce, and similar stock building by consumers and some companies, with related price increases, might be expected. On the energy side, because LNG shipments to the Everett LNG terminal would be affected, the terminal may need to draw down its stocks. While residential natural gas consumers would not have the ability to store it, electric utilities and natural gas distributors might increase inventories, depending on how full existing storage is and whether there is transportation capacity to move stocks to their facilities.

After the first week or so, Boston Harbor petroleum stocks likely would be depleted, although price increases could act to curtail demand somewhat. The short-term price elasticity of demand for refined petroleum products is quite low, so large price increases would be required to significantly reduce demand.

As previously noted, in 2012 New England consumed some 735,000 barrels per day of delivered energy in the form of refined petroleum products. About 58 percent of this was motor gasoline and 29 percent was distillate fuel oil. For homes, distillate fuel oil and natural gas provided about 33 percent and 29 percent, respectively, of delivered energy consumption, with electricity providing an additional 25 percent. As discussed above, the harbor closing not only would directly affect gasoline and distillate supplies, but also it could indirectly affect residential natural gas and electricity supplies since some 40 percent of New England’s electricity is generated from natural gas.

As these shortages develop, efforts would be made to fill anticipated and actual shortfalls of petroleum products from other sources, including using the ultra-low-sulfur diesel reserves both in Revere, Massachusetts, and in Groton, Connecticut, as well as the newly established gasoline reserves in Revere and elsewhere. However, with limited petroleum product pipeline infrastructure in New England, the shortages may need to be made up by increasing waterborne shipments to other ports (e.g., New York City, Providence, Portland, and New Haven), and then shipping the fuels by truck or rail to the affected area, as available transportation capacity permits. Weather certainly could be a factor here as well. Both federal and state governments would be expected to be actively involved in helping meet these shortfalls, which might include temporary suspension of certain rules/regulations that affect supply. And the private sector, seeing higher prices for refined petroleum products, would have strong incentives to help as well.

Because of the potential environmental and economic damage from the spill, we would expect that every effort would be made to contain and clean up the spill and then to re-open the Harbor as soon as possible. As noted earlier, this "schedule" is unlikely to be known in advance, and could proceed in fits and starts.

As more information is known about the cleanup rate and the actual length of the harbor closure, market anticipation would begin to work toward helping to reduce the shortages and bring prices down. Rates of gasoline/diesel tank and other storage tank anticipatory filling would be expected to decline. And expectations for falling petroleum prices likely would feed this process, with the expectation that petroleum products could be purchased at lower prices in the days ahead.

A hypothetical Boston Harbor oil spill that would close Boston Harbor for three weeks during the winter would be expected to cause some disruption in petroleum supplies, as well as supplies of natural gas and other goods normally entering Boston Harbor. Major contributors to the physical shortage of petroleum products would be the limited petroleum product pipeline infrastructure serving New England and the significant share of petroleum products entering New England through Boston Harbor. This would necessitate moving additional petroleum product supplies from neighboring ports in other states and possibly Canada via truck and rail, available capacity permitting, and with winter weather possibly a factor as well. In addition, expectations about the duration of the Boston Harbor closure would exacerbate the impact of the actual physical shortages and price spikes both on the upside and on the downside. Managing expectations is usually difficult, especially when the conclusion of the event initially is uncertain, and delays may be possible.

This scenario focused on a three-week Boston Harbor closure. With support from involved governments and the private sector, petroleum product flows to the region would be expected to come back into balance with a relative minimum of disruption. However, if the successful cleanup of the spill were delayed, due to severe weather, for instance, the petroleum product system dislocations could be much greater and it could take considerably longer for the system to come back into balance.

3.4 Denver Refinery Explosion

This analysis assesses the availability of liquid fuels after a hypothetical explosion at the refinery complex in Denver (Commerce City), Colorado. This stressing event scenario is patterned after the explosion at the BP Texas City (near Houston, Texas) refinery in March 2005,[8] but is set in Denver rather than Texas City to stress a different part of the liquid fuels system.

The Denver area is served by five refined-product pipelines, which are estimated to provide approximately half the fuel needs under normal conditions. The analysis examines the severity

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[8] See, for example, http://www.csb.gov/bp-america-refinery-explosion/, accessed November 17, 2014.

of the fuel shortfall in the Denver area and the adjustments in the pipeline network flows that result from the loss of the Commerce City refineries.

3.4.1 Event Definition

The Denver refining complex has two refineries next to each other: Commerce City West, with a refining capacity of 67,000 barrels per day, and Commerce City East, with a refining capacity of 36,000 barrels per day. Both refineries are owned by Suncor Energy (USA). This analysis examines how the regional liquid fuels sector might respond to an extended outage of these refineries, which are estimated to provide approximately half the fuel needs for the Denver area under normal conditions.

The hypothetical stressing event is based on the refinery explosion at the BP Texas City refinery in March 2005. After that incident, the Texas City refinery was shut down for a very long time. The Energy Information Administration's annual Refinery Capacity Reports show that the refinery was still completely shut down at the beginning of 2006 and was at only 50 percent capacity at the beginning of 2007 and 2008. (It was finally back in full operation at the beginning of 2009.) Of interest to this analysis is the initial period when the entire refinery is closed. The question addressed is how much of the lost refining capacity can be replaced by changing flows on the liquid fuels network. To answer this question, refinery outage duration is not critical because the flows will come to a new steady state within a few months; thus the disruption was simulated with a nominal outage duration of one year. The modified steady-state flows were examined just before the end of the outage. All infrastructure elements other than the disrupted refinery (pipelines, storage tanks, etc.) were assumed to be intact.

3.4.2 Simulated Impacts

This is a very simple stressing-event scenario, with only one network component disrupted. This basic simplicity provides an opportunity to explore some uncertainty issues in more depth.

Within the NTFM, two methods are available for calculating flows during and after a disruption. These methods are represented in this analysis by two separate simulations that illuminate different aspects of the problem:

- A Physical Availability simulation, which assumes that all local fuel storage and the full capacity of incoming product pipelines are used to alleviate the fuel shortage as much as possible. In terms of reducing the severity of fuel shortages in the Denver area, this method represents the best case.
- A Market Response simulation, which assumes a market-like response with effects dispersed over more time and over a larger area. This method is more realistic in that price increases caused by the refinery disruption can be expected to spread beyond the Denver area and affect fuel consumption in surrounding areas, which does not happen in the Physical Availability simulation. (The Market Response method is the one used for the other stressing events in this report.)

In the Physical Availability simulation, use of local fuel storage plus increased flow in the incoming product pipelines combine to keep fuel consumption at normal levels for over a month after the refinery disruption. After that, fuel consumption in the Denver area decreases by only about 8 percent. Increased production at other refineries and increased flow on product pipelines can only partially compensate for the loss of refining at the Denver (Commerce City) refineries because the total incoming pipeline capacity (see Table 7) is less than the normal fuel consumption rate for the Denver area. Note that the pipeline capacities and normal fuel consumption rate are all estimates, so the actual mismatch could be more or less than the estimated shortfall of 8 percent. The fuel shortfall can be reduced further by bringing in additional fuel by truck or rail. Which refineries increase production is determined by the connectivity and capacity of the product pipeline network and the available excess refinery capacity. In this simulation, production increases (from less than one percent up to about 20 percent) occur at refineries in Montana, Wyoming, Texas, Kansas, and Oklahoma.

Table 7. Product pipelines supplying the Denver area.

Owner	From Node	Diameter (inches)	Estimated Capacity (barrels/day)
Sinclair	Sinclair, WY	6	14,000
Plains (Rocky Mountain)	Cheyenne, WY	8	43,000
NuStar	Borger-McKee, TX	10	49,000
Phillips 66	Borger-McKee, TX	8	31,000
Magellan	Wichita-El Dorado, KS	10	50,000
Total			**187,000**

In the Market Response simulation, fuel consumption falls much sooner (starting after about a week) than in the Physical Availability simulation and falls significantly more (about 23 percent). Fuel shortages (i.e., reductions in fuel consumption) occur not only in the Denver area, but also in surrounding areas (although less severe). Most notably, fuel consumption decreases by about 6 percent in the Cheyenne, Wyoming, area. The concept embodied in this simulation is that fuel prices increase throughout the region, causing reductions in fuel consumption, with the effects declining with distance from Denver (and depending on the connectivity and capacity of the pipeline network). Refineries outside Denver with excess capacity also respond to this price signal and increase production. Like consumption reductions, the refinery response is also much more widespread in this simulation than in the Physical Availability case, with many refineries having a slight increase in production.

Figure 12 shows the simulated reduction in consumption for the area around Denver, Colorado, caused by the loss of the Commerce City refineries on Day 1. Results for the Physical Availability (blue curve) and Market Response (red curve) simulations are shown. As already noted, the Market Response case also has less-severe reductions in consumption in surrounding areas, whereas in the Physical Availability case, fuel shortages are limited to the Denver area.

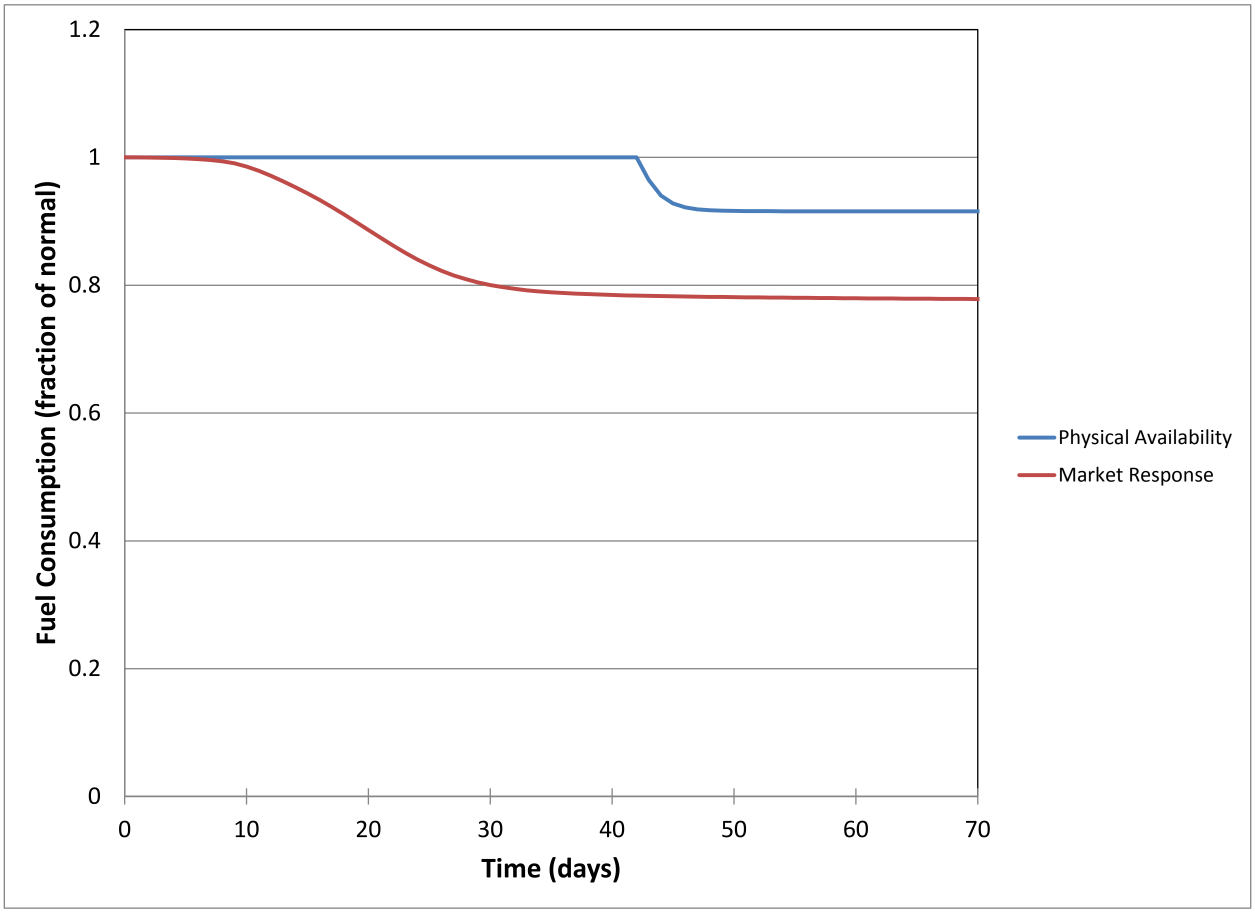

Figure 12. Simulated changes in fuel consumption in the Denver service area.

Figure 13 shows how flows change in the refined-product pipeline network to provide additional fuel to the Denver area in the Physical Availability model simulation. Model edges with a flow increase greater than one percent are colored green. In this simulation, refineries in Montana, Wyoming, Texas, Kansas, and Oklahoma increase production by varying amounts to compensate for the loss of refining at Denver.

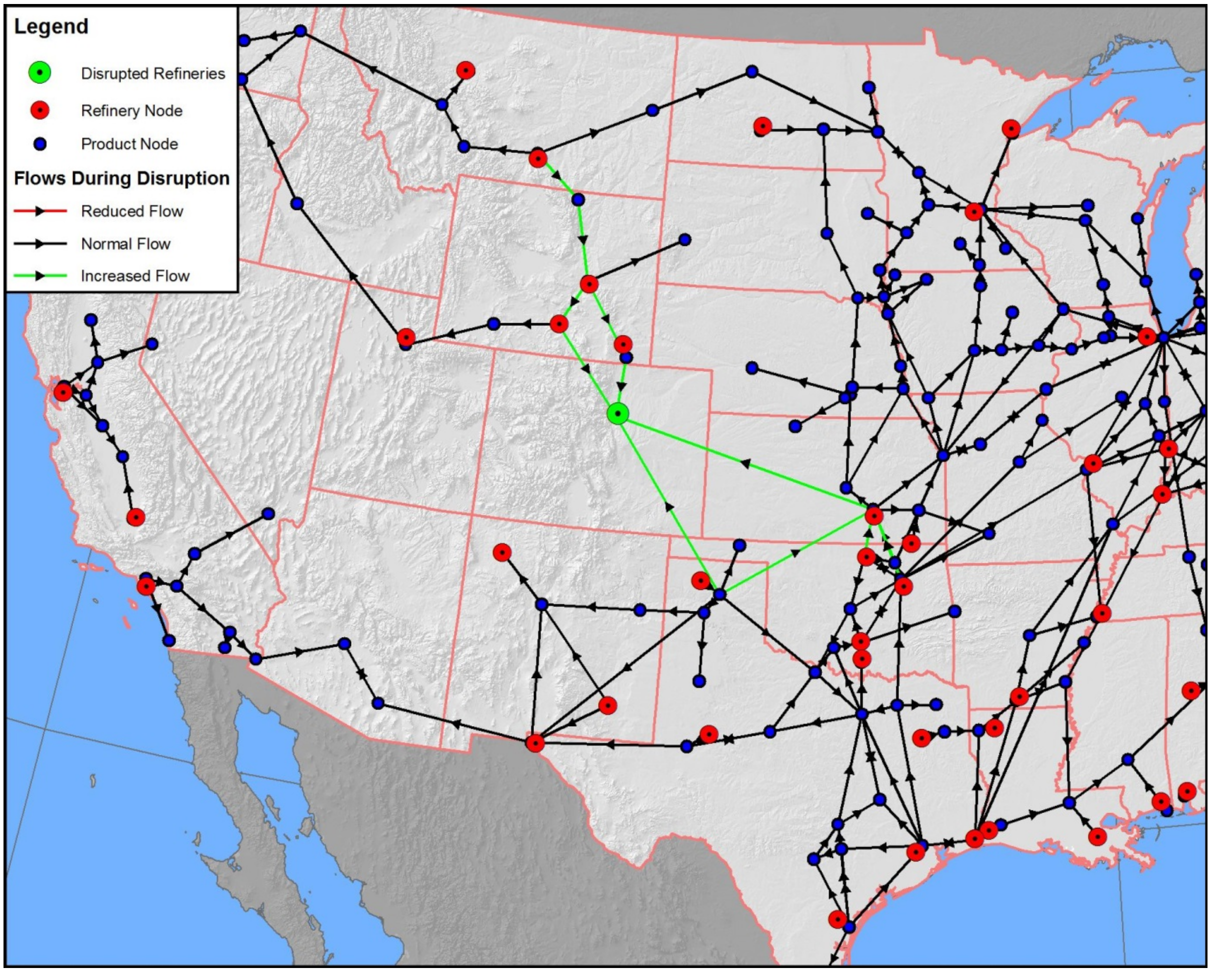

Figure 13. Simulated changes in the flow on product pipelines for the Physical Availability case.

Figure 14 shows the flow pattern changes for the Market Response model simulation. Model edges with a flow increase greater than one percent are colored green and edges with a flow decrease greater than one percent are colored red. The response is much more widely dispersed than the flow pattern changes for the Physical Availability case shown in Figure 13. The Market Response simulation results show a slight increase in production at many refineries and small changes in flow along many pipelines.

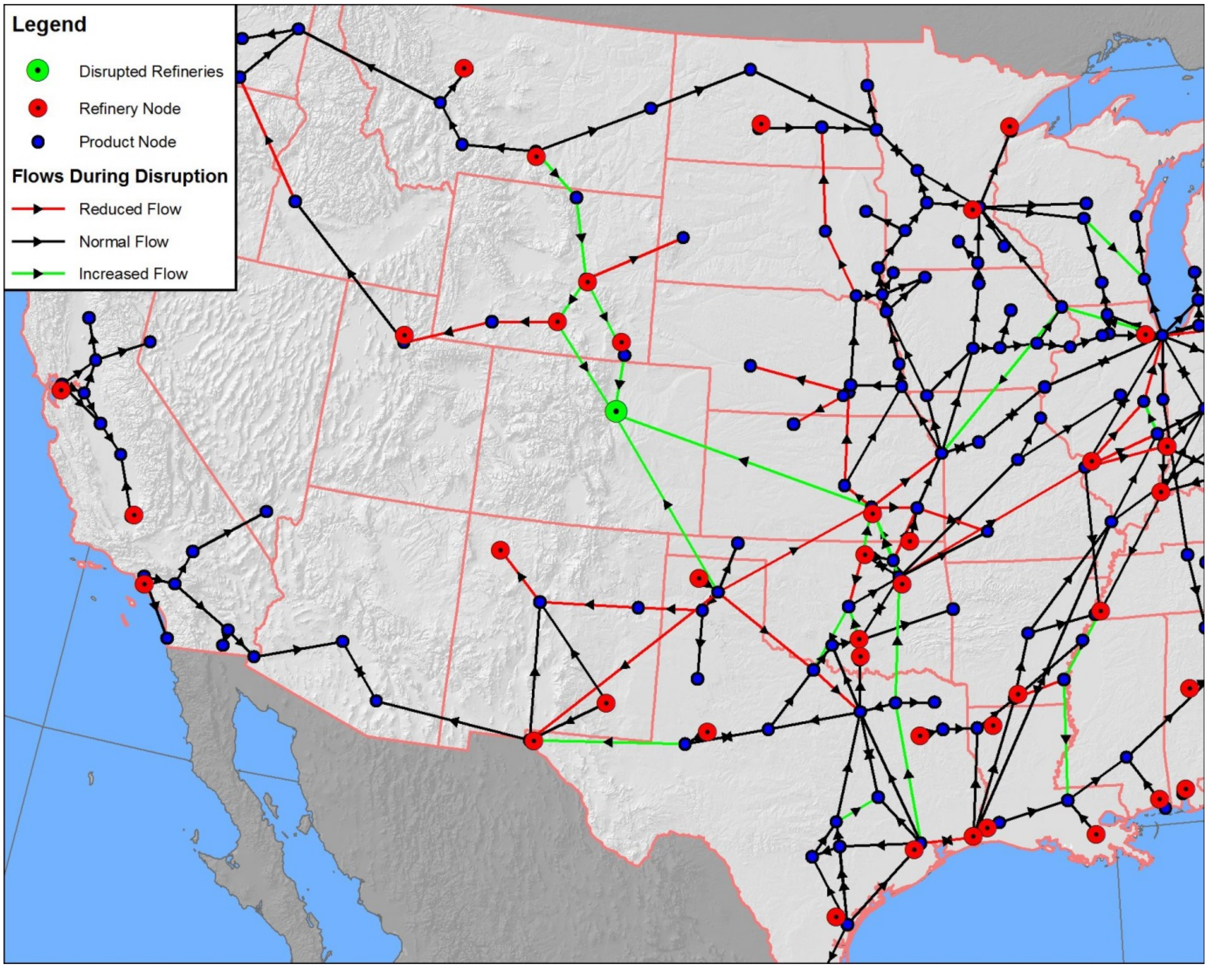

Figure 14. Simulated changes in the flow on product pipelines for the Market Response case.

3.5 New Madrid Earthquake

This analysis assesses the availability of liquid fuels after a hypothetical large earthquake in the New Madrid Seismic Zone (NMSZ). The NMSZ, stretching along the Mississippi River Valley from southern Illinois to Memphis, Tennessee, is the site of some of the largest historical earthquakes to strike the continental United States.[9] The most recent of these very powerful earthquakes occurred in a cluster during the winter of 1811–12. The earthquakes of 1811–12 included at least six magnitude-7 and two magnitude-8 earthquakes.[10] The U.S. Geological Survey (USGS) estimates that there is a 7- to 10-percent chance of earthquakes with magnitudes equivalent to the 1811–12 quakes occurring in any 50-year period,[11] which is approximately the

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[9] Gomberg, J., and E. Schweig, 2007, “Understanding Earthquake Hazards in the Central United States: Earthquake Hazard in the Heart of the Homeland,” U.S. Geological Survey Fact Sheet 2006-3125, 4 pp.

[10] Johnston, Arch C., and Eugene S. Schweig, 1996, “The Enigma of the New Madrid Earthquakes of 1811–1812,” *Annual Reviews of Earth Planet. Sci,.*, 24:339–84.

[11] Gomberg, J. and E. Schweig, 2007, “Understanding Earthquake Hazards in the Central United States: Earthquake Hazard in the Heart of the Homeland,” U.S. Geological Survey Fact Sheet 2006-3125, 4 pp.

same frequency as predicted for very large earthquakes in California. However, the geology of the NMSZ is such that an earthquake could damage structures over a much larger area than a similar earthquake in California.[12] A repeat of the 1811–12 cluster of earthquakes today not only would cause a human catastrophe, but also would cause extensive damage to crude oil and refined product transmission pipelines, a refining complex in Memphis, and water transportation facilities on stretches of the Mississippi River.

3.5.1 Event Definition

The hypothetical earthquake is based on a scenario developed by the USGS Earthquake Hazards Program for a 7.7-magnitude earthquake with an epicenter northwest of Memphis, Tennessee.[13] A standard measure of the degree of shaking intensity of seismic events is the Modified Mercalli Intensity (MMI). Levels of MMI are designated by Roman numerals ranging from I to XII, with larger numbers indicating greater shaking intensity. Shaking at MMI intensity IX or greater is thought to be sufficient to liquefy lowland soils in river valleys.[14] Even robustly engineered structures will fail if their ground support is removed. The most important components of petroleum infrastructure within the area of severe damage are four major transmission pipelines and the Memphis refinery. The Capline and Mid-Valley pipelines carry crude oil to Midwest refineries. The Enterprise/TEPPCO and Marathon Centennial pipelines carry refined products. A map showing projected MMI contours and pipelines and refinery locations is presented in Figure 15. Shaded regions represent the shaking intensity of the scenario earthquake. The red region is at MMI intensity IX and the amber region is at MMI intensity VIII.

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[12] Schweig, E., J. Gomberg, and J. W. Hendley, II, 1995, “Whole Lotta Shakin’ Goin’ On,” U.S. Geological Survey Fact Sheet 168-95, 2 pp.

[13] http://earthquake.usgs.gov/regional/ceus/products/download/regional/nm_sw_mmi.gif , accessed October 15, 2008.

[14] Obermeier, S. F., 1985, “Nature of liquefaction and landslides in the New Madrid earthquake region,” *in* Estimation of Earthquake Effects Associated with Large Earthquakes in the New Madrid Seismic Zone, M. G. Hopper (Ed.), U. S. Geological Survey Open File Report 85-457, pp. 24–38.

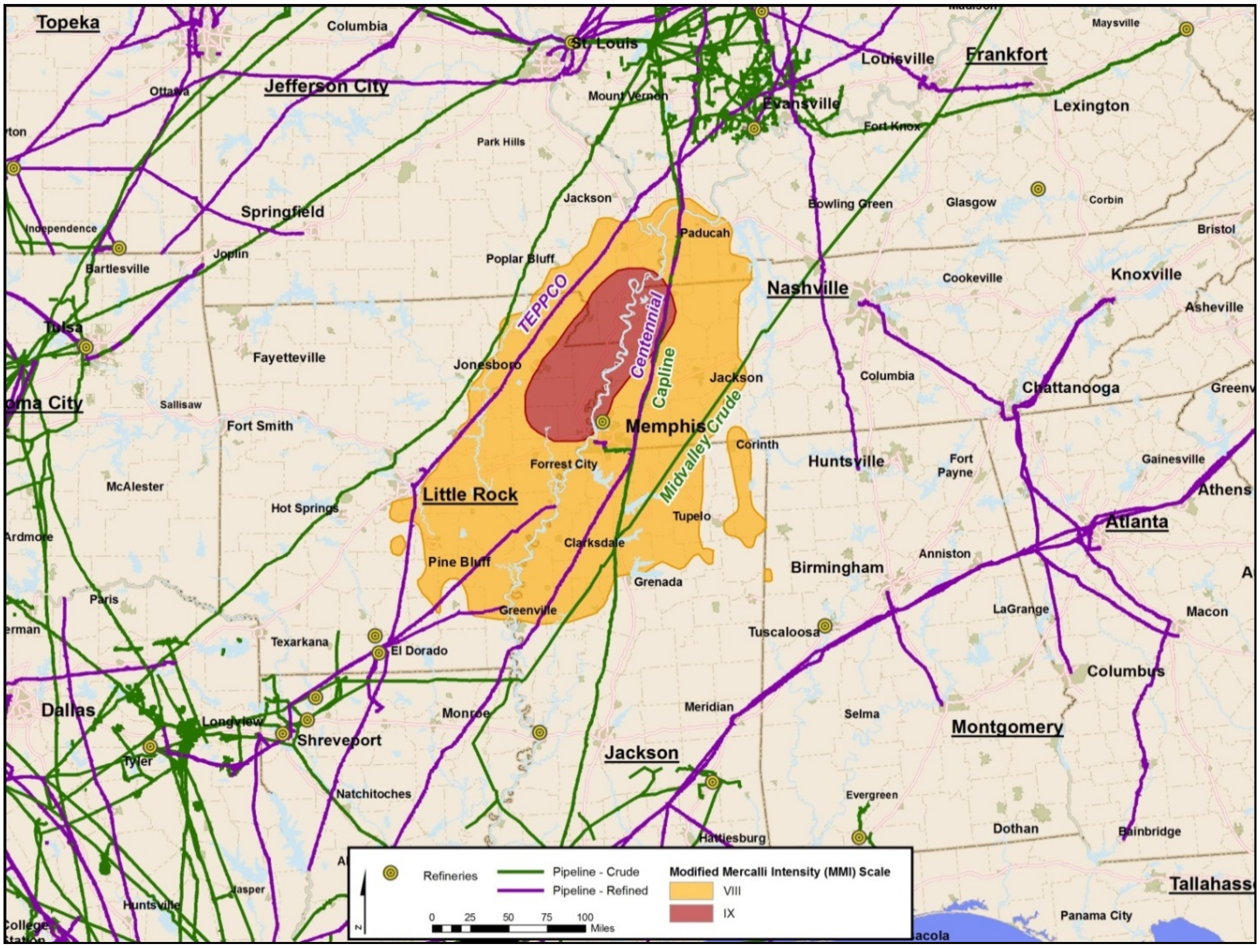

Figure 15. Hypothetical NMSZ earthquake shaking contours and affected petroleum pipelines.

Barge transportation of petroleum on the Mississippi River and a major rail line in eastern Arkansas that currently transports Bakken crude to the Saint James Terminal in Louisiana also could be affected. Although rail shipments could be re-routed around the NMSZ, barge transportation would not have alternative routes.

More generally, a New Madrid earthquake could severely disrupt navigation on the Mississippi and Ohio rivers. Disruptions could be due to destruction of terminals and other shore facilities, damage to locks on the Ohio River, or to changes to the rivers themselves. Landslides caused by an earthquake could block river channels, change the course of rivers, and dump massive amounts of sediment into navigation channels. Several types of landslides have occurred during historic large earthquakes. During the 1811–12 earthquakes, thousands of landslides occurred along the Mississippi River from Cairo, Illinois, to Memphis.[15] The analysts are not aware of geologic studies that have estimated the total impact of these landslides on the rivers or of engineering studies that have estimated the time required to repair locks and terminal facilities or

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[15] Obermeier, S. F., 1985. "Nature of liquefaction and landslides in the New Madrid earthquake region," *in* Estimation of Earthquake Effects Associated with Large Earthquakes in the New Madrid Seismic Zone, M. G. Hopper (Ed.), U. S. Geological Survey Open File Report 85-457, pp. 24–38.

to dredge and chart new river channels. Because it seems likely that these tasks could take several months, this analysis considers the possible consequence of no barge traffic on the Mississippi and Ohio rivers for an extended period.

Damage is expected to be most severe within the MMI IX area and extensive within the MMI VIII area. For the purposes of this stressing-event analysis, the following specific assumptions were made:

- The only refinery directly affected is in Memphis, Tennessee; it is shut down for approximately one year.
- The Mississippi River is closed to barge traffic from the Ohio River down to Greenville, Arkansas, for approximately one year.
- Pipelines that go through the MMI IX area, which includes segments of the Capline crude pipeline, a Premcor crude pipeline that supplies the Memphis refinery, and the Marathon Centennial refined-product pipeline, are shut down for 100 days.
- Pipelines that go through the MMI VIII area , which includes segments of the Mid-Valley crude pipeline and Enterprise/TEPPCO refined-product pipelines, are shut down for 60 days. Barge traffic on the Mississippi River below Greenville is shut down for 60 days also.
- The distribution terminals in the NTFM that are directly affected by the scenario earthquake are Memphis, Tennessee, and West Memphis, Arkansas (both shut down for 30 days), Helena, Arkansas (shut down for 7 days), and Arkansas City, Arkansas (shut down for 3 days). These outage durations are based on estimates of electric-power restoration times[16] and do not include possible extended down times and loss of fuel storage that could be caused by physical damage to storage tanks.

3.5.2 Simulated Impacts

In addition to the areas directly affected by the hypothetical earthquake, there are fuel shortages in areas that are supplied by pipelines that transit the earthquake area. In particular, shortages occur in parts of Arkansas, Missouri, Illinois, Indiana, Kentucky, Ohio, and West Virginia because of the disruption of the TEPPCO and Centennial refined-product pipelines. Detailed observations from the simulation include:

- Fuel consumption drops to zero in the directly affected areas, including the areas around Memphis, Tennessee, and Cape Girardeau, Missouri, and around the Arkansas cities of West Memphis, Arkansas City, Helena, and Little Rock. (As a practical matter, fuels are not expected to completely run out because emergency measures likely would be taken: for example, trucking in fuels to mitigate the shortages from disrupted pipelines.)
- Areas not directly affected by the earthquake do not run out of fuels immediately, but are able to continue their consumption using local storage. For example, in Little Rock, local storage lasts for almost two weeks before it runs out. Normally there is not enough local

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[16] 2008 NISAC New Madrid Seismic Zone Study: Scenario Analysis of Earthquake Impacts to Infrastructures and the Economy, National Infrastructure Simulation and Analysis Center, DHS Office of Infrastructure Protection, February 2009.

storage for that long, but there is extra storage of fuels that would normally be sent to West Memphis and Cape Girardeau but cannot because the pipelines are out.

- Consumption rebounds after 60 days when the Enterprise/TEPPCO pipelines are brought back into service, but lesser fuel shortages remain in some locations until the Marathon Centennial pipeline is back in service after 100 days.
- Normal fuel supplies for Memphis are cut off for a year because the local refinery and barge traffic on the Mississippi River are both assumed to be disrupted for that period. Demand for fuels likely would be lower than normal because of earthquake damage. At the same time, alternative supply methods, such as truck and possibly rail, likely would be used to meet remaining demand.
- Several refineries in Ohio and Kentucky have temporary reductions in output because of the disruption to the Mid-Valley crude pipeline, but they are not severely affected because they also have other supply routes. Of note is that the Chicago area refineries are not affected. Until fairly recently, the Capline pipeline was a major supply artery for the Midwestern refineries, but now they are getting more of their supply from Canada and thus are not as vulnerable to an NMSZ earthquake as in the past.

The spatial extent and severity of shortages in the simulation are shown in Figure 16. The areas with darker colors have severe shortages, while the yellowish areas have milder shortages. Shortages are calculated as the total amount of lost consumption over the 120 days after the earthquake divided by the normal amount of consumption for those 120 days.

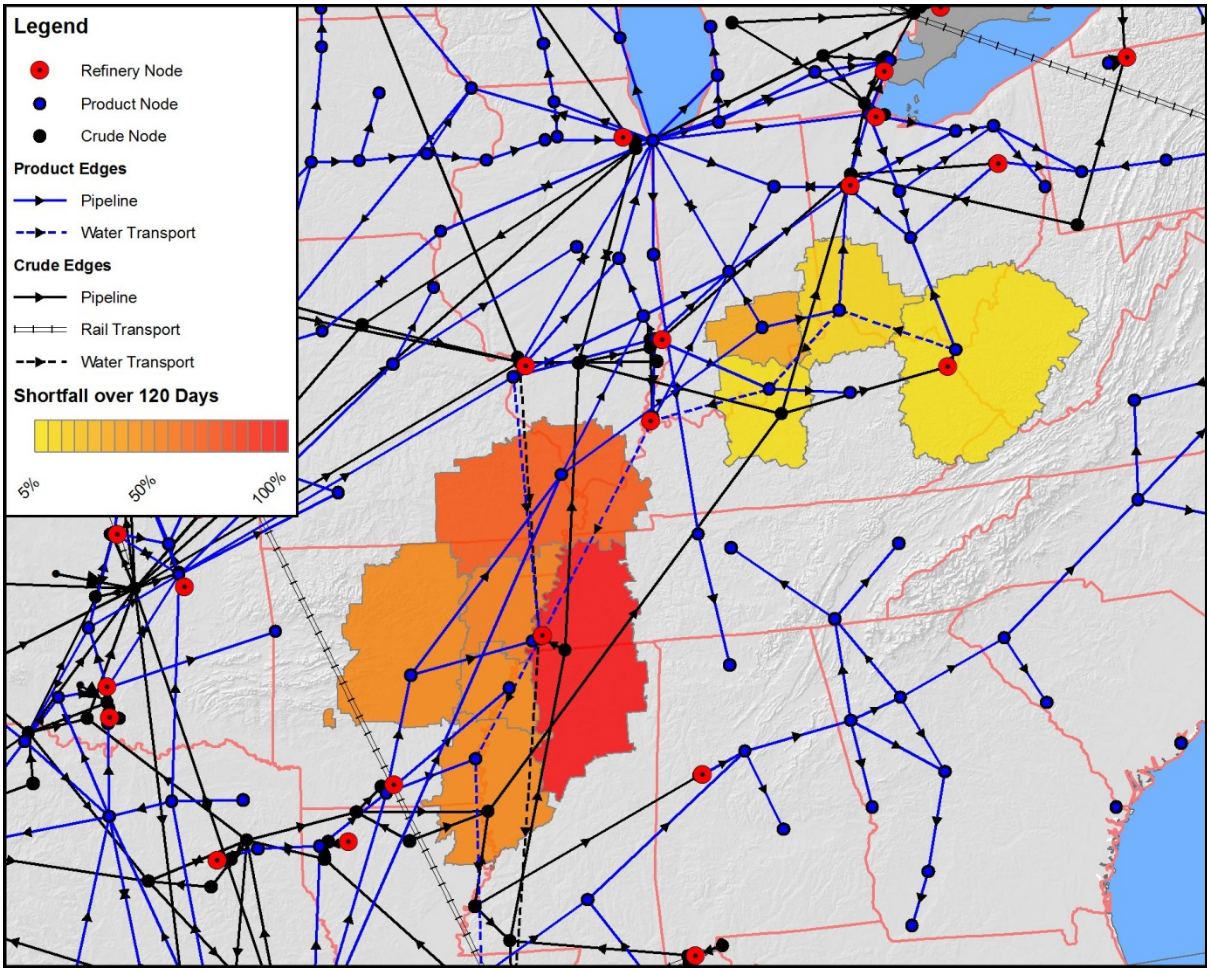

Figure 16. Simulated areas of fuel shortages.

Figure 17 shows that as distance from the directly affected area increases, the severity is less, but the basic timing is similar. Shortages are severe in some areas until the Enterprise/TEPPCO pipelines are brought back into service after 60 days, and lesser fuel shortages remain in some locations until the Marathon Centennial pipeline is brought back into service after 100 days. Fuel consumption in Memphis (not shown in the figure) drops to zero for a year in this scenario because the local refinery and barge traffic on the Mississippi River are both assumed to be disrupted for a year.

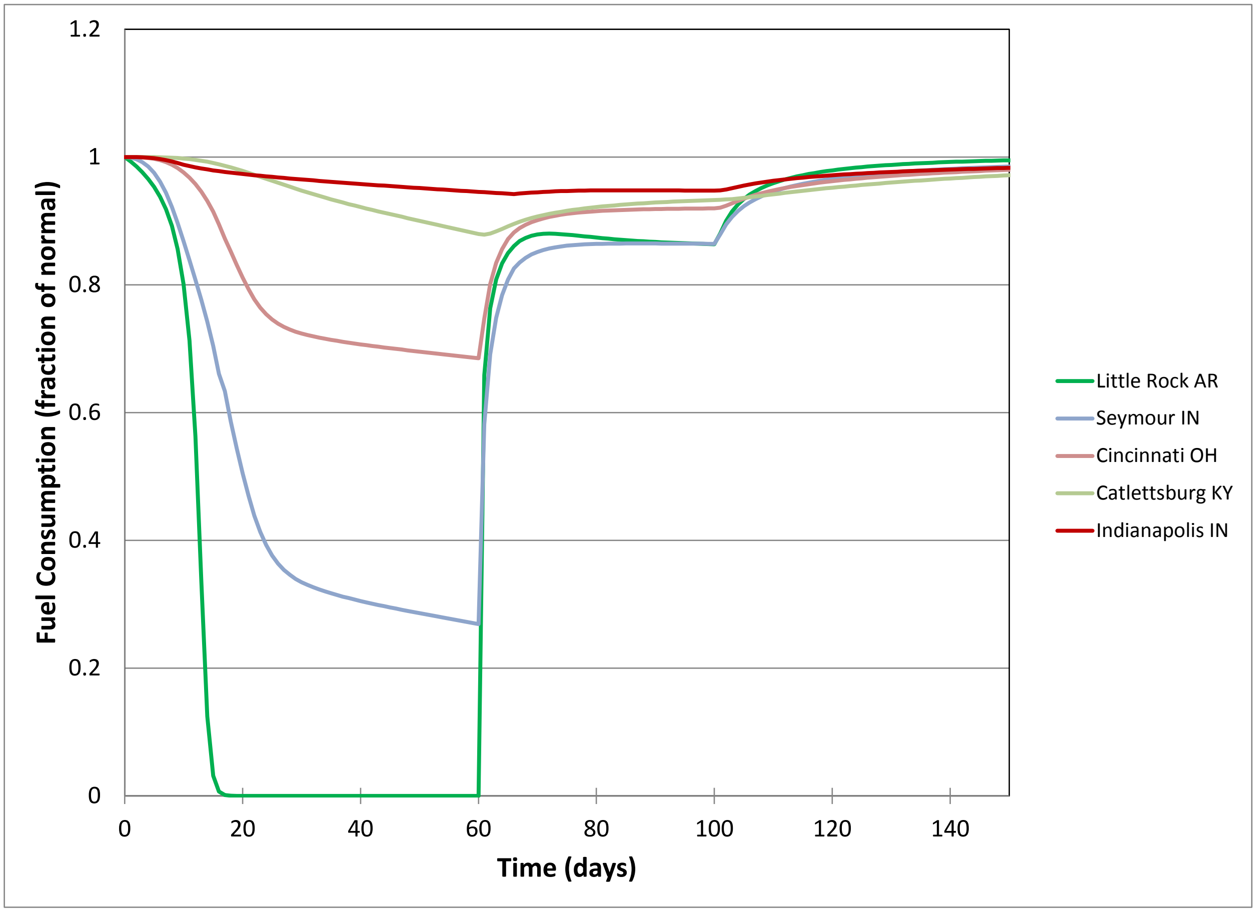

Figure 17. Simulated changes in fuel consumption in selected areas.

3.6 Southern California Earthquake

This analysis assesses the availability of liquid fuels after a hypothetical 7.8-magnitude earthquake caused by a rupture along a 300-km segment of the Southern San Andreas Fault east of Los Angeles. This earthquake impacts liquid fuels infrastructure that serves southern California and cities to the east, including Las Vegas and Phoenix. The entire liquid fuels supply chain for this region, including the Port of Los Angeles–Long Beach, oilfield gathering systems, refineries, transmission pipelines, and distribution terminals, would be damaged. Most importantly, several major refined-product transmission pipelines that cross the fault line would be severely damaged.

3.6.1 Event Definition

This stressing event is based on a scenario earthquake, the ShakeOut, which was developed by the USGS, the California Geological Survey, and other participants to be used for emergency response and preparedness exercises.[17] The scenario 7.8-magnitude earthquake was caused by a

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[17] Jones, Lucile M., et al., 2008. The ShakeOut Scenario, USGS Open File Report 2008-1150, CGS Preliminary Report 25, Version 1.0, 308 pp.

rupture along a 300-km segment of the Southern San Andreas Fault from the Salton Sea in southern Riverside County to Lake Hughes in Los Angeles County. Porter et al. (2011) provide a summary of the ShakeOut Scenario.[18]

The ShakeOut Scenario noted that liquid fuels infrastructure would be damaged, but did not identify individual facilities or the extent of their damages. This analysis uses a model-based shaking intensity map developed by the USGS for the ShakeOut Scenario to identify liquid fuels infrastructure that would likely be damaged by the earthquake.[19] A map showing projected MMI contours and pipeline, refinery, and terminal locations is presented in Figure 18. Figure 19 provides a regional view that shows the refined-product pipeline connections to Las Vegas, Phoenix, and San Diego.

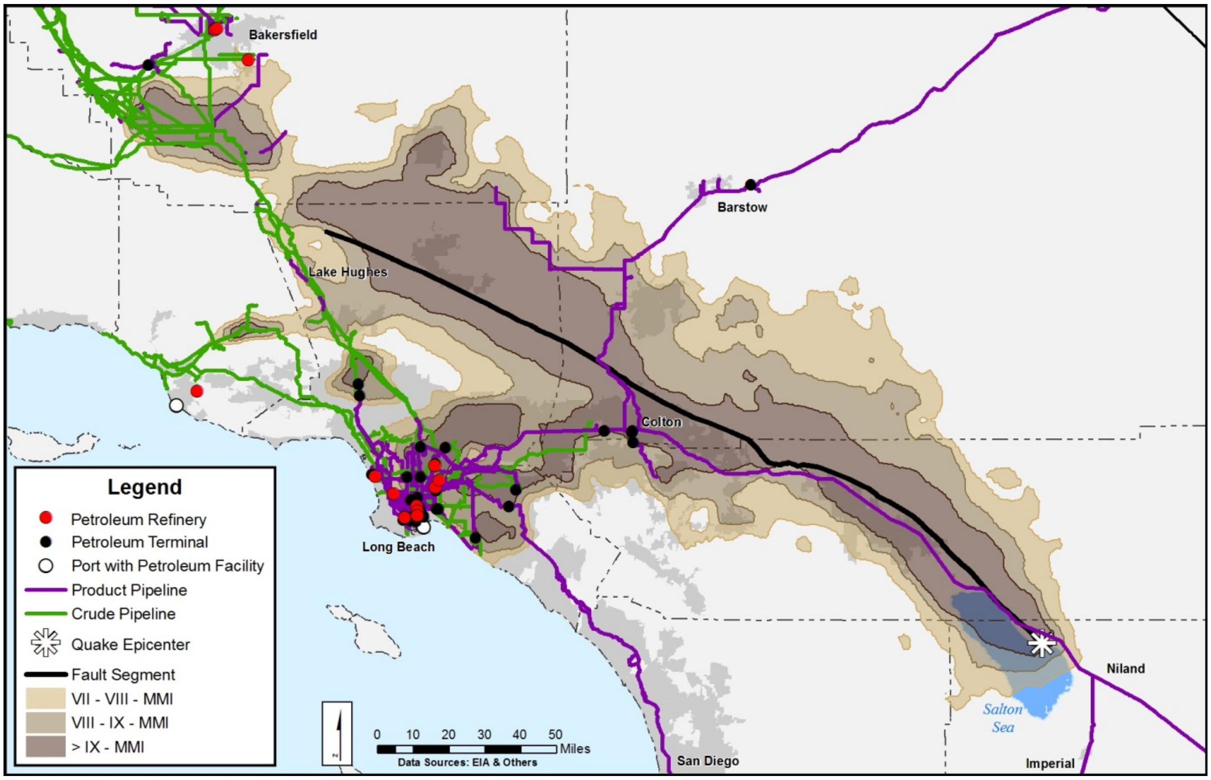

Figure 18. Refineries, ports, pipelines, and terminals relative to fault location and shaking intensity.

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[18] Porter, Keith, et al., 2011. The ShakeOut Scenario: A Hypothetical M_w7.8 Earthquake on the Southern San Andreas Fault, *Earthquake Spectra*, Volume 27, No. 2, pages 239–261, May 2011.

[19] Scenario earthquakes are provided by the USGS ShakeMap product. Scenario earthquakes can be obtained at http://earthquake.usgs.gov/earthquakes/shakemap/ (accessed 11 December 2014)

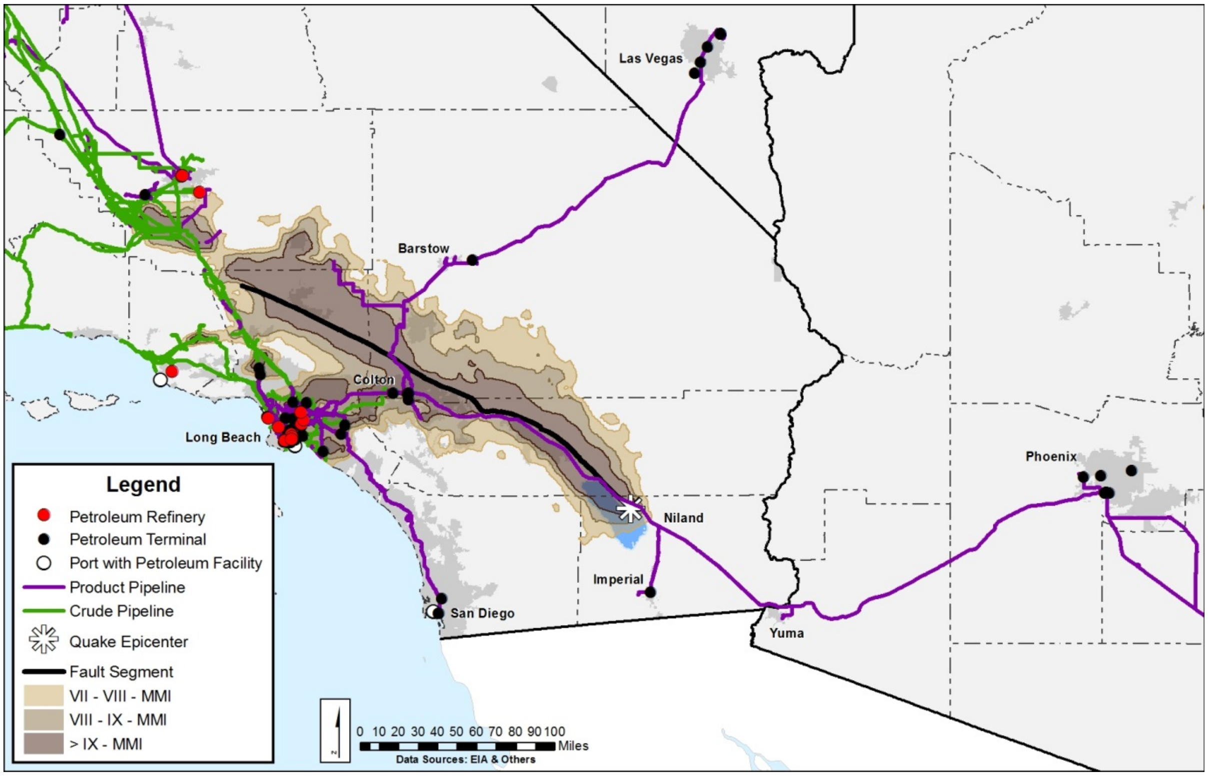

Figure 19. Regional view of liquid fuel infrastructure showing pipeline connections to Las Vegas, Phoenix, and San Diego.

The ShakeOut Scenario included a widespread electric power outage across southern California for several days after the earthquake. This analysis assumes a three-day power outage. With respect to liquid fuels infrastructure, this power outage is assumed to cause a hard shutdown of all seven refineries in the Los Angeles area (see Table 8), and to close the Los Angeles–Long Beach port and Los Angeles area distribution terminals for 3 days. Refineries require cleaning and maintenance before restarting after an unexpected shutdown. Consequently, this analysis assumes the Los Angeles area refineries to be closed for a minimum of 14 days. The combined capacity of the shut-down refineries is about 1 million barrels per day.

Table 8. Refineries in the Los Angeles area.

Refiner	City	Capacity (barrels/day)	Modified Mercalli Intensity Zone
Lunday Thagard Co.	South Gate	8,500	IX–X
Valero Refining Co. California	Wilmington	78,000	VIII–IX
Tesoro Refining and Marketing Co.	Carson	251,000	VII–VIII
Tesoro Refining and Marketing Co.	Wilmington	104,500	VII–VIII
Chevron USA Inc.	El Segundo	269,000	VI–VII
ExxonMobil Refining and Supply Co.	Torrance	149,500	VI–VII
Phillips 66 Company	Wilmington	139,000	VI–VII

In addition to the power outage, ground displacement and shaking would also damage refineries and pipelines. This analysis assumes that pipelines that experience a shaking intensity of MMI IX or greater, but do not cross the fault line, are shut down for 21 days. Specifically included in this 21-day shutdown would be two crude-oil pipeline systems:

- ExxonMobil and Plains crude-oil pipelines from oilfields near Bakersfield, California, to Los Angeles refineries; and
- Crude-oil gathering pipelines from oilfields (Los Angeles Basin) to Los Angeles refineries.

These two crude pipeline systems provide about 25 percent of the input to Los Angeles refineries. The rest is provided by water shipment to the Los Angeles–Long Beach port.

Also included in this 21-day shutdown would be a refined-product pipeline:

- Kinder Morgan SFPP refined-product pipeline from Los Angeles to Colton, California.

The Kinder Morgan product pipeline to Colton typically transports about 25 percent of the refineries' output to terminals west of Los Angeles. In addition, two refined-product transmission pipelines that cross the fault line are expected to be damaged by both fault displacement and shaking. The Kinder Morgan SFPP pipeline from Colton to Niland, California, runs parallel to the fault line for130 km and will likely experience severe damage along much of this distance. The following assumptions are made for these pipelines:

- The Kinder Morgan CALNEV refined-product pipeline from Colton to Barstow, California, is shut down for 42 days,
- The Kinder Morgan SFPP refined-product pipeline from Colton to Niland is shut down for 88 days.

Shaking can also damage refineries. The Valero refinery in Wilmington would experience an MMI shaking intensity between VIII and IX. The South Gate refinery would experience an MMI shaking intensity between IX and X. These refineries are assumed to be shut down for repairs for 28 and 84 days respectively. Together, these refineries contribute about 20 percent of Los Angeles area refining capacity.

3.6.2 Simulated Impacts

Simulated fuel shortages occur in cities that receive all or a portion of their fuel supplies by pipeline from Los Angeles. Fuel consumption in several cities drops to zero. The NTFM utilizes only the transportation modes that normally transport fuel to a particular location. It would be expected that cities with very low simulated consumption rates for extended periods of time would actually arrange for temporary shipments by truck or rail to partially offset the loss of supply from normal sources. Detailed observations from the simulation include:

- Although the Los Angeles area refineries are shut down for 14 days and pipeline shipments of crude oil are shut down for an additional 7 days, fuel consumption in Los Angeles is not reduced except for the first 3 days after the earthquake when the distribution terminals do not have electric power. The resilience of the Los Angeles fuel supply to this stressing event is due both to inventories of fuel at port facilities, refineries, and terminals and to the shut-down of pipelines that normally deliver fuel produced at Los Angeles refineries to other regions.
- Fuel consumption in San Diego drops rapidly to zero 8 days after the earthquake and does not recover until the refined-product pipeline to San Diego is returned to service 21 days after the earthquake. While the NTFM assumes that all fuel consumed in San Diego is from pipeline shipments, San Diego actually receives a small portion of its fuel supply by water shipments. The amount of fuel received by water could possibly be increased temporarily to reduce shortages.
- Fuel consumption in Las Vegas, Nevada, and Barstow, California, drops to zero 12 days after the earthquake and does not recover until the refined-product pipeline to Barstow is returned to service 42 days after the earthquake.
- Fuel consumption in Phoenix is gradually reduced to half of normal 21 days after the earthquake and remains at that level until the refined-product pipeline to Niland is returned to service 88 days after the earthquake. The delay in Phoenix experiencing the loss of half of its fuel consumption is due to the availability of inventory at Phoenix terminals and in storage along the undamaged portion of the pipeline from Niland. The remaining half of Phoenix's normal consumption is supplied by a pipeline from El Paso, Texas. The NTFM assumes that flow on this pipeline increases, but there is not enough excess capacity on it to supply all Phoenix fuel needs. The pipeline capacity in the NTFM is an estimate, so the actual amount that could be supplied to Phoenix from El Paso is uncertain.
- Imperial, California, is located on the Kinder Morgan system between Los Angeles and Phoenix. The timing of fuel shortages in Imperial is therefore similar to the timing in Phoenix. Imperial, however, has no additional source of fuel, so consumption there drops to zero.

The spatial extent and severity of shortages in the simulation are shown in Figure 20. The areas with darker colors have severe shortages, while the yellowish areas have milder shortages. Shortages are calculated as the total amount of lost consumption over the 120 days after the earthquake divided by the normal amount of consumption for those 120 days.

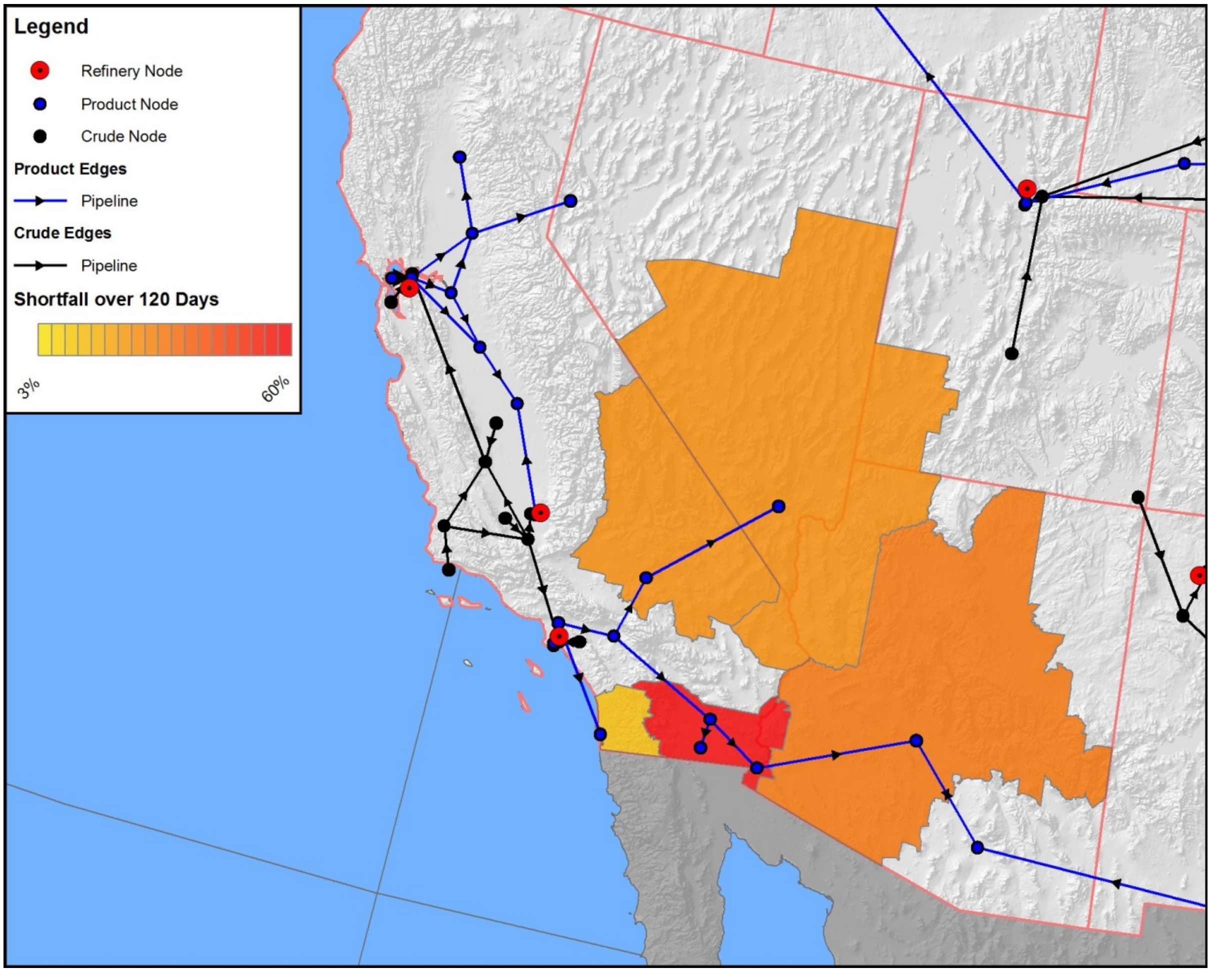

Figure 20. Simulated areas of fuel shortages. Also shown is the NTFM liquid fuels network.

Figure 21 shows that the duration of fuel shortage depends mainly on the time required to repair the refined-product pipeline serving each area. Fuel supplies in Imperial and Phoenix do not recover until the Kinder Morgan pipeline from Colton to Niland is repaired 88 days after the earthquake. Fuel consumption in Phoenix is only reduced by half because it also receives fuel by pipeline from El Paso.

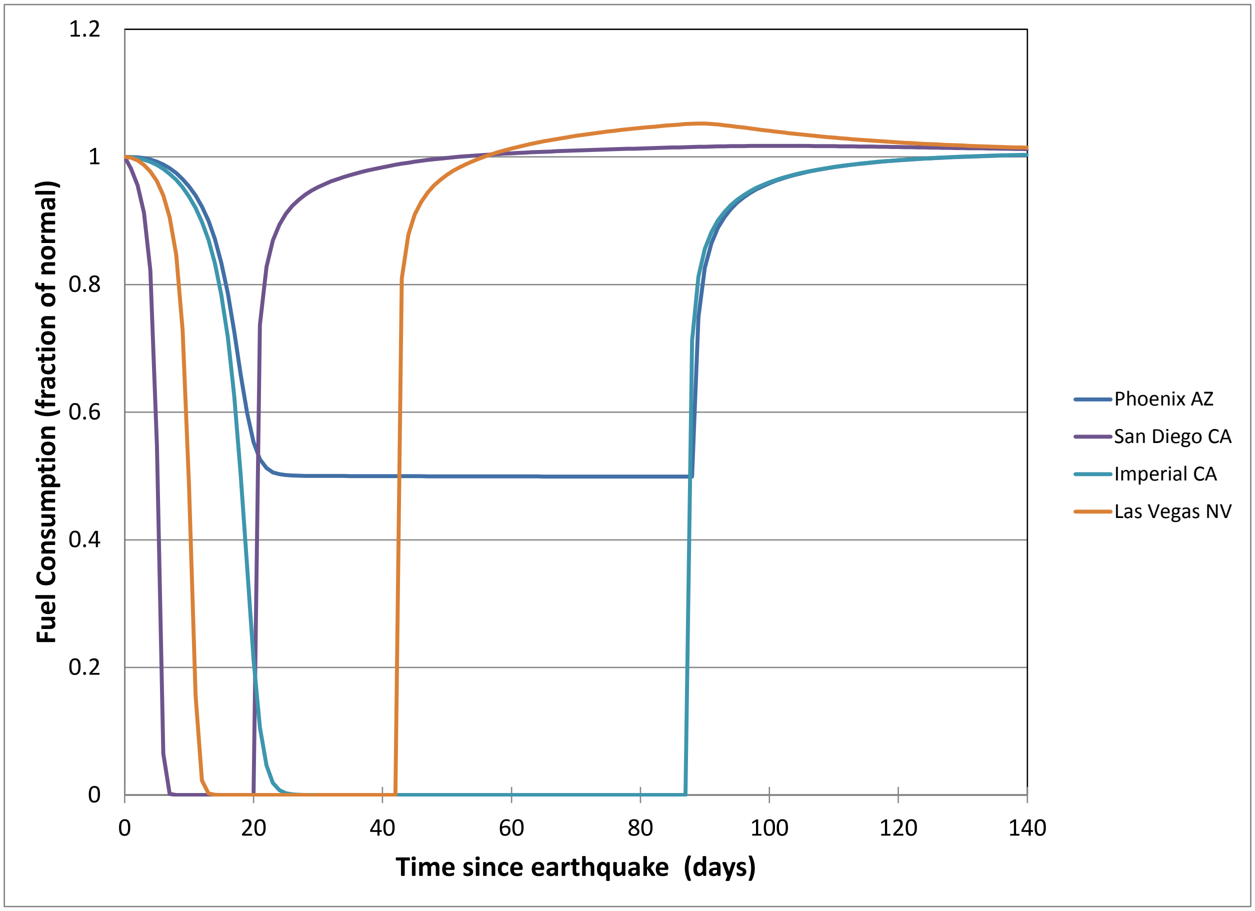

Figure 21. Simulated changes in fuel consumption in selected areas.

3.7 Northern California Earthquake

This analysis assesses the availability of liquid fuels after a hypothetical 7.0-magnitude earthquake caused by a rupture along the Hayward fault east of San Francisco, California. The greatest impact is expected to be in the San Francisco Bay area, with small impacts in communities to the east, such as Sacramento

3.7.1 Event Definition

This stressing event is based on a scenario shaking intensity map developed by the USGS for a magnitude 7.0 earthquake on the Hayward fault with epicenter in Berkeley, California.[20] A map showing projected MMI contours and pipeline, refinery, and terminal locations is presented in Figure 22.

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[20] Scenario earthquakes are provided by the USGS ShakeMap product. Scenario earthquakes can be obtained at http://earthquake.usgs.gov/earthquakes/shakemap/ (accessed 12 December 2014)

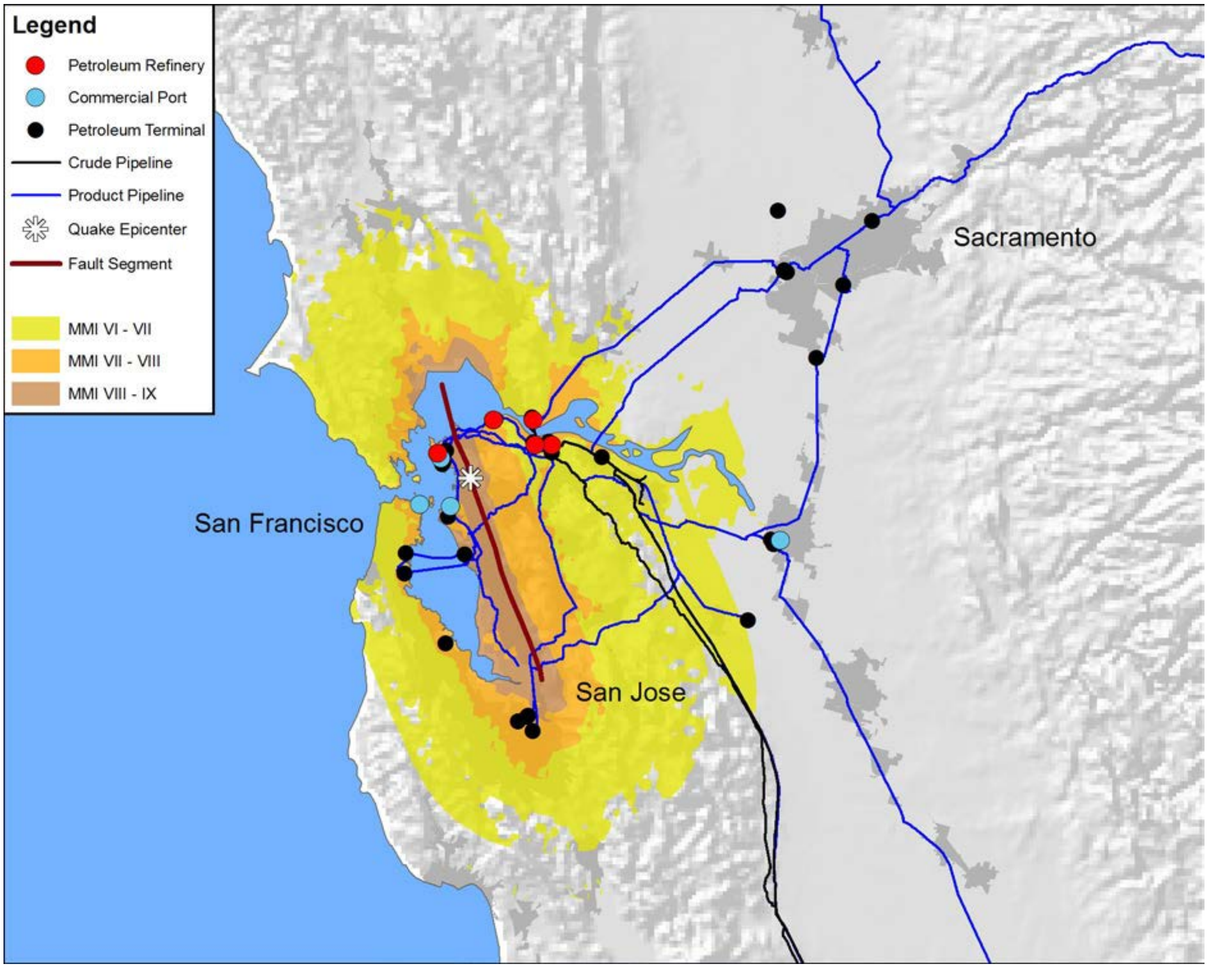

Figure 22. Refineries, ports, pipelines, and terminals relative to shaking intensity.

This earthquake scenario has not been developed in as much detail as the ShakeOut scenario, but some development has been done for a similar scenario.[21] For this analysis, assumptions were chosen to be consistent with those made for the ShakeOut analysis (Section 3.6.1). In particular:

- Electric power in the area is out for three days after the earthquake.
- The power outage causes a hard shutdown of all five refineries in the area (see Table 9). Although the refineries are not expected to be severely damaged, they are assumed to be closed for 14 days for cleaning and maintenance before restarting. The combined capacity of the shut-down refineries is about 820,000 barrels per day.
- The ports in the area are closed for 3 days.

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[21] Earthquake Engineering Research Institute, 1996. Scenario for a Magnitude 7.0 Earthquake on the Hayward Fault, Report HF-96, 110 pp.

Table 9. Refineries in the San Francisco area.

Refiner	City	Capacity (barrels/day)	Modified Mercalli Intensity Zone
Chevron USA Inc.	Richmond	245,271	VII–VIII
Phillips 66 Company	Rodeo	120,200	VII–VIII
Valero Refining Co. California	Benicia	132,000	VI–VII
Shell Oil Products US	Martinez	156,400	VI–VII
Tesoro Refining & Marketing Co.	Martinez	166,000	VI–VII

The main damage to liquid fuels infrastructure would be to refined-product pipelines that cross the fault. These pipelines normally carry transportation fuels from refineries in the north Bay Area to consumers, most of whom are west of the fault. Approximately 70 percent of the San Francisco area refining capacity is from four refineries east of the fault (in Rodeo, Benicia, and Martinez), with the other 30 percent from one refinery west of the fault (in Richmond).

The refined-product pipelines that cross the fault would be severely damaged. This analysis assumes that the pipelines would be out of service for 28 days. Consequently, fuel would not be delivered to terminals west of the fault for 28 days. Terminals east of the fault can begin to receive new fuel shipments after the refineries re-start, 14 days after the earthquake. This analysis assumes fuel consumption in the San Francisco area to be 20 percent of normal during the period after electric power is restored until the pipelines are repaired.

3.7.2 Simulated Impacts

Figure 23 shows impacts on consumption in San Francisco and Sacramento, California. Fuel consumption in San Francisco (including the entire Bay Area) drops to zero for three days because of the power outage and then is reduced by 80 percent until the pipelines are repaired. Sacramento experiences less than a 5 percent decrease in consumption. Other cities to the east that receive fuel from San Francisco refineries feel even less impact than Sacramento. As in previous sections, the model used for this analysis only includes the modes of transportation normally used to supply fuel. During a real event, it is likely that temporary shipments by truck or rail from nearby regions would partially offset the loss of supply from normal sources.

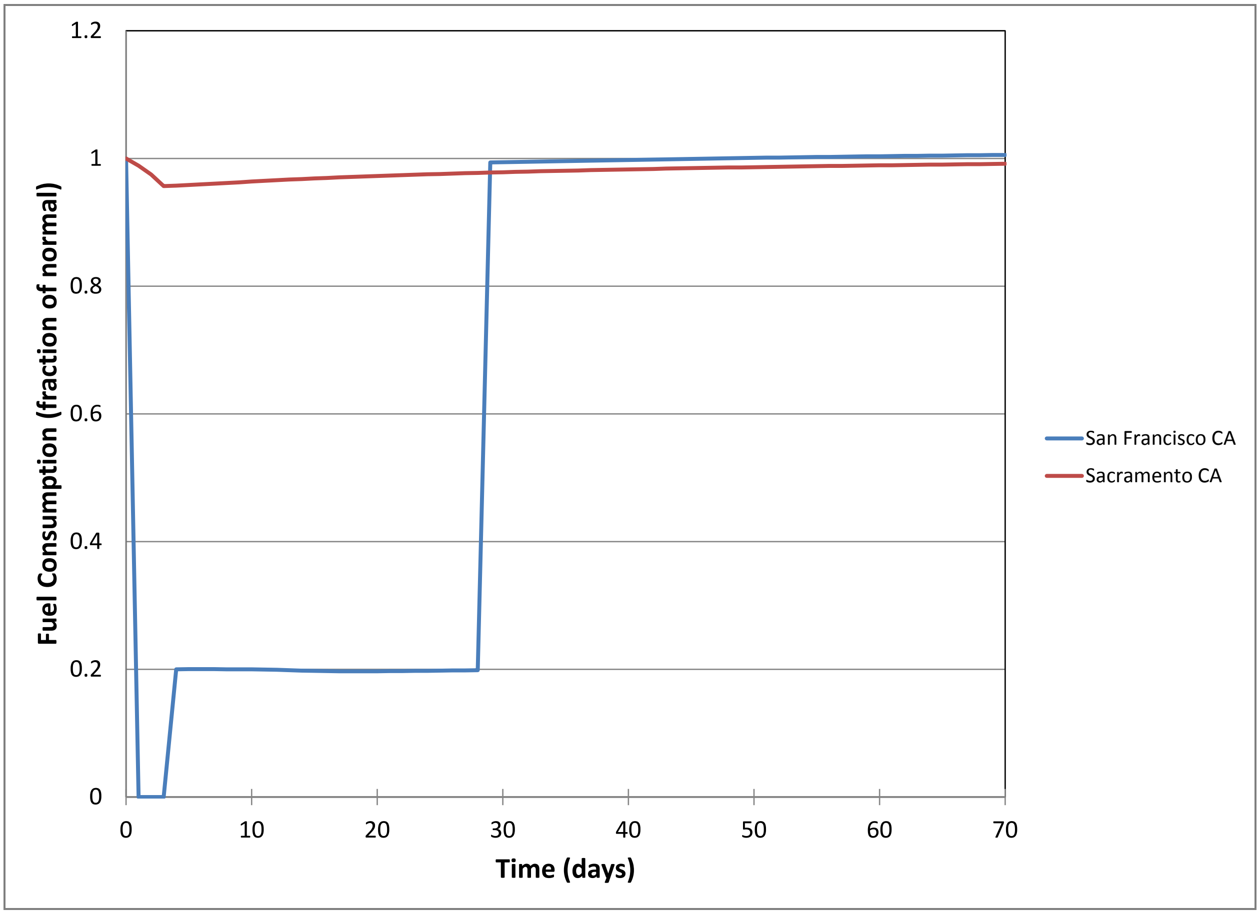

Figure 23. Simulated fuel consumption in San Francisco and Sacramento in the days following the scenario earthquake event.

4 UNCERTAINTY OF SIMULATION RESULTS

The two main categories of uncertainty in the simulation results are uncertainty about the event definition and uncertainty about behavioral responses. The former includes such items as the level of damage to individual facilities and the time for their repair. The latter includes consumption rates and business decisions by infrastructure operators.

Within the NTFM, the willingness of facility operators to draw inventories below normal levels during stressing events to mitigate fuel shortages can be adjusted to represent a range of market responses. Willingness to release storage relates to a fundamental tradeoff of impacts: the balance between decreasing consumption and decreasing inventories. In the NTFM, this balance also affects the spatial extent of fuel shortages. Greater willingness to release storage results in a more spatially concentrated region of fuel shortages. Lesser willingness to release storage spreads shortages over a greater area, but results in a somewhat smaller aggregate drawdown of inventories, and a somewhat larger aggregate decrease in fuel consumption.

The simulation results presented for each event analysis apply for a single set of assumptions about levels of damage to individual facilities, the time required for repair, and the reactions of consumers and infrastructure operators (two sets of assumptions, in the case of the Denver stressing event). Additional simulations using other sets of plausible assumptions would yield somewhat different forecast impacts. For example, simulations that assume longer repair times would result in more severe fuel shortages. Simulations that assume a different willingness to release storage would alter the forecast balance between impacts on inventory and impacts on consumption and the spatial extent of the impacts.

However, simulations using other sets of plausible assumptions would not be expected to result in a qualitatively different forecast of impacts because physical constraints imposed by material balance and the capacities and connectivity of individual infrastructure facilities (e.g., pipelines, refineries, terminals) limit the range of simulation outcomes.

5 DISCUSSION AND COMPARISON OF STRESSING EVENTS

The seven stressing events differ with respect to the infrastructure components disrupted, the durations of the disruptions, and the magnitude, duration, and spatial extent of fuel shortages. For each individual event, the level of impact depends on which system-level adaptive responses are available to mitigate fuel shortages. That is, what options are there to receive fuels by alternative transportation routes, make use of surge capacities, or draw down inventories? It is the role of the NTFM to discover and simulate these adaptive responses in order to guide intuition about the impact severity of a specific stressing event. There are also analysis approaches that complement the use of simulation. These approaches are aimed at characterizing which parts of the national-scale infrastructure network are disrupted.

There are two ways of looking at the infrastructure network that are helpful in characterizing a stressing event. The first is a supply-chain view that is more concerned with the logistical flow of oil and fuels from their sources to consumers than with the details of the various connections between parts of the supply chain. In this view, the supply chain can be divided, from start to end, into Crude Oil Sources (oil fields), Crude Oil Transmission to Refineries (pipelines, rail lines, water shipments, including imports), Refined Product Sources (refineries), Refined Product Transmission to Distribution Terminals (pipelines, water shipments, including imports), and Distribution. Distribution is typically by truck transportation from terminals to customers and includes retail fueling stations. Disruptions to the upstream part of the supply chain often result in a broader extent of fuel shortages, but after a delay from the start of the disruption. In contrast, disruptions of the downstream part of the supply chain often result in more immediate fuel shortages, but over a less extensive region. Table 10 shows which parts of the supply chain are disrupted by each stressing event.

Table 10. Parts of the fuels supply chain disrupted by each of the seven stressing events.

	Crude Oil Sources	Crude Oil Transmission			Refined product Sources	Refined product Transmission		Distribution
	Oil Fields	Pipelines	Rail	Water	Refining	Pipelines	Water	Terminals and Trucks
Gulf Coast Hurricane	X	X		X	X	X	X	X
Mid-Atlantic Hurricane					X		X	X
Boston Harbor							X	
Denver Refinery					X			
New Madrid earthquake		X	X	X	X	X	X	X
S. California earthquake		X		X	X	X	X	X
N. California earthquake		X		X	X	X	X	X

The second way of looking at the infrastructure network can be referred to as the network view. In this view, specific connections between infrastructure components matter. A distribution terminal, for example, that is supplied by only a single disrupted pipeline will experience a more severe impact than a terminal that is also connected to a non-disrupted pipeline. Also, the position of the disrupted components in the national-scale network is important. The impact of a disruption in the center of the national network (e.g., New Madrid earthquake) is different than the impact due to a disruption on a downstream edge of the network (e.g., Boston Harbor closure).

Consider the supply-chain view of the Southern California earthquake event. Nearly all parts of the supply chain are disrupted by this event. A supply-chain view of the Northern California earthquake event is similar with respect to the parts of the supply chain that are disrupted. This view suggests that both the southern and northern earthquakes could be expected to result in immediate short-duration fuel shortages (due to disruption at the downstream part of the supply chain) as well as longer-duration shortages over a broader area. The simulation results confirm these expectations.

At the same time, the simulation results also show major differences between these events. Although both earthquakes are centered on fault segments to the east of their respective urban centers, the regions of fuel shortages show almost opposite patterns. Shortages due to the southern earthquake are severe in cities far to the east of the fault line (e.g., Las Vegas) but are insignificant in the much closer Los Angeles area. The northern earthquake shows the opposite impact, with the most severe shortages in the San Francisco area. The difference is due to details of network connectivity that are apparent when taking the network view of these disruptions. The main factor is that in the southern case, the refining complex is on the Los Angeles (west) side of the fault line. The earthquake severely damages transmission pipelines that carry fuels to service areas to the east. In the northern case, the refining capacity is located mostly on the east side of the fault and pipelines that carry fuels west to the San Francisco area are damaged.

The New Madrid earthquake also disrupts much of the supply chain. Consequently fuel shortages occur in the region of direct earthquake damage because local refining capacity and distribution infrastructure is severely damaged, as well as in areas downstream of the area of direct damage (e.g., Cincinnati) because transmission pipelines carrying crude and product downstream to those areas are damaged.

The Boston Harbor stressing event is different from the previously discussed earthquake events from both the supply-chain view and the network view. The Product Transmission part of the supply chain (receipt of shipments of fuels at the port) is disrupted. From the network view, Boston Harbor is located on a downstream margin of the national network. Together, these views explain why the fuel shortages caused by the harbor closure occur quickly, have only local extent, and are relieved quickly when the port re-opens.

The Denver refinery event is also located on a downstream margin of the national network because the output of the damaged refinery is normally consumed only in the Denver area and the Denver area does not provide fuels to other consuming regions.[22] As such, it is expected that this event would directly impact only the Denver area and the decrease in fuel availability depends on the extent to which other refineries upstream of the Denver area can increase output.

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[22] Geographically, Denver is located in a central part of the national network. However, when viewed in terms of its position in the supply chain, it is on a downstream margin of the network.

The Gulf Coast hurricane event results in the most extensive damage to liquid fuels infrastructure of the seven events presented here. This is because the event damages parts of the supply chain spanning from the upstream end (crude oil production) to the downstream end (fuels distribution), and also because the Gulf Coast supplies much of the U.S. with crude and fuels. It is therefore not unexpected that this event results both in immediate fuel shortages within the distribution areas directly impacted by the storm as well as delayed fuel shortages downstream of Gulf Coast refining and transmission infrastructure.

The Mid-Atlantic hurricane event is a similar storm to the Gulf Coast hurricane but has much less impact on fuel supplies because disruptions are mainly at the downstream end of the supply chain (operation of distribution terminals and receipt of water shipments of fuel). Several refineries are also disrupted, but these refineries normally do not provide fuel to the areas of most severe shortage.

Distribution

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