Fuel Distribution System Analysis to Support Emergency Planning for a New Madrid Seismic Zone Event

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ABSTRACT

The New Madrid Seismic Zone (NMSZ) poses a major risk to fuel distribution infrastructure across the central U.S., where disruption could severely limit fuel availability during an emergency. This project, developed in partnership with the MIT Humanitarian Supply Chain Lab, analyzes downstream fuel supply under earthquake conditions using operational flow capacity (OFC) queuing theory and discrete event simulation in Python. The objective is to evaluate how different infrastructure disruptions affect delivery capacity and simulate which interventions are the most effective. Seven emergency scenarios were modeled across 12 terminal groups and over 5,000 gas stations using data from the Energy Information Administration (EIA), Oil Price Information Service (OPIS), and ArcGIS. Results show a systemwide OFC decrease from 31.56 to 14.82 MMgal/day. Memphis, TN, is the most critical terminal group and lost 20% of its throughput during a modeled shutdown. While the major metropolitan area interdiction scenario reached 200% surge capacity with full interventions, the TEPPCO pipeline scenario peaked at only 182%, highlighting system vulnerability. These findings emphasize the need for targeted operational interventions (e.g., reduce bay time, increase driver hours) and structural upgrades to build a resilient emergency fuel distribution network in the NMSZ.

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1. INTRODUCTION

Emergency preparedness relies on fuel as an essential commodity to support evacuation and relief operations tied to natural disasters. Fuel distribution during disastrous events often does not meet demand. In the United States, average daily fuel consumption exceeds 12 million barrels of fuel, which is supported by one of the most intricate fuel distribution systems globally (Stratas Advisors, 2016). Consequently, when demand exceeds capacity, bottlenecks result. This lack of resources drives the need to better understand fuel distribution systems before and during natural disasters. Therefore, several downstream fuel distribution analyses have been completed by MIT's Humanitarian Supply Chain Lab in various regions in the U.S., including Florida, the Northwest, Utah, Cascadia, and Puerto Rico. The final outputs of each study have included recommended interventions for bulk storage terminals, emergency fuel contracts, and third-party involvement (e.g., National Guard) to support emergency planning for federal, state, and local jurisdictions.

This research includes a case study of the New Madrid Seismic Zone (NMSZ), also known as the New Madrid Fault, that leverages previous regional research studies and offers the Federal Emergency Management Agency (FEMA), as well as other public and private sector actors, with strategic intervention that could be applied during and after an NMSZ seismic event.

1.1 MOTIVATION

The NMSZ covers approximately 150 miles of the Midwest region of the United States from Arkansas to Illinois, including eight states and roughly seven million people (United States Geological Survey [USGS], 2021). The region has several thrust faults covered by river sediment in the Mississippi embayment; its historical consequential seismic activity suggests that in the next 50 years, there is a 25 – 40% probability of a minimum magnitude 6.0 earthquake(s). Furthermore, the historical precedence is highlighted by a set of earthquakes between 7 and 8 on the Richter scale in the early 1800s that caused the Mississippi River to change the direction of its flow (USGS, n.d.b). Compared to the San Francisco earthquake in 1906, the NMSZ earthquakes from 1811-1812 caused shaking over approximately 2.5 million square kilometers, or 10 times that of the impacted West Coast region (Rohman, 2015).

Of the roughly 9.1 million people residing within the area of interest (AOI), an estimated two million would be without shelter following a seismic event similar in magnitude to that of the 1811-1812 events (Jefferson et al., 2012). In addition, 15% of the homes in the NMSZ are unreinforced masonry (URM) buildings, which are more susceptible to earthquake damage than other types of construction and contribute to the region's vulnerability (FEMA, n.d.). Seismic building codes are inconsistent across the NMSZ (Mallet et al., 2016). However, the American Association of State Highway and Transportation

Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications (2013) and the Seismic Guide Specifications (2014) provide more recent guidance when considering the magnitude of potential earthquakes in the NMSZ region and the type of building infrastructure (U.S. Department of Transportation Federal Highway Administration, 2014).

Financial impacts are also significant for this region. FEMA estimates the average Annualized Earthquake Loss (AEL), based on a magnitude 7.7 earthquake to be more than 700,000 people displaced and nearly $300 billion in damages (Missouri Department of Natural Resources, [MO DNR], n.d.). In such scenarios fuel supply becomes crucial as it is needed for powering emergency vehicles, supporting evacuation efforts, and powering generators that maintain operations at essential facilities, such as hospitals.

East of the Mississippi River, NMSZ has the highest expected level of activity, as illustrated in Figure 1 (USGS, 2022). Although the zone has not experienced an earthquake on the scale of the 1811–1812 events in the last century, the area remains seismically active, regularly generating small to moderate earthquakes, as portrayed in Figure 2 (USGS, n.d.b; USGS, 2009). See Figure 2 note for the date ranges corresponding to the seismic activity. In the latter portion of the 20th century, roughly 20 earthquakes occurred annually. More recently, from 2011 to 2013, the number of regional earthquakes increased to 100 earthquakes per year on average. Although the more recent earthquakes are not as catastrophic as those of the early 19th century, the frequency and quantity of tremors are concerning (Rohman, 2015).

Figure 1. United States Seismic Hazard Map, as Outlined by the National Seismic Hazard Model Project (USGS, 2022)

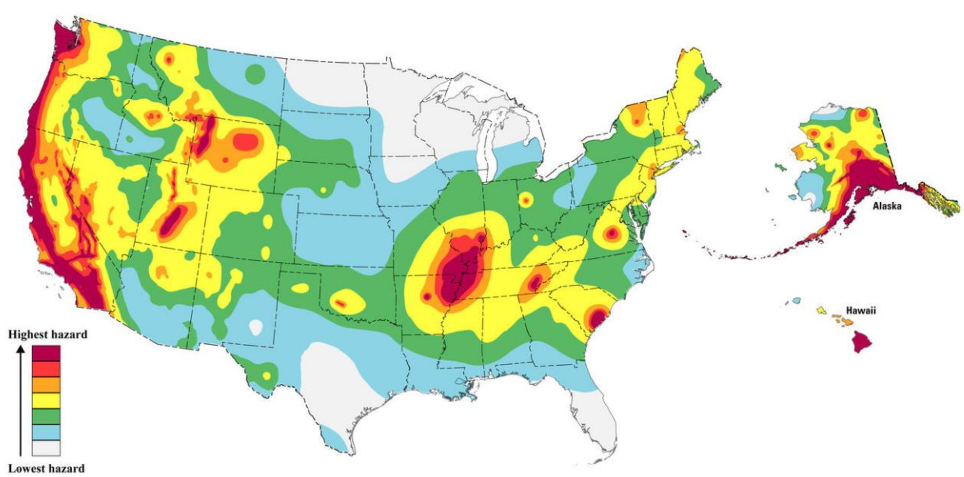
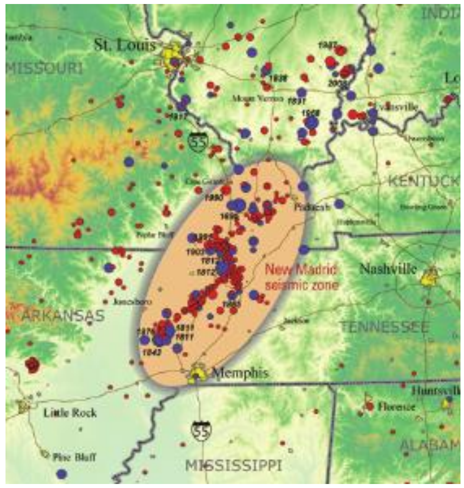


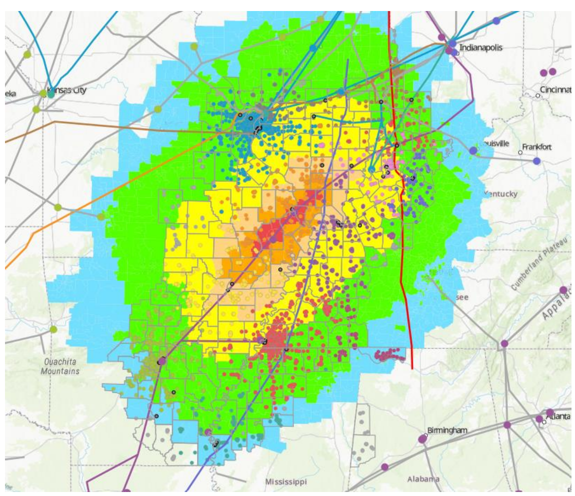
Figure 2. Map of the NMSZ Seismic Activity (USGS, 2009)



Note: Blue circles represent earthquakes before 1973, and red circles represent earthquakes after 1972. The size of the circle represents the earthquake's magnitude. Yellow-shaded areas represent more than 10,000 people.

The seismic activity in this area is challenging to study due to undetermined fault line locations, coupled with unique geography. Soft soils along the Mississippi River allow seismic energy to spread rapidly and further than hardened bedrock (Rohman, 2015). Compared to West Coast seismic events, the NMSZ region's earthquakes can be up to approximately 20 times more expansive (MO DNR, n.d.). An example seismic event is illustrated in Figure 3, based off a magnitude 7.5 earthquake.

Figure 3. Estimated Levels of Shake Impact in the NMSZ Area of Interest (AOI) Following a Magnitude 7.5 Earthquake (USGS, 2017)



The NMSZ region has major pipelines, such as the TEPPCO pipeline, that are critical in transporting refined petroleum products like gasoline and diesel to Midwest markets. Other at-risk infrastructure includes key refineries, such as the Memphis Valero Refinery, which supports regional fuel supply. Furthermore, over 40 storage terminals in the region are vulnerable to disruption, which could severely impact fuel distribution networks (United States Department of Energy [US DOE], 2010).

An urban area of particular interest is Memphis, TN, and the surrounding metropolitan area for its key role in the movement of freight. Partially due to FedEx's global hub, the Memphis International Airport (MEM) is the second-busiest air cargo airport globally by freight volume, responsible for more than 4.5 million annual metric tons (Transmodal, 2024). Additionally, the Port of Memphis is one of the most important ports in the U.S., as it connects multiple transportation networks along the Mississippi River (Port of Memphis, n.d.). Of the 10 bridges that cross the Mississippi River, the largest is in Memphis (Memphis Metropolitan Planning Organization, 2023).

Looking to the future, by 2050, the volume of products transported through Memphis is expected to increase by approximately 78%, as compared to 2019, with trucking as the primary mode of transport. Given Memphis is within two days transit time of 68% of the country's population, its convenient location likely drives part of this shift. Additionally, roughly 16% of the country's logistics workers live in the Memphis urban area (William Sale Partnership Limited (WSP), 2023).

Fuel is essential to the response and early recovery from an event like an NMSZ earthquake. Our objective is to ensure that proactive fuel management strategies are aligned with the region for effective execution. Intervention guidelines will be developed to assess potential fuel management strategies in this region to recommend the more effective actions that stakeholders such as FEMA, and state and local jurisdictions can take.

1.2 PROBLEM STATEMENT AND KEY QUESTIONS

The magnitude of economic and human impact in a future NMSZ seismic event is the primary purpose for developing intervention guidelines for public and private sector actors. The MIT Humanitarian Supply Chain Lab has developed a steady state fuel distribution model, focused on discrete event simulation and queuing theory, that is used to inform fuel management strategies for the NMSZ. The primary NMSZ regions within the scope of this study are FEMA Regions 4, 5, 6, and 7, which include the following eight states in the Midwest region of the United States: Illinois, Missouri, Arkansas, Kentucky, Tennessee, Indiana, Alabama, and Louisiana.

The states within this study's scope are also classified by the Petroleum Administration for Defense Districts (PADD). As depicted in Figure A1 in Appendix A, most states fall within PADD 2, Midwest, with a smaller subset within PADD 3, Gulf Coast region.

The primary research questions to be answered are:

- How can fuel distribution system analysis best support emergency planning efforts for federal (FEMA), state, and local jurisdictions in the U.S. based on a future NMSZ event?

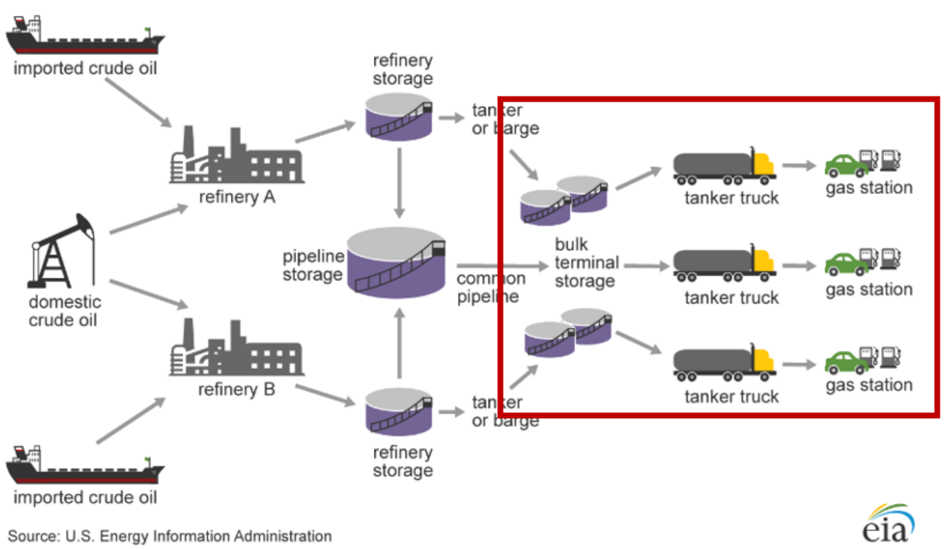
- How could the results from the updated modeling assist with government interventions, including policy action and improved operational efficiencies?

1.3 PROJECT GOALS AND EXPECTED OUTCOMES

The final deliverable is the output of an operational flow capacity analysis that can be used by FEMA, state, local, and private actors to support proactive emergency preparedness and fuel shortage mitigation during and after disasters. The project will assess the downstream fuel supply chain's steady state and non-steady state conditions. Figure 5 highlights the portion of the fuel supply chain within the project scope.

Steady state analysis focuses on gasoline distribution in normal conditions and identifies potential improvements to the existing system. Non-steady state analysis simulates the anticipated impact of a seismic event on the distribution network and assesses how gasoline could be delivered to critical areas.

Figure 5. Project Scope Highlighting the Emphasis on the Downstream Fuel Supply Chain (US EIA, 2024b)



2. STATE OF THE PRACTICE

While the historical earthquakes in the NMSZ are widely discussed within the literature, the strategy of "how" to react to a future seismic event, as it relates to fuel supply chains, is largely unstated. Stakeholders are aware of the risk; however, the planning and guidance on how to advise government and public-private partnerships are lacking in the literature.

The first section details the global fuel industry and domestic fuel supply chains. Following this discussion, existing emergency management planning, including the evaluation of fuel throughput research and hazard resilience planning, is detailed. This literature analysis identifies current gaps in providing recommendations for efficient fuel transport during and after emergencies.

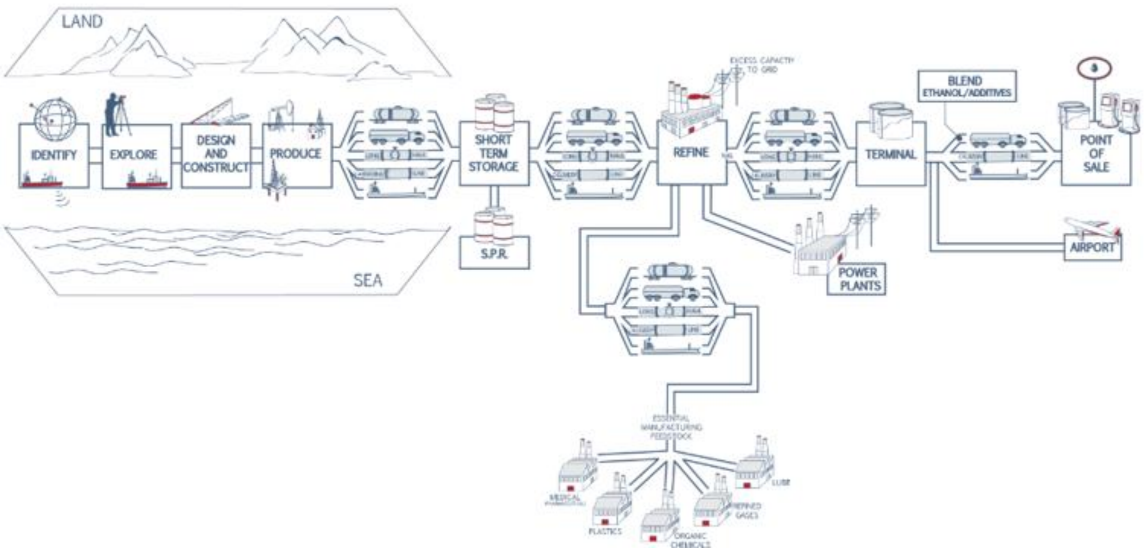
2.1 OVERVIEW OF THE U.S. OIL AND FUEL INDUSTRY AND INFRASTRUCTURE

Since the mid-1800s, the United States, Russia, and Saudi Arabia have been the primary leaders in oil production and refining technologies. The United States averaged 21.91 million barrels of oil per day in 2023, including crude oil, petroleum products, and biofuel (EIA, 2024a). Cumulative oil production from 1859 to 2022 within the NMSZ AOI is 4.3% of total historical U.S. production (Cleveland, 2024). By the 1940s, seven oil companies were designated as the major players in the industry, known as the "Seven Sisters." Since World War II, the oil industry has continued to be characterized by a volatile market, which has led to significant impacts on pricing and supply (Library of Congress, n.d.).

The fuel supply chain consists of three phases that are integral to ensuring a consistent fuel supply globally. The *upstream*, *midstream*, and *downstream* phases are characterized by different infrastructure and stakeholders, as outlined in Figure 6.

The *upstream* phase begins with geological and seismic surveys, followed by exploration drilling to identify the presence of oil and gas. Once an economically viable reservoir is confirmed, the production phase starts. This phase involves extracting oil and gas to the surface through production drilling, which has a longer time horizon than exploration drilling. The primary objective is to achieve efficient and sustainable extraction (MAJR, 2024). A key technique for enhancing production is hydraulic fracturing, also known as fracking. This technique involves injecting fluid into the ground with high pressure to unlock the trapped oil and gas in tight rock, primarily shale rock (USGS, 2019). Fracking has played an essential role in establishing the United States as a global oil and gas industry leader (EIA, 2024a). While fracking does not cause most induced earthquakes, there has been a simultaneous increase in seismic activity as oil production increases, specifically within the central U.S. (USGS, n.d.).

Figure 6. Oil Supply Chain Phases (Lemieux, S., n.d.)



Note: S.P.R. stands for Strategic Petroleum Reserve.

After the oil is extracted, pipelines serve as the primary *midstream* vehicle for transporting the resource. Crude oil is then converted at the refinery into subcomponents, such as gasoline, diesel, and kerosene, "*downstream*" (Corporate Finance Institute, 2024). These fuel sources are transported to fuel terminals. Pipelines support most fuel transport to the terminals; however, trucks, barges, and rail are also utilized (Allison & Mandler, 2018). The final step in the fuel supply chain is to transfer the fuel to end markets and consumers, such as retail gas stations (AFPM, 2021).

2.2 FUEL SUPPLY CHAIN MANAGEMENT FOR EMERGENCY RESPONSE AND PLANNING

During and after a seismic event, the expected surge in fuel demand is not as well-understood as the anticipation and response to a hurricane. Previous research by MIT's Humanitarian Supply Chain Lab focused on hurricane response and proactive preparedness. The critical difference is that seismic-related responses tend to be reactive, given there is no warning of these 'no-notice' events. As compared to hurricane responses in which fuel sales have climbed at a rate of 300% before the hurricane's landfall (Goentzel & Windle, 2017), earthquake responses are not always characterized by excessive demand in a short period. An estimated spike in demand for seismic events is not defined and has mixed trends in the literature (Wilson et al., 2015; Nishimura, 2015). Furthermore, there is no additional time to pre-purchase fuel for a 'no-notice' event.

Collaboration is critical to the development of proactive seismic emergency planning. Aside from FEMA, the Central United States Earthquake Consortium (CUSEC), which receives funding from FEMA, was founded in 1983 and focuses on the NMSZ. Covering eight member states, the organization integrates mitigation plans and proactive resourcing and strategies across the region to decrease "...deaths, injuries, property damage and economic losses resulting from earthquakes in the Central United States" (Central United States Earthquake Consortium [CUSEC], n.d.). An example report is the "After Action Report," which serves as a resource for future NMSZ planning efforts and infrastructure implications for the AOI (CUSEC, 2011).

Another organization that provides developmental and support services is the International City/County Management Association, ICMA. As a nonprofit organization serving local governments worldwide, its mission is to empower governments to effect change within their jurisdictions and highlight the need for preparedness. ICMA conducted a recent survey to identify gaps in local governments' preparedness for disaster response. The survey is analogous to the purpose of this project as it provides insight into how local jurisdictions can be better equipped to prepare for and manage emergencies. Out of the survey respondents, less than 50% have contracts in place to address building infrastructure damage, such as temporary housing needs (International City/County Management Association [ICMA], 2019).

The American Planning Association (APA), known by its motto of "creating great communities for all," is another nonprofit organization that surveys communities and publishes research to drive community planning. One of their published papers establishes how to plan and develop a more resilient infrastructure in preparation for, and in response to, disasters, with an emphasis on partnerships between private and public sectors. A primary consideration is the identification and ongoing assessment of infrastructure at risk within the region of concern. The inclusion of stakeholders from various backgrounds and roles, including engineering, disaster response, and planning is foundational to their approach to driving resilient infrastructure development and community planning (American Planning Association National, 2014).

Public hazard planning resources and research studies primarily include risk identification and previous seismic event analyses. The National Institute of Standards and Technology (NIST)'s Community Resilience Program highlights key resource gaps in their 2021 resilience planning tools and programs database. Concluding themes include the reactive nature of most federal programs, scope limitations that are non-transferable to other hazards for future event planning, and ambiguity in how resilience is defined across different programs (i.e., private vs. federal). To build off these findings, NIST recommends that further surveys should be conducted to poll communities on whether the tools are being used and, if so, whether they are effective (Olszewski et al., 2021).

Strategies rooted in efficient fuel transport for seismically active areas are lacking. In addition to this analytical gap, burgeoning risks to the fuel industry, such as ransomware attacks, can result in similar effects to a natural disaster (e.g., pipeline shutdowns) (U.S. Department of Homeland Security [U.S. DHS], 2023). While such risks are not within the current scope of MIT's Humanitarian Supply Chain Lab models, optimal fuel distribution for government intervention and strategy is the focus of the methodology.

2.3 FUEL DISTRIBUTION SYSTEMS

Fuel inventory is not typically a bottleneck within the downstream fuel supply chain. Terminal operational efficiency and fuel transportation to retail gas stations are the culprit. The objective of the methodology is to identify interventions that enhance downstream fuel operations. The analytical procedures are adopted from Rana et al. (2024), with an emphasis on the gaps within emergency relief and mitigation planning literature. The research results will provide an additional case study following MIT Humanitarian Supply Chain Lab's blueprint for proactive disaster interventions (Rana et al., 2024).

Optimization methods are common tools in current supply chain research. Researchers primarily study steady state parameters, with limited studies addressing operational flow using simulation methods for fuel distribution. Additionally, current research is typically limited to upstream optimization models that do not include capacity constraints within downstream fuel distribution. Furthermore, the scope of previous studies is often limited to a single terminal, instead of multiple facilities (Reis et al. 2017), and tends to not analyze the effect of reducing bay and gate waiting time or fleet size on the system's outcome. Lastly, the development and ranking of solutions for public-private engagement and intervention are lacking in the literature. In response, the methodology within this project identifies resource allocation and policy recommendations, as well as operational flow capacity (OFC) improvements (Rana et al., 2024).

The first model, applied from Rana et al. (2024), is a queueing system that calculates the steady state OFC. Each terminal group's throughput, or OFC, is calculated based on the amount of fuel, in million gallons per day (MMgal/day), that can supply all respective retail gas stations' demand. The throughput is the work in progress over the cycle time, or the amount of fuel delivered to retail stations in one day from the terminals (Rana et al., 2024).

Building off the first model, or the baseline data set, the second model (the non-steady state) is a discrete event simulation that delineates disaster scenarios to understand downstream fuel distribution. The output of the two models will inform recommendations for emergency management fuel strategies and improve stakeholder engagement at the federal, state, and local levels (Rana et al., 2024).

2.4 EMERGENCY FUEL SHORTAGE MITIGATION STRATEGIES

Emergency fuel strategies operate across several levels, including federal, state, and private. At the federal level, emergency fuel contracts support fast access to fuel during crises. The Defense Logistics Agency (DLA) Energy manages these contracts to support federal agencies, including FEMA. For example, during Hurricane Laura in 2020, DLA Energy activated a contingency fuel contract within 18 hours of FEMA's request, delivering more than 70,000 gallons of fuel across Louisiana from an incident support base in Texas (Braesch, 2020).

Some states have detailed emergency fuel plans that outline how fuel is secured and distributed during disasters. Florida's plan, for example, includes pre-negotiated contracts with private providers to deliver fuel, equipment, and staff within 24 to 72 hours of activation. The plan sets daily delivery targets, outlines spot-fueling capabilities, and defines coordination roles. It also includes procedures for risk assessment, fuel prioritization, and communication with local governments (State of Florida, 2016). This structured approach helps ensure fuel availability for critical services during emergencies.

Many private organizations and critical facilities have their own emergency fuel plans to stay operational during disasters. For example, long-term care facilities are required to keep on-site fuel for generators during emergencies, as required by the Centers for Medicare & Medicaid Services (CMS) Emergency Preparedness Rule (CMS, 2021). Healthcare facilities are also encouraged to create Continuity of Operations (COOP) plans that include backup fuel strategies in case of power outages (U.S. Department of Health and Human Services, 2025).

In addition to pre-planned contracts and coordination strategies, the government may implement reactive measures during fuel emergencies. One common tool is fuel rationing, which has been deployed during major events such as Hurricane Sandy in 2012 to control demand and prioritize critical users. For instance, New York City and part of New Jersey implemented an odd-even license plate system, where drivers can only buy fuel on certain days based on the last digit of their license plate, to manage fuel distribution amid shortages (CBS News, 2012). Federal and state agencies may also issue temporary waivers on environmental regulations to ease fuel supply restrictions. For example, the U.S. Environmental Protection Agency (EPA) has allowed temporary sales of E15 gasoline, which is normally restricted in the summer, to address shortages caused by the war in Ukraine (U.S. EPA, 2023). These actions require close collaboration between state energy offices, fuel distributors, and regulatory agencies (FEMA, 2016).

3. METHODOLOGY

The objective of the primary data collection and subsequent modeling is to develop a baseline reference model. The next step is to create situational analyses to inform emergency fuel availability and planning efforts for federal, state, and local jurisdictions in FEMA Regions 4, 5, 6, and 7. Following model output analysis, government intervention recommendations will be detailed.

The methodology follows the previous regional case studies conducted by the MIT Humanitarian Supply Chain Lab, most notably the Florida study completed in 2024 (Rana et al., 2024). Puerto Rico, Utah, the Pacific Northwest, and a national fuel study are other previous FEMA-supported research projects with a similar theme.

3.1 DATA GATHERING

The first steps to better understand the AOI, and subsequent system analyses, were data collection and cleaning. The categories of information for all subsequent modeling are listed below.

- Fuel terminal group names and identification numbers
- Active fuel terminals
    - Location (address, latitude/longitude)
    - Number of gates and bays
    - Capacity (barrels, tanks)
    - Fuel types
    - Modes of transport (pipeline, rail, barge)
- Retail gas stations
    - Location (address, latitude/longitude)
    - Terminal group, and the average distance from the terminal group

Some of the key terminal group characteristics, as illustrated in Table 1, include the number of bays and gates at each terminal, the capacity (number of barrels and tanks), and the number of retail stations supplied. The retail gas stations are the most granular data points, and each is assigned to a specific terminal group. There are a total of 12 terminal groups across the seven states within the AOI. Appendix C details each terminal’s location, infrastructure, modes of transport (rail, river, pipeline), and lever guidance, which is further detailed in Section 4.1.

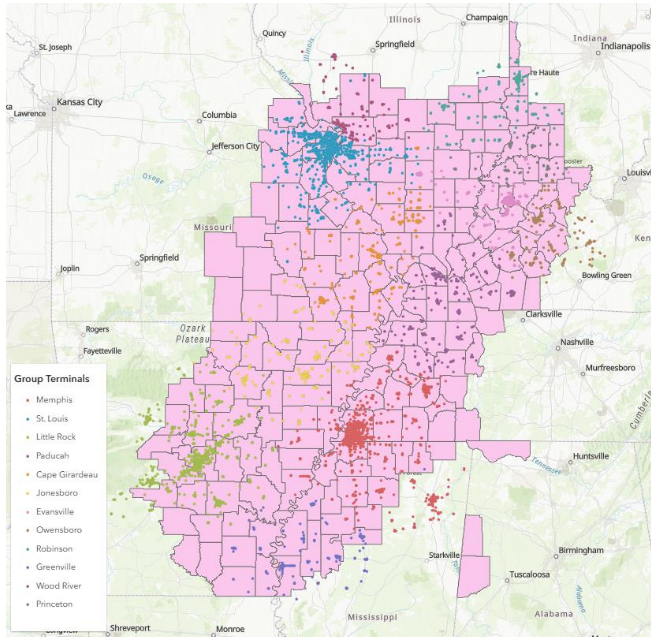
Table 1. Key Characteristics of the 12 Terminal Groups Within the AOI

Terminal Group	Number of Bays	Number of Tanks	Number of Barrels	Number of Stations
Cape Girardeau	8	25	640,228	323
Evansville	16	75	1,820,171	226
Greenville	5	21	652,044	203
Jonesboro	6	9	311,590	282
Little Rock	27	54	2,185,135	769
Memphis	22	58	1,961,357	1,211
Owensboro	6	17	509,153	221
Paducah	4	22	481,100	329
Princeton	2	10	600,000	114
Robinson	6	8	120,000	204
St Louis	19	64	1,608,000	953
Wood River	21	65	4,494,373	177
Grand Total	**142**	**428**	**15,383,151**	**5,012**

The first step in the baseline data collection process involved cleaning the data by segregating both terminals and retail gas stations within and outside the AOI and removing outliers. Following the compilation of the final dataset, data gaps were identified. While all supply chain sectors are characterized by data sensitivity, the downstream process has the most readily available public data. This reduced the number of assumptions within the methodology required to conduct system analyses and scenario development for emergency response and planning.

With the utilization of ArcGIS shape files, the AOI for the NMSZ was demarcated. The 194 counties within the seven states of the NMSZ study region were determined. All fuel supply chain infrastructure was mapped to the AOI across four FEMA regions and informed by two primary data sources: the Energy Information Administration (EIA) and Oil Price Information Service (OPIS). Figure 7 maps the location of the retail stations for each of the terminal groups. Additionally, a list of the terminal groups is in Table A1 in Appendix A.

Figure 7. Retail Gas Stations and Corresponding Terminal Groups Within the NMSZ AOI



Several assumptions were also included based on previous research (Rana et al., 2024). The first assumption involves estimating retail gas station demand based on per capita gasoline consumption at the county level. State population information was pulled from the 2020 census (United States Census Bureau, 2023), and gasoline consumption data was sourced from EIA (U.S. EIA, 2022). Each state's per capita gasoline consumption was calculated by dividing its total gasoline demand by population. County-level demand was then assigned equally across all gas stations within each county.

The second assumption related to terminal group demand involved summing the demand of all retail gas stations within the AOI. Terminal group demand can be interpreted as the aggregated demand of the gas stations it supplies. After calculating each terminal group's demand, trucks were allocated proportionally based on demand shares. Specifically, the number of trucks assigned to each terminal group was estimated by multiplying the terminal group's share of national demand by the total number of petroleum product tractors in the U.S, approximately 23,896 tractors (National Tank Truck Carriers [NTTC], 2022).

Additional modeling assumptions, including an average truck speed (45 miles per hour) and truck capacity (9,000 gallons) are assumptions adopted from previous research (Rana et al., 2024). To determine distances between the retail stations and the terminals, the retail station radius is analogous to the 90th percentile of all station-terminal distances. Following the incorporation of data assumptions into the baseline data files, the next step was to update the format of the data files for ingestion into

Python. All data files and storage are in GitHub (Alsukairi & Morton, 2025) for reference to accompany the following results and discussion in Section 4.

3.2 APPLICATION OF METHODOLOGY

There are two components of the operational flow capacity analysis. The steady state analysis utilizes a queueing model, while the non-steady state analysis is based on discrete event simulation. The purpose of the operational flow capacity analysis is to first understand the NMSZ's system baseline capacity and then analyze what parameters can be manipulated to meet surge capacity expectations during and after a seismic event. The parameters for the non-steady state analysis are in Table A3 in Appendix A.

The objective of the steady state analysis is to understand the baseline throughput, also referred to as the operational flow capacity (OFC), of each terminal group. A queueing model is used to define the steady state, as defined in Little's Law (Little & Graves, 2008). The parameters that remain constant within the steady state queueing model are listed in Appendix A in Table A1 (Rana et al., 2024).

The first OFC value, OFC_1, represents the total processing capacity of each terminal group, based on the number of gates and bays available at each terminal and their respective cycle times. OFC_1 does not consider the fleet size. The second OFC value, OFC_2, focuses on the availability and productivity of the truck fleet, including the fleet size (fi), the number of hours the fleet operates (h), and the time it takes to travel to and from each gas station within the terminal group. Therefore, the addition of trucks will only impact OFC_2. Equations 1 and 2 below calculate OFC_1 and OFC_2 for the steady state, respectively. Equation 1 is simply the throughput for each terminal group, whereas Equation 2 considers fleet size (Rana et al., 2024).

$$\phi_i^1 = \sum_{t \in T_i} \frac{c \times 10^{-6} \times 60 \times 24}{\frac{r_{g,t}}{n_{g,t}} + \frac{r_{b,t}}{n_{b,t}}} \tag{1}$$

$$\phi_i^2 = \sum_{t \in T_i} \frac{c \times 10^{-6} \times 60 \times f_i \times h}{\frac{r_{g,t}}{n_{g,t}} + \frac{r_{b,t}}{n_{b,t}} + \frac{2d_i}{v_i} + r_s} \tag{2}$$

Each terminal group's final OFC value is the minimum of the two OFC values, per Equation 3 (Rana et al., 2024).

$$\bar{\gamma}_i^S = \min\{\phi_i^1, \phi_i^2\} \tag{3}$$

Following the steady state analysis, the objective of the non-steady state analysis is to introduce stochasticity to the baseline assumption model for each terminal group's OFC. This discrete event simulation framework adds variability to the input parameters using an upper and lower bound of 10%. The purpose of this threshold is to mimic real-world uncertainty. Lastly, to further consider stochasticity, truck departures are modeled as uniformly distributed within the first six hours of the day, reflecting how dispatch time can vary during an emergency.

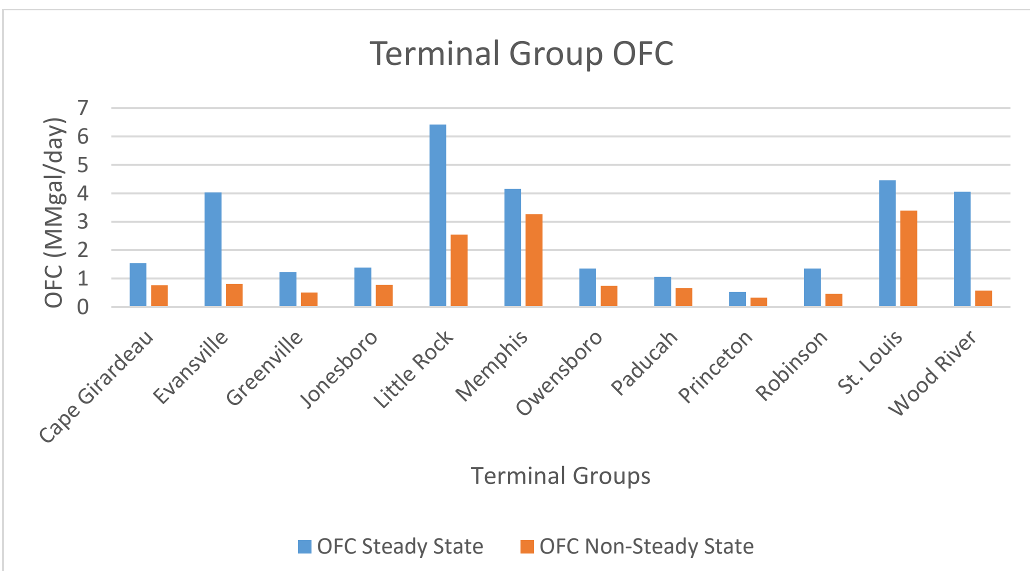
4. RESULTS AND DISCUSSION

For developing recommendations that could be applied by public and private sector actors after a disaster or other disruption to the fuel system, it is important to note that particular focus was placed on the terminal groups in the four major cities within the area of interest. These major metropolitan areas are Memphis, TN, Evansville, IN, Little Rock, AR, and St. Louis, MO.

For the steady state, the cumulative minimum operational flow capacity across all terminal groups is 31.56 MMgal/day. This value is representative of OFC_1 as it is the smaller of the two values between OFC_1 and OFC_2. In other words, this throughput value represents the operational flow capacity when only considering the constraints of the terminal group (no fleet considerations).

As illustrated in Figure 8, the Little Rock terminal group has the highest OFC value of 6.42 MMgal/day. Memphis and St. Louis have roughly the same OFC value. Princeton has the lowest OFC due to the existing limited bay and gate infrastructure.

Figure 8. Comparison of OFC Steady State and Non-Steady State



The delta between OFC_1 and OFC_2 represents the amount of additional throughput the terminal group could handle if infrastructure changes were made. By either (1) adding gates and/or bays, or (2) reducing the gate and/or bay times, terminal groups with the highest OFC should be considered for additional infrastructure investments to increase NMSZ resilience. These include St. Louis, Little Rock, Evansville, and Memphis.

As compared to the steady state results, the non-steady state OFC decreased by roughly half across all terminal groups, resulting in a cumulative OFC of 14.82 MMgal/day. Python output is detailed in the graph shown in Figure 8. St. Louis has the highest OFC value (3.38 MMgal/day) in the non-steady state, and Memphis is slightly lower. Little Rock has the third largest OFC value. The reduction in Little Rock's OFC, as compared to the steady state, is likely due to the lower number of trucks allocated per the cumulative counties' demand. Terminal groups with the lowest OFC values are Princeton and Robinson, at 0.32 and 0.46 MMgal/day, respectively.

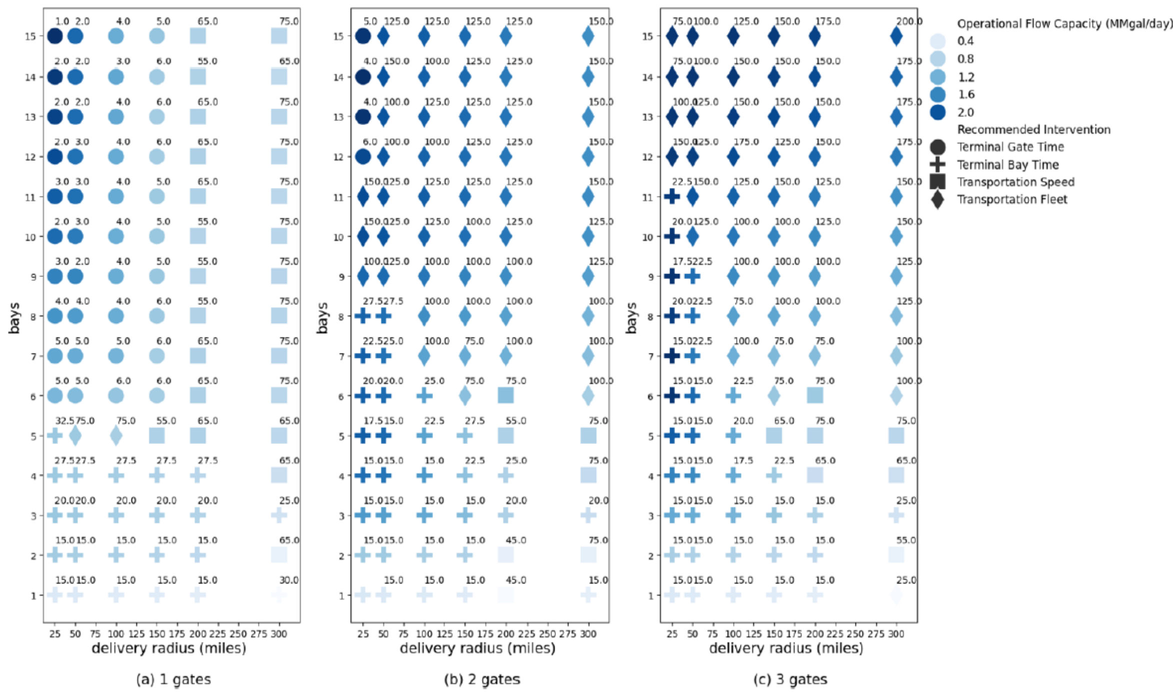
4.1 IMPLICATIONS

Next, several parameters or levers were quantified to determine the recommended interventions for supporting fuel supply during and after a seismic event. First, the levers' impact under the steady state, or not under a disruption, was reviewed. Then, disruption scenarios were added, as outlined in Section 4,.2.

The objective of the lever guidance is to identify emergency interventions that can be used to create the highest OFC for each terminal design. The levers are truck speed, bay time, gate time, and fleet size. Although this template only identifies one intervention per terminal design structure, the execution of more than one intervention could further increase OFC.

The lever guidance, as portrayed in Figure 9, includes the number of bays, n_b, number of gates, n_g, and station distances, d, as primary parameters. The drivers' hours of service parameter is not included. Previous research was extended to capture the three-gate infrastructure identified in the NMSZ.

Figure 9. Lever Guidance by Terminal Type



Note: The color, symbol shape, and text correlate to increasing the OFC for each terminal type/design. The darker the symbol color, the more significant the OFC improvement. Each symbol represents the type of intervention that is recommended. The numbers listed are the improvement thresholds.

4.2 SCENARIO ANALYSIS

Seven scenarios were identified with the highest probability of coring and the most significant impact on the fuel system in the AOI. These scenarios could be considered when preparing for a future disaster in the NMSZ.

Interdictions are the focus of the first five scenarios. An interdiction is the shutting down, or being offline, of the area of interest. For example, a Memphis interdiction assumes that none of the fuel terminals are operational. Instead, the metropolitan area and all supplied retail stations within the terminal group must rely on the most proximal terminal group(s) for fuel supply. Scenarios 1-4 are the most probable, followed by Scenario 6. However, the probability of any one scenario is tied to the magnitude of the seismic event. Therefore, consideration for intervention should be placed on Scenario 1 given Memphis, TN, is the closest region to the center of the NMSZ region.

1. Scenario 1 | Memphis, TN, interdiction (FedEx)
2. Scenario 2 | Little Rock, AR, interdiction
3. Scenario 3 | St Louis, MO, interdiction
4. Scenario 4 | Evansville, IN, interdiction

5. Scenario 5 | Open only the major metropolitan terminal groups; shut down all others
6. Scenario 6 | TE Products Pipeline Company, L.P. (TEPPCO) pipeline system offline
7. Scenario 7 | Mississippi River crossing impassable

Complementary to Table 3 are the intervention options, or changes to the parameters, listed in Table 2. The intervention values improve the baseline parameters. For example, rather than limiting truck speed to 45 miles per hour (mph), the “High” lever allows trucks to drive at 65 mph to speed up the time it takes to reach fuel terminals and deliver fuel.

Table 2. Emergency Scenario Intervention Levers and Associated Values

Description of Intervention	**Baseline Value**	**Intervention Value**
Gate Time (minutes)	7	3.5
Bay Time (minutes)	35	17.5
Truck Speed (miles per hour)	45	67.5
Fleet Size (number of trucks)	759	Gain 1 truck every 20 trucks
Hours of Service (hours)	14	18

Scenario 1 serves as an example scenario, as Memphis, TN, supplies 22% of the NMSZ’s OFC, or 3.3 MMgal/day, and is a critical hub for transportation, including domestic and international means, as signified by FedEx’s headquarters location. Of all 1,211 gas stations supplied by the Memphis terminal group, 100% of the gas stations were allocated to new terminal groups because of the interdiction, with the majority (82%) reallocated to Jonesboro. The average distance between Jonesboro’s gas stations increased from 57 to 96 miles. The original fleet size in the Memphis terminal group is 168 trucks. Trucks are rerouted based on the nearest neighbor (terminal group) assumption. As a result, 138 trucks are diverted to Jonesboro, followed by 27 trucks to Greenville.

Two scenarios without levers under normal and emergency conditions are listed in Table 1b. The first row within Table 1a is representative of 100% normal conditions, which is the NMSZ baseline. The second row is the interdiction conditions for the area of focus (in this example, Memphis, TN). The subsequent five rows reflect one parameter intervention per row. For example, the baseline gate time is 7 minutes. When this parameter is transitioned to “High,” the gate time is reduced to reflect a more rapid truck turnover time at the gate. The final row, with all parameters set as “High,” is the best-case scenario and has all parameters optimized. In the case of Memphis, if all levers are pulled, the surge capacity reaches 235%, as compared to a baseline value under normal conditions of 101%. Without any levers utilized, a Memphis, TN interdiction, resulted in a 20% reduction in OFC and 24% decrease in surge capacity.

Table 3. OFC Analysis for a Memphis, TN, Interdiction

Gate Rate	Bay Rate	Speed	Fleet Size	Hours of Service	Surge Capacity (Truck Diversion)		Gate Wait Time (hours)	Driving Time (hours)	Trips per Day	NMSZ OFC	NMSZ Demand
					0%	100%					
Normal	Normal	Normal	Normal	Normal	**125%**		**0.30**	**4.36**	**2.42**	**14.84**	**11.86**
Normal	Normal	Normal	Normal	Normal	**94%**	**101%**	**0.65**	**4.32**	**2.25**	**11.95**	**11.86**
High	Normal	Normal	Normal	Normal		101%	0.63	4.30	2.25	11.93	11.86
Normal	**High**	Normal	Normal	Normal		**139%**	0.36	5.36	2.82	16.50	11.86
Normal	Normal	**High**	Normal	Normal		111%	0.76	3.35	2.53	13.22	11.86
Normal	Normal	Normal	**High**	Normal		103%	0.69	4.28	2.24	12.26	11.86
Normal	Normal	Normal	Normal	**High**		138%	0.81	5.95	3.07	16.43	11.86
High	**High**	**High**	**High**	**High**	**207%**	**235%**	0.35	6.22	4.68	**27.91**	11.86

Note: Green is indicative of the parameter(s) that are set as "High." Blue represents the normal baseline conditions. Yellow represents the interdiction phase for all terminals in the Memphis, TN, terminal group.

There is an important distinction within Table 3 that demonstrates two extremes for surge capacity. Truck diversion was modeled at either a 0% or 100% level. The surge capacity percentage values are higher for a 100% truck diversion level because this scenario assumes that all trucks from Memphis will be diverted to nearby terminals, receive fuel, and then supply the Memphis area. The zero percent truck diversion scenarios model no reliance on other terminal groups for fuel supply during an interdiction.

As will be further discussed in Section 5.1, reducing the amount of time that trucks spend at the bays by 50% and increasing the number of hours truck drivers are allowed to drive (hours of service) by 29% are the two most impactful levers. If all parameters were to be fully optimized, Memphis could supply nearly double NMSZ's baseline OFC. Depending on the ability to divert trucks to nearby terminal groups, Memphis can support anywhere from 207% to 235% of baseline surge capacity if running all parameters at an optimal, or "High" level.

The remaining four scenarios are outlined in Tables B1 – B4 in Appendix B. Of these scenarios, two provided additional critical insights for shaping management recommendations. When the NMSZ is only able to rely on the four major metropolitan areas being open, and there is no fuel supply from smaller, supporting terminals nearby, the surge capacity is minimized to 72% with no trucks being diverted. Conversely, if all parameters are optimized to illustrate the best-case scenario, the maximum total surge capacity when there is no reliance on truck diversion is only 168%. This significant reduction in surge capacity illustrates the importance of having smaller, supporting terminals online and being able to provide fuel during and after a seismic emergency.

Scenario 6 supports a different type of emergency scenario, as compared to the metropolitan area interdictions. Sixteen terminals, or roughly 36% of all terminals in the NMSZ, supply the TEPPCO pipeline. Table 4, which provides the same layout as described previously for the Memphis, TN, interdiction, models the TEPPCO pipeline being offline. The main assumption in developing this scenario is if the terminal supplies TEPPCO, it will be fully shutdown, even if other modes of transporting fuel are used such as other pipelines, barges, or rail.

As a result of the TEPPCO pipeline being offline, two terminal groups shut down completely – Cape Girardeau and Princeton. Given that the TEPPCO pipeline plays an essential role in supplying fuel to the AOI, the only way to compensate for its disruption is to activate multiple interventions.

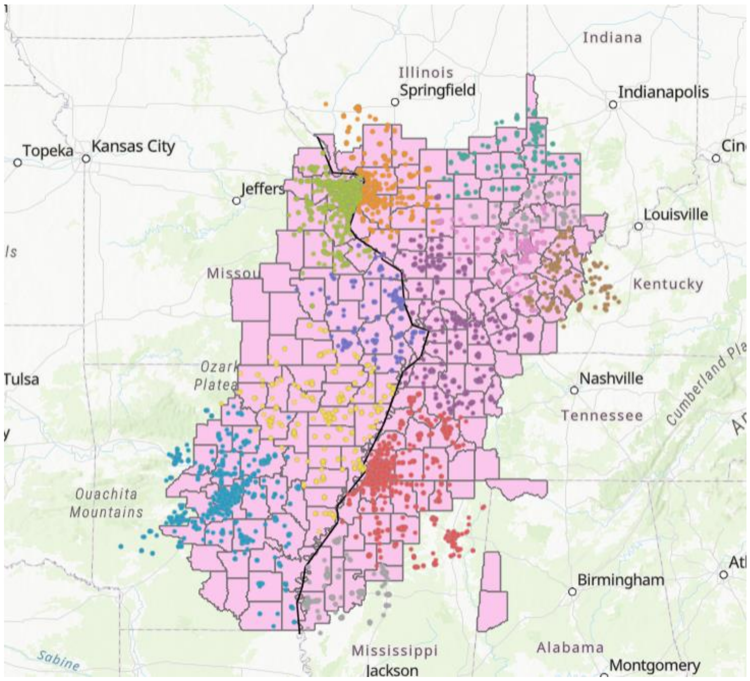
Table 4. TEPPCO Pipeline Shutdown Emergency Scenario Analysis

Gate Rate	**Bay Rate**	**Speed**	**Fleet Size**	**Hours of Service**	**Surge Capacity** (Truck Diversion)		**Gate Wait Time (hours)**	**Driving Time (hours)**	**Trips per Day**	**NMSZ OFC**	**NMSZ Demand**
					0%	100%					
Normal	Normal	Normal	Normal	Normal	**125%**		**0.30**	**4.36**	**2.42**	**14.84**	**11.86**
Normal	Normal	Normal	Normal	Normal	**75%**	**77%**	1.45	3.75	2.00	9.17	11.86
High	Normal	Normal	Normal	Normal		80%	1.37	3.74	2.01	9.52	11.86
Normal	**High**	Normal	Normal	Normal		**108%**	1.10	4.73	2.49	12.82	11.86
Normal	Normal	**High**	Normal	Normal		83%	1.55	2.90	2.26	9.88	11.86
Normal	Normal	Normal	**High**	Normal		78%	1.52	3.69	1.97	9.30	11.86
Normal	Normal	Normal	Normal	**High**		105%	1.83	5.12	2.69	12.50	11.86
High	**High**	**High**	**High**	**High**	**177%**	**182%**	1.13	5.37	4.05	**21.55**	11.86

Note: Green is indicative of the parameter(s) that are set as "High." Blue represents the normal baseline conditions. Yellow represents the interdiction phase for all terminals that are supplied by the TEPPCO pipeline.

Scenario 7 represents a customer divide along the Mississippi River, as visualized in Figure 10 and Table 5. The objective of Scenario 7 is to understand the best-case scenario if the population were to be split to either the east or west of the Mississippi River due to bridges being impassable. This model mimics no reliance on transportation methods across the Mississippi River and results in 9.2% of gas stations being reassigned to new group terminals to model the lack of river crossings.

Figure 10. Map of Retail Gas Stations in Relation to the Mississippi River



Note: Each colored circle is representative of a retail gas station. The colors are for different terminal groups as outlined in Figure 7. The thick black line through the pink AOI is the Mississippi River.

To calculate the customer divide, gas stations are assigned to terminal groups using an if-then rule to avoid river crossings. For example, if a gas station is in Illinois, the station cannot receive fuel from a terminal in St. Louis. This ensures all assignments stay on the same side of the Mississippi River. ArcGIS was also leveraged to inspect and confirm the split along the Mississippi River visually. After splitting the gas station assignments based on their location relative to the Mississippi River, the results identified four terminal groups on the west side and eight on the east side of the river. Before the split, the four western group terminals supplied 2,327 gas stations, accounting for 46% of all stations in the AOI. Following the split, these same four terminals now supply 2,123 gas stations, representing 42% of the total stations in the AOI. Most of this reduction comes from the St. Louis terminal group, which previously supplied 19% of all gas stations. However, following the customer divide, the St. Louis terminal group only supplies 15%, a decrease of approximately 200 gas stations.

Table 5. Customer Divide Along the Mississippi River Emergency Scenario Analysis

Gate Rate	Bay Rate	Speed	Fleet Size	Hours of Service	Surge Capacity (Truck Diversion)		Gate Wait Time (hours)	Driving Time (hours)	Trips per Day	NMSZ OFC	NMSZ Demand
					0%	100%					
Normal	Normal	Normal	Normal	Normal	**125%**		**0.30**	**4.36**	**2.42**	**14.84**	**11.86**
Normal	Normal	Normal	Normal	Normal	**N/A**	**125%**	0.29	4.41	2.42	14.80	11.86
High	Normal	Normal	Normal	Normal		127%	0.24	4.42	2.42	15.00	11.86
Normal	**High**	Normal	Normal	Normal		163%	0.14	5.42	3.00	19.38	11.86
Normal	Normal	**High**	Normal	Normal		137%	0.39	3.45	2.73	16.22	11.86
Normal	Normal	Normal	**High**	Normal		128%	0.33	4.34	4.34	2.38	11.86
Normal	Normal	Normal	Normal	**High**		**171%**	0.33	6.20	3.34	20.31	11.86
High	**High**	**High**	**High**	**High**	**N/A**	**271%**	0.07	6.36	4.99	**32.17**	11.86

Note: Green is indicative of the parameter(s) that are set as "High." Blue represents the normal baseline conditions. Yellow represents the interdiction phase for the scenario in which terminals support either the east or west of the Mississippi. A zero percent truck diversion is not applicable to this scenario because a terminal group is not being shut down.

4.3 LIMITATIONS

When completing the data collection and scenario analyses, some limitations impacted the final recommendations due to underlying assumptions. The first limitation is sparse publicly available data regarding fuel terminal characteristics, including capacity and fuel infrastructure supplied (pipelines, barges, railroads). Information is more readily available for larger, private fuel companies that make their data public. However, most of the fuel terminals' capacity and infrastructure have some estimations given they were based on ArcGIS mapping and proximity to pipelines, railways, and rivers. These assumptions are foundational in the emergency scenario (Section 4.2) that analyzes the impact of the TEPPCO pipeline being shut down.

When developing each emergency intervention scenario, the backup, or secondary, terminal is selected based on the nearest neighbor. This solution allows the trucks to travel the least miles and is the fastest and most recommended option. A potential issue is that local decision-makers may not choose the nearest terminals to support the impacted terminal group due to contractual obligations with specific fuel terminals, among other sociopolitical factors.

Truck diversion routing is made up of two scenarios that rely on assumptions. For the 100% truck diversion scenario, all trucks receive fuel from the nearest neighboring fuel terminal and then return to the interdicted area to provide fuel. For the 0% truck diversion scenarios, the assumption is no trucks will be able to support the interdicted area from other terminal groups. For future scope extensions, sensitivity analyses could be applied to additional truck diversion ratios (e.g., 25%, 50%, 75%).

5. CONCLUSION

Fuel is essential to the response and early recovery from an event like an NMSZ earthquake. This project aims to ensure that proactive fuel management strategies are aligned with the region for effective execution. Policy and operational levers assess potential fuel management strategies in this region to recommend actions that stakeholders such as FEMA, state, and local jurisdictions can take.

The magnitude of economic and human impact in a future NMSZ seismic event is the primary purpose for developing intervention guidelines for public and private sector actors. The MIT Humanitarian Supply Chain Lab's fuel distribution model, focused on discrete event simulation and queuing theory, informs fuel management strategies for the NMSZ. The results from the updated modeling assist with government interventions, including policy action and improved engagement with private sector actors.

By assessing the downstream fuel supply chain's steady state and non-steady state conditions, the operational flow capacity analysis output can be used by FEMA, state, local, and private actors to support proactive emergency preparedness and fuel shortage mitigation during and after disasters. Steady state analysis focuses on gasoline distribution in normal conditions and identifies potential improvements to the existing system. Non-steady state analysis simulates the anticipated impact of a seismic event on the distribution network and assesses how gasoline could be delivered to critical areas.

Previous fuel studies found that hours of service was the parameter that provided the best outcome. Across this project's seven scenarios, either bay rate or hours of service interventions provided the highest surge capacity. For example, decreasing the bay rate is most impactful for Memphis, TN, and Little Rock, AR, interdictions, as well as the TEPPCO shutdown. The largest difference in surge capacity due to a reduced bay rate occurs during a Little Rock, AR, interdiction. This is likely driven by Little Rock having the largest number of bays compared to all other terminal groups within the area of interest.

Little Rock and Memphis terminal groups have the most bays compared to the other terminal groups. Therefore, reducing the amount of waiting time at the bays should be prioritized. More broadly, seven policy recommendations to support a proactive response to a future NMSZ seismic event are provided in Section 5.1.

5.1 POLICY AND OPERATIONAL LEVER RECOMMENDATIONS

The market outlook for United States gasoline demand serves as the foundation for the strategic recommendations. Over the ten-year period from 2021 to 2031, there is an expected 36% increase in U.S. gasoline demand. In 2021, total annual demand was 690 tons of gasoline, whereas in 2031, 940 tons is the expected demand. While not as significant of an increase, diesel demand in the U.S. is expected to rise from 497 million tons/year to 581 million tons/year by 2031, a roughly 17% increase (NTCC, 2022). Given the market outlook, interventions that increase operational throughput capacity are worthy of additional resource allocation and/or investment, regardless of the occurrence of a disaster event. Improvement of system capacity is a proactive measure that not only prepares the system for emergency response but also allows the system to support predicted future growing demand.

Table 6 provides an overview of the minimum requirements to reach at least a 25% surge capacity increase; however, this increase is not sufficient to support efficient seismic event responses. Fleet size is the bottleneck for scenarios 3, 4, and 7. Gate rate is also a bottleneck in scenarios 4 and 7. Scenarios 3 and 7 reach at least a 25% increase by deploying any lever and, therefore, have the most flexibility in which lever can be utilized. If the TEPPCO pipeline were to be shut down, the maximum surge capacity with a single intervention is only 8%, driven by a bay rate increase.

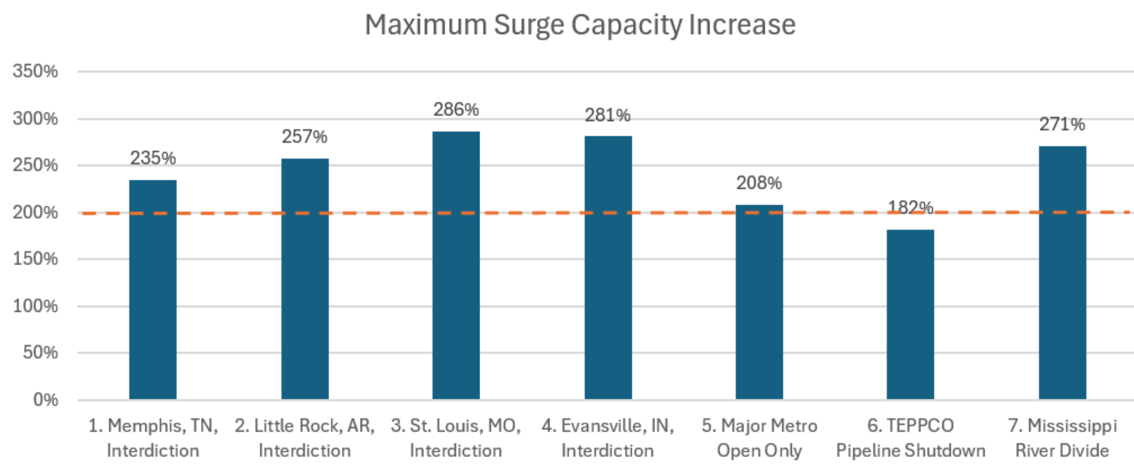
Table 6. Surge Capacity Analysis (25%) of Top Seven Emergency Scenarios in the NMSZ

Scenario	Minimum 25% Surge Capacity Increase Levers
1. Memphis, TN, Interdiction	Hours of service (HoS) or bay rate
2. Little Rock, AR, Interdiction	HoS or bay rate
3. St. Louis, MO, Interdiction	Any lever
4. Evansville, IN, Interdiction	Bay rate, truck speed, or HoS
5. Major Metro Open Only	HoS
6. TEPPCO Pipeline Shutdown	**None**
7. Mississippi River Divide	Any lever

During an emergency response, a 25% surge capacity increase is insufficient. Figure 11 highlights the maximum surge capacity increase when all levers are set to “High” in each scenario. The only scenario that does not support the minimum threshold is Scenario 6. When considering this scenario for intervention measures, it is critical to consider that the TEPPCO pipeline could be shut down for other reasons besides a seismic event, or natural disaster. Similar events to the six-day shutdown of the

Colonial Pipeline in 2021, caused by a ransomware attack, denote the importance of intervention development. (U.S. DHS, 2023) While natural disaster reactive response is the focus of this project, other exogenous factors can lead to widespread emergencies.

Figure 11. Maximum Surge Capacity Analysis of Top Seven Emergency Scenarios in the NMSZ



The foundation of the recommended policy and operational levers in Table 7 is based on a 200% surge capacity increase baseline minimum target. Given that hurricanes are an extreme scenario with demand surges of up to 300%, and there is no preparatory time in anticipation of a seismic event, the assumption is that demand will not peak as high as hurricanes. Additionally, the recommendations in Table 7 prioritize infrastructure development to support the expected growing gasoline demand in the U.S. A secondary recommendation is to ensure sufficient labor and hours of service to accompany rising gasoline needs. The recommendation to increase the number of associates is regarding gate management and/or truck drivers to accompany extended hours of service.

Table 7. Strategic Recommendations Based on the Top Seven Emergency Scenarios in the NMSZ

Scenario	Feasibility	Increase the Number of Bays	Open Additional Gate	Increase the Number of Associates	Increase the Hours of Service
1. Memphis, TN, Interdiction			X	X	X
2. Little Rock, AR, Interdiction			X	X	X
3. St. Louis, MO, Interdiction			X		X
4. Evansville, IN, Interdiction			X	X	X
5. Major Metro Open Only		X	X	X	X
6. TEPPCO Pipeline Shutdown		X	X		
7. Mississippi River Divide			X		X

High implementation difficulty
Moderate implementation difficulty
Low implementation difficulty

The ‘Implementation Feasibility’ column is color-coded to represent varying levels of implementation difficulty. The primary variables assessed are infrastructure change, fiscal considerations, and the number of people impacted. Red is the most difficult to implement, while green is the easiest to implement, relative to all proposed recommendations.

In addition to the recommendations outlined in Table 7, the review, and potential upgrades to the current pump infrastructure across all terminal groups within the NMSZ, would provide significant value. Understanding and improving baseline flow rates, and therefore, the level of gasoline output improvement, would yield significantly lower costs, not require additional labor, and reduce overall implementation difficulty. Additionally, strategic action in response to current pump analysis and improvements would reduce truck idle time by optimizing the truck throughput at each terminal.

5.2 FUTURE WORK

To further expand on this capstone project, five scope extensions would complement this analysis and support more robust conclusions.

1. Diesel: Analyze how diesel fuel’s supply and demand impact backup power generators during and after a state of emergency.

2. Jet Fuel: Jet fuel's supply and demand can have potential adverse impacts on airport operations in and around the NMSZ. Analyze which terminal groups provide jet fuel and the potential OFC implications.
3. Barge Transport: Develop scenario analyses for sole reliance on barges for fuel transit instead of trucks. The NMSZ has a notable reliance on barges for fuel transportation, both inbound and outbound, for most of the fuel terminals within the region. However, the barges' capacity, frequency of usage, and the delineation between inbound and outbound are not well known in the current data and research. Contacting fuel terminal managers would allow researchers to better understand primary transportation methods and relevant supporting data.
4. Sensitivity Analysis: The discrete simulation (non-steady state) could be further assessed to include different parameters that would analyze system resilience under more severe disruptions. For example, scenarios could simulate increases in bay processing times and gate waiting times, as well as extended offloading times at gas stations. Such sensitivity analyses would provide valuable insights into potential bottlenecks and help guide contingency planning.
5. Intervention Costs: Intervention costs for each emergency response strategy are critical in understanding the level of impact of this study's OFC and surge capacity analysis. The strategic recommendations in this study focus on infrastructure and labor changes. Cost and time impacts associated with infrastructure and labor should be detailed to complement the recommendations.

   The project's initial methodology should include interviews with terminal managers and other relevant officials to better understand the costs, challenges during emergency scenario planning, and feasibility of the suggested labor and infrastructure changes. Example infrastructure changes include the addition of bays and an entrance gate at the current exit gate, as well as fuel pump upgrades. For labor changes, the addition of associate(s) at gates, increasing the number of driving hours, and/or the addition of an associate to each truck should be reviewed. An example summary table is provided in Table A4 in Appendix A.

Potential future seismic events in the NMSZ could have devastating human and economic impacts. This project aims to ensure that proactive fuel management strategies are aligned with the region for the effective execution of government interventions. These strategies drive recommended actions that federal, state, and local jurisdictions can take to support proactive emergency preparedness and fuel shortage mitigation during and after seismic events.

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APPENDIX A

Figure A1. Map of U.S Petroleum Administration for Defense Districts (United States Energy Information Administration [US EIA], 2012)

Table A1. Terminal Groups and Associated State(s) in the NMSZ

Terminal Group	Terminal Group ID	State
Jonesboro	418	
Memphis	435	Arkansas
Little Rock	695	
Evansville	340	
Robinson	510	Illinois
St. Louis	540	
Wood River	574	
Evansville	340	Indiana
Princeton	502	
Evansville (IN)	340	
Owensboro	487	Kentucky
Paducah	490	
Greenville	655	Mississippi
Cape Girardeau	275	
Jonesboro	418	Missouri
St. Louis	540	
Memphis	435	Tennessee

Table A2. Fixed Variables, or Assumptions, in the Steady State OFC Model

gate time, rg (minutes)	bay time, rb (minutes)	service, h (hours)	truck speed, h (miles per hour)	truck capacity, c (gallons)	station time, rs (minutes)
7	35	14	45	9000	60

Table A3. Non-Steady State Simulation Parameters

Parameter	Definition	Values
n_g	number of gates (check-in)	{1,2,3}
n_b	number of fueling bays	{1, 2,…,15}
d	station distance (miles)	uniform [0, μ], ∀μ∈ {25, 50, 100, 150, 200, 300}
m	number of parking spaces	3
a	trucks start time (hours of day)	uniform [000,0600]
τ	trucks stopping criteria (minutes)	30
c	truck capacity (gallons)	9000
h	drivers' hours of service	14*
r_s	time at station (minutes)	triangular (50,70,60)
r_g	time at terminal gates (minutes)	triangular (6.3,7.7,7)
r_b	time at terminal bays (minutes)	triangular (31.5,38.5,35)
v	truck speed (miles/hour)	triangular (40.5,49.5,45)
f	fleet size	50

*Maximum daily driving hours per U.S. federal regulations

Table A4. Emergency Intervention Cost for Top Seven Scenarios

Scenario	Intervention Cost (S)	Fiscal Impact
Memphis, TN Interdiction		
Little Rock, AR, Interdiction		
St. Louis, MO, Interdiction		
Evansville, IN, Interdiction		
Major Metro Open Only		
TEPPCO pipeline Shutdown		
Mississippi River Customer Divide		

Note: The 'Fiscal Ease' column is color-coded to represent the range of fiscal responsibility and impact associated with each scenario. The primary resources assessed are infrastructure changes and associates' time and labor. Red is the costliest, while green is the least costly, relative to all proposed recommendations.

APPENDIX B

Table B1. OFC Analysis for a St. Louis, MO, Interdiction

Gate Rate	Bay Rate	Speed	Fleet Size	Hours of Service	Surge Capacity (Truck Diversion)		Gate Wait Time (hours)	Driving Time (hours)	Trips per Day	NMSZ OFC	NMSZ Demand
					0%	100%					
Normal	Normal	Normal	Normal	Normal	**125%**		**0.30**	**4.36**	**2.42**	**14.84**	**11.86**
Normal	Normal	Normal	Normal	Normal	**96%**	**121%**	0.34	4.39	2.34	14.37	11.86
High	Normal	Normal	Normal	Normal		126%	0.25	4.44	2.37	14.97	11.86
Normal	**High**	Normal	Normal	Normal		151%	0.21	5.45	2.90	17.85	11.86
Normal	Normal	**High**	Normal	Normal		133%	0.47	3.40	2.62	15.73	11.86
Normal	Normal	Normal	**High**	Normal		124%	0.39	4.33	2.30	14.71	11.86
Normal	Normal	Normal	Normal	**High**		**167%**	0.39	6.18	3.24	19.77	11.86
High	**High**	**High**	**High**	**High**	**208%**	**286%**	0.10	6.52	5.01	**33.91**	11.86

Note: Green is indicative of the parameter(s) that are set as "High." Blue represents the normal baseline conditions. Yellow represents the interdiction phase for all terminals in the St. Louis, MO, terminal group.

Table B2. OFC Analysis for a Little Rock, AR, Interdiction

Gate Rate	Bay Rate	Speed	Fleet Size	Hours of Service	Surge Capacity (Truck Diversion)		Gate Wait Time (hours)	Driving Time (hours)	Trips per Day	NMSZ OFC	NMSZ Demand
					0%	100%					
Normal	Normal	Normal	Normal	Normal	**125%**		**0.30**	**4.36**	**2.42**	**14.84**	**11.86**
Normal	Normal	Normal	Normal	Normal	**100%**	**106%**	0.53	4.35	2.22	12.58	11.86
High	Normal	Normal	Normal	Normal		108%	0.48	4.37	2.23	12.81	11.86
Normal	**High**	Normal	Normal	Normal		**156%**	0.18	5.51	2.78	18.52	11.86
Normal	Normal	**High**	Normal	Normal		114%	0.69	3.40	2.47	13.54	11.86
Normal	Normal	Normal	**High**	Normal		108%	0.61	4.28	2.18	12.81	11.86
Normal	Normal	Normal	Normal	**High**		146%	0.58	6.12	3.04	17.29	11.86
High	**High**	**High**	**High**	**High**	**223%**	**257%**	0.11	6.68	4.73	**30.46**	11.86

Note: Green is indicative of the parameter(s) that are set as "High." Blue represents the normal baseline conditions for all terminals in the Little Rock, AR, terminal group. Yellow represents the interdiction phase.

Table B3. OFC Analysis for an Evansville, IN, Interdiction

Gate Rate	Bay Rate	Speed	Fleet Size	Hours of Service	Surge Capacity (Truck Diversion) 0%	Surge Capacity (Truck Diversion) 100%	Gate Wait Time (hours)	Driving Time (hours)	Trips per Day	NMSZ OFC	NMSZ Demand
Normal	Normal	Normal	Normal	Normal	**125%**		**0.30**	**4.36**	**2.42**	**14.84**	**11.86**
Normal	Normal	Normal	Normal	Normal	**118%**	**120%**	0.56	4.20	2.23	14.27	11.86
High	Normal	Normal	Normal	Normal		123%	0.52	4.21	2.25	14.54	11.86
Normal	**High**	Normal	Normal	Normal		161%	0.23	5.31	2.84	19.07	11.86
Normal	Normal	**High**	Normal	Normal		131%	0.68	3.30	2.52	15.59	11.86
Normal	Normal	Normal	**High**	Normal		123%	0.62	4.13	2.19	14.59	11.86
Normal	Normal	Normal	Normal	**High**		**165%**	0.66	5.87	3.07	19.61	11.86
High	**High**	**High**	**High**	**High**	**266%**	**281%**	0.23	6.21	4.77	**33.36**	11.86

Note: Green is indicative of the parameter(s) that are set as “High.” Blue represents the normal baseline conditions. Yellow represents the interdiction phase for all terminals in the Evansville, IN, terminal group.

Table B4. Only Major Metropolitan Areas Open Emergency Scenario Analysis

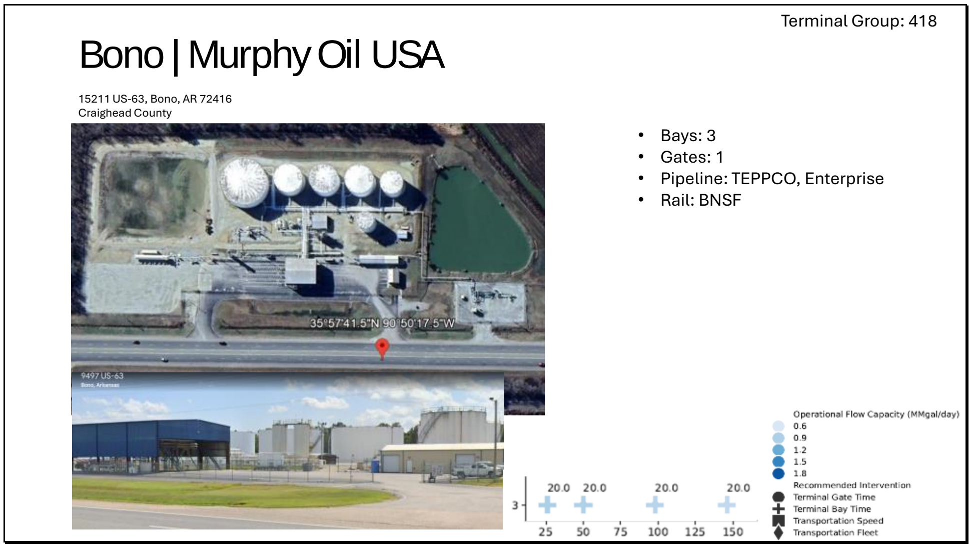
Gate Rate	Bay Rate	Speed	Fleet Size	Hours of Service	Surge Capacity (Truck Diversion) 0%	Surge Capacity (Truck Diversion) 100%	Gate Wait Time (hours)	Driving Time (hours)	Trips per Day	NMSZ OFC	NMSZ Demand
Normal	Normal	Normal	Normal	Normal	**125%**		**0.30**	**4.36**	**2.42**	**14.84**	**11.86**
Normal	Normal	Normal	Normal	Normal	**72%**	**84%**	1.23	4.18	1.71	9.94	11.86
High	Normal	Normal	Normal	Normal		86%	1.11	4.20	1.73	10.21	11.86
Normal	**High**	Normal	Normal	Normal		114%	0.81	5.06	2.10	13.47	11.86
Normal	Normal	**High**	Normal	Normal		92%	1.36	3.40	1.95	10.92	11.86
Normal	Normal	Normal	**High**	Normal		85%	1.32	4.12	1.69	10.13	11.86
Normal	Normal	Normal	Normal	**High**		**126%**	1.68	4.68	2.61	14.90	11.86
High	**High**	**High**	**High**	**High**	**168%**	**208%**	0.68	6.45	3.67	**24.70**	11.86

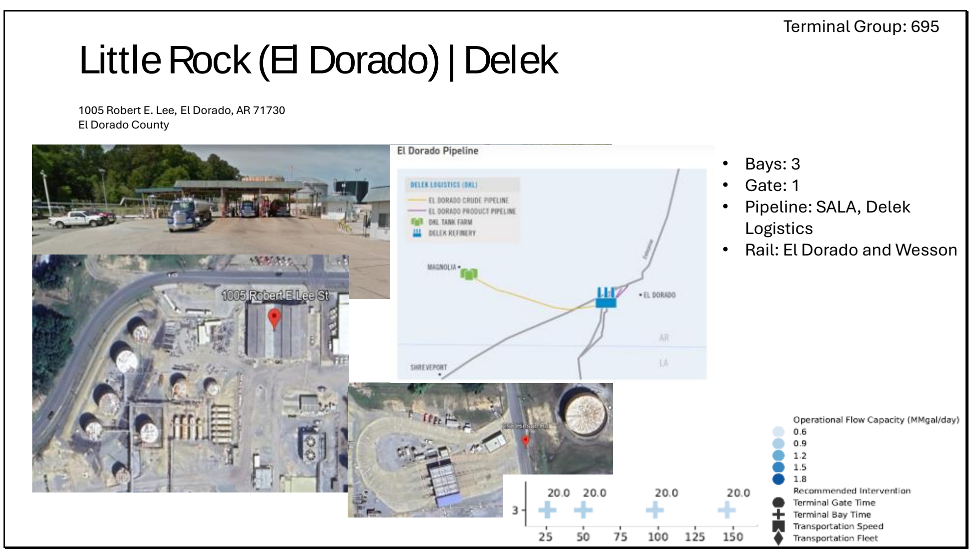
Note: Green is indicative of the parameter(s) that are set as “High.” Blue represents the normal baseline conditions. Yellow represents the interdiction phase for the scenario in which only the terminal groups supporting the four major metropolitan areas (Evansville, IN, Little Rock, AR, Memphis, TN, St. Louis, MO) are open.

APPENDIX C

Fuel Terminal Details by State

Note: Fuel terminal group identification numbers are listed in the top right-hand corner of each terminal group information image.



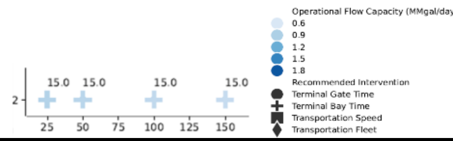


Terminal Group: 695

North Little Rock | Petroleum Fuels & Terminal Co

3206 Gribble Street, North Little Rock, Arkansas 72114
Pulaski County

- Bays: 2
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Barge: Arkansas River
- Rail: Arkansas Midland

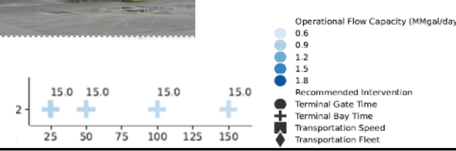


Terminal Group: 695

North Little Rock | Oakley Fuels

300 River Park Road, North Little Rock, Arkansas 72114
Pulaski County

- Bays: 2
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Barge: Arkansas River
- Rail: Saint Louis Southwestern

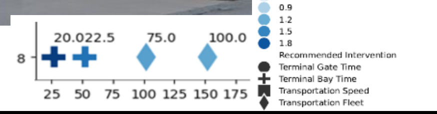


Terminal Group: 695

North Little Rock | Sunoco

2207 Central Airport Road, North Little Rock, AR 72117
Pulaski County

- Bays: 8
- Gates: 3
- Pipeline: TEPPCO, Enterprise
- Rail: Arkansas Midland, AKMD (offload for ethanol)



Assumption: entry and exit gate - able to use both

Terminal Group: 695

North Little Rock | HWRT

2626 Central Airport Road, North Little Rock, AR 72117
Pulaski County

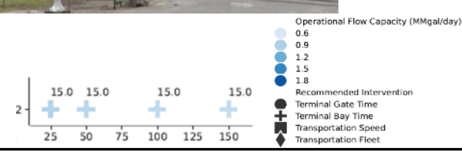
- Bays: 3
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Rail: Arkansas Midland, AKMD

Terminal Group: 695

North Little Rock | Delek Refining Ltd

2724 Central Airport Road, North Little Rock, AR 72117
Pulaski County

- Bays: 2
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Rail: Arkansas Midland, AKMD

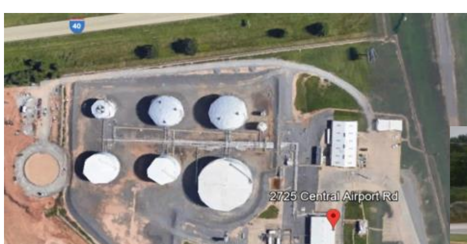


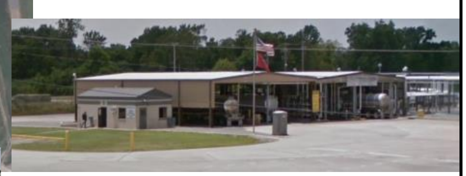
Terminal Group: 695

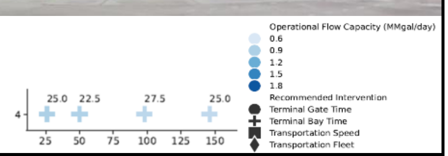
North Little Rock | Magellan Pipeline Co

2725 Central Airport Road, North Little Rock, AR 72117
Pulaski County

- Bays: 4
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Rail: Arkansas Midland, AKMD





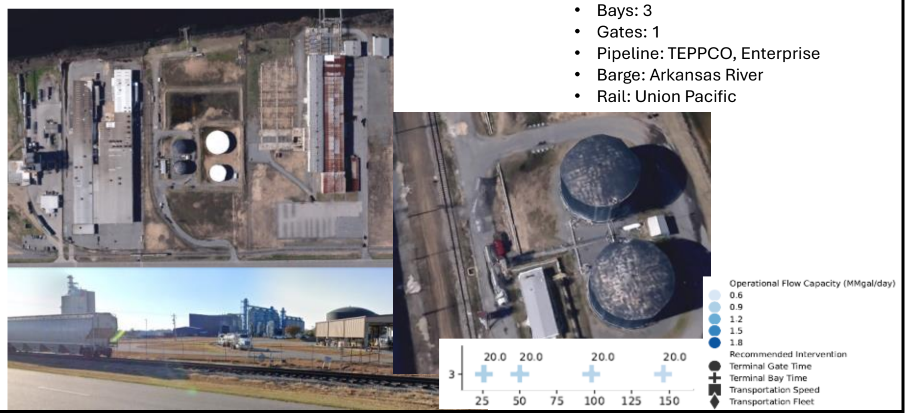


Terminal Group: 695

Pine Bluff | Petroleum Fuel & Terminal Co

4303 Emmett Sanders Rd, Pine Bluff, AR 71601
Jefferson County

- Bays: 3
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Barge: Arkansas River
- Rail: Union Pacific

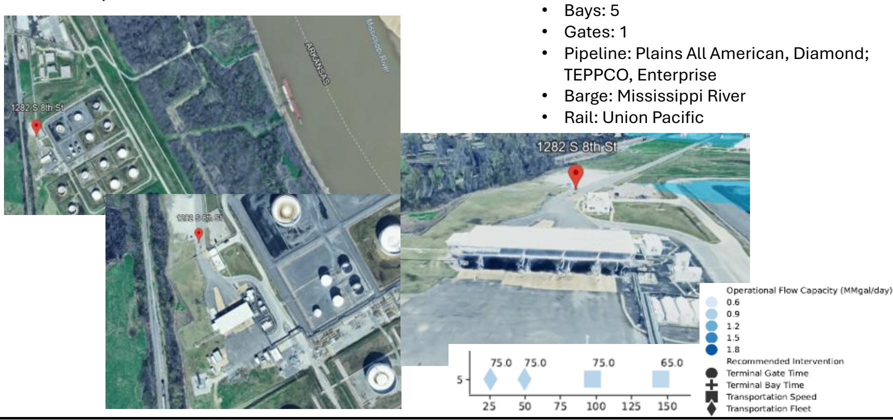


Terminal Group: 435

West Memphis | Premcor Refining Group (Valero)

1282 South 8th Street, West Memphis, AR 72301
Crittenden County

- Bays: 5
- Gates: 1
- Pipeline: Plains All American, Diamond; TEPPCO, Enterprise
- Barge: Mississippi River
- Rail: Union Pacific



Terminal Group: 510

Effingham | Buckeye

18264 US-45, Effingham, Illinois 62401
Effingham County

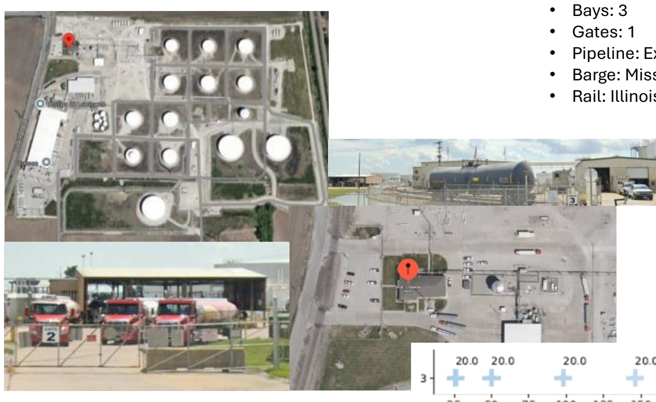
- Bays: 2
- Gates: 1
- Pipeline: Buckeye Partners
- Rail: Illinois Central

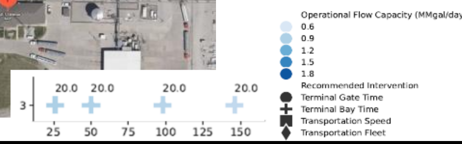
Terminal Group: 574

Hartford | Phillips 66

2300 S Delmar Ave, Hartford, Illinois 62048
Madison County

- Bays: 3
- Gates: 1
- Pipeline: Explorer
- Barge: Mississippi River
- Rail: Illinois Terminal (IT)



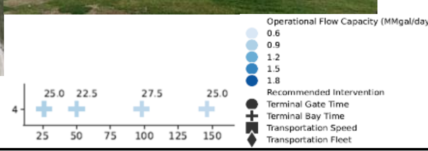


Terminal Group: 574

Hartford | HWRT Oil Company

900 N Delmar Ave, Hartford, Illinois 62048
Madison County

- Bays: 4
- Gates: 1
- Pipeline: Keystone, TransCanada
- Barge: Mississippi River
- Rail: Illinois Terminal (IT)



Terminal Group: 574

Hartford | Marathon Pipe Line LLC

459 Hawthorne Ave, Hartford, Illinois 62048
Madison County

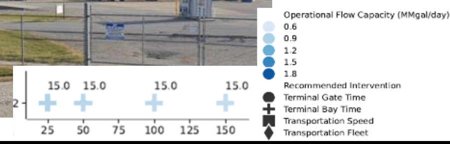
- Bays: 5
- Gates: 1
- Pipeline:
  - Explorer /Marathon, Platt
  - Koch, Minncan
- Barge: Mississippi River
- Rail: Illinois Central

Terminal Group: 574

Hartford | Omega Partners

1402 S Delmar Ave, Hartford, Illinois 62048
Madison County

- Bays: 2
- Gates: 1
- Pipeline
  - Explorer (Houston & St Louis – Wood River)
  - Buckeye
- Barge: Mississippi River
- Rail: Illinois Terminal (IT)

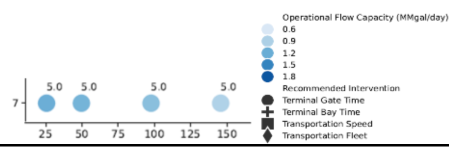


Terminal Group: 574

Hartford | Kinder Morgan Phoenix Holdings

1000 Bp Ln, Hartford, Illinois 62048
Madison County

- Bays: 7
- Gates: 1
- Pipeline:
  - BP - Milan-Wood River
  - Marathon – Wabash 12 in product
  - Spectra Energy - Platte
- Rail:
  - Illinois Central
  - Illinois Terminal (IT)

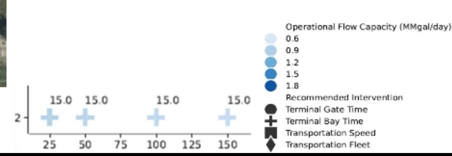


Terminal Group: 340

Norris City | HWRT Oil

317 County Rd 750 N, Norris City, Illinois 62869
White County

- Bays: 2
- Gates: 1
- Pipeline: TEPPCO, Enterprise

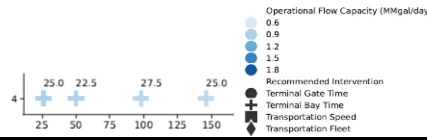


Terminal Group: 510

Robinson | Marathon Pipe Line LLC

12345 E. 1050th Ave, Robinson, Illinois 62454
Crawford County

- Bays: 4
- Gates: 1
- Pipeline:
  - Marathon, Robinson-Lima
  - Marathon, Wabash 12 in products
- Rail: Illinois Central

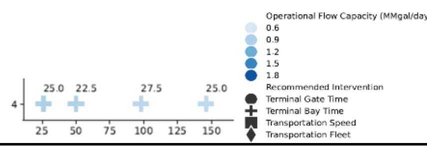


Terminal Group: 540

Sauget | Gateway Terminals

4 Pitzman Ave, Sauget, Illinois 62201
St. Clair County

- Bays: 4
- Gates: 1
- Pipeline:
  - Phillips 66, Goldline
  - Buckeye
- Barge: Mississippi River
- Rail:
  - Gulf Mobile and Ohio --> IC
  - Tomahawk Railway (TR)

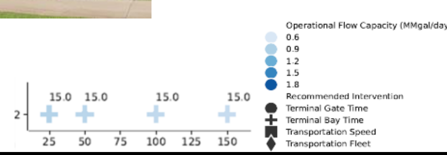


Terminal Group: 340

Evansville | TransMontaigne

2630 Broadway Ave, Evansville, IN 47712
Vanderburgh County

- Bays: 2
- Gates: 1
- Barge: Ohio River (diesel only for outbound)
- Rail: L&N --> CSX

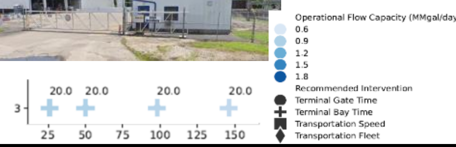


Terminal Group: 340

Evansville | Marathon Petroleum

2500 Broadway Ave, Evansville, IN 47712
Vanderburgh County

- Bays: 3
- Gates: 1
- Barge: Ohio River
- Rail: CSX

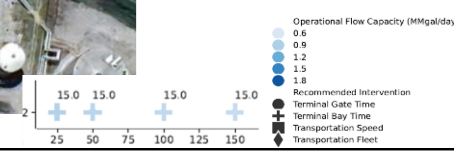


Terminal Group: 340

Mount Vernon | Countrymark Refining & Logistics

1200 Refinery Road, Mount Vernon , IN 47620
Posey County

- Bays: 2
- Gates: 1
- Pipeline: MTV to Jolietville, Countrymark
- Barge: Ohio River
- Rail: CSX

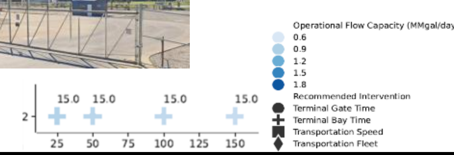


Terminal Group: 340

Mount Vernon | Marathon Petroleum

129 Barter Street, Mount Vernon, IN 47620
Posey County

- Bays: 2
- Gates: 1
- Pipeline: MTV to Jolietville, Countrymark
- Barge: Ohio River
- Rail: Evansville Western Railway (EVWR)



Terminal Group: 502

Oakland City | Enterprise Refined Products

3475 Co Rd 950, Oakland City, IN 47660
Columbia Township

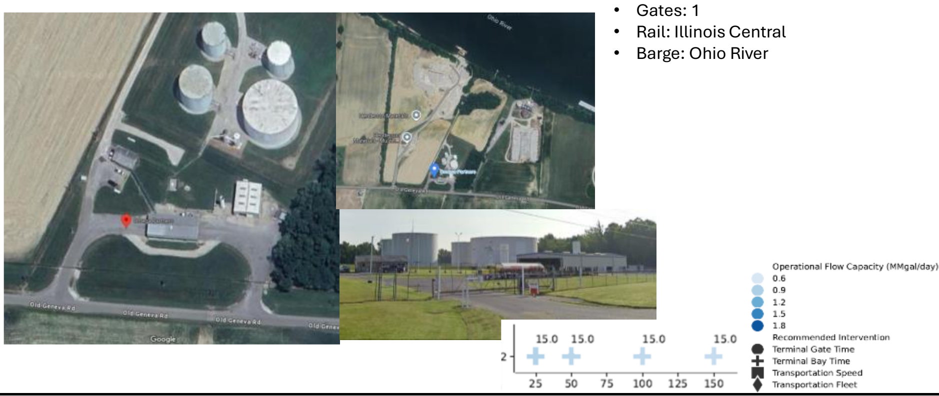
- Bays: 2
- Gates: 1
- Pipeline: TEPPCO, Enterprise

Terminal Group: 340

Henderson | Omega Partners

2321 Old Geneva Rd, Henderson, Kentucky 42420
Henderson County

- Bays: 2
- Gates: 1
- Rail: Illinois Central
- Barge: Ohio River

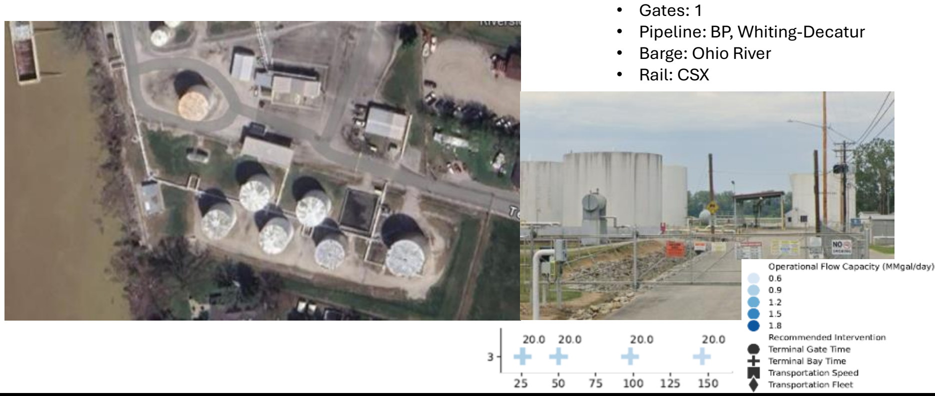


Terminal Group: 340

Henderson | TransMontaigne

2633 Sunset Ln, Henderson, Kentucky 42420
Henderson County

- Bays: 3
- Gates: 1
- Pipeline: BP, Whiting-Decatur
- Barge: Ohio River
- Rail: CSX

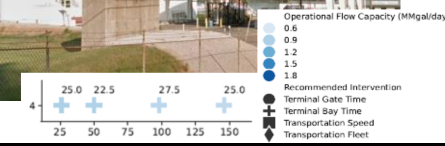


Terminal Group: 487

Owensboro | Southern States Cooperative

150 Coast Guard Ln, Owensboro, Kentucky 42303
Daviess County

- Bays: 4
- Gates: 1
- Pipeline: Marathon, Patoka, IL - Owensboro, KY
- Barge: Ohio River
- Rail: Seaboard System --> CSX

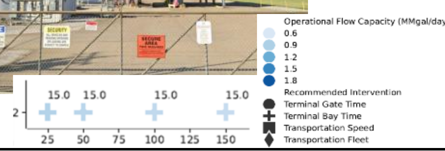


Terminal Group: 487

Owensboro | TransMontaigne

980 Pleasant Valley Rd, Owensboro, Kentucky 42303
Daviess County

- Bays: 2
- Gates: 1
- Pipeline: Marathon, Patoka, IL - Owensboro, KY
- Barge: Ohio River
- Rail: Seaboard System --> CSX

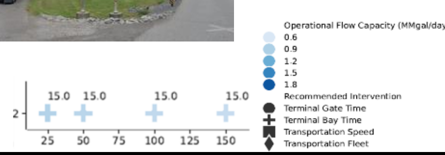


Terminal Group: 490

Paducah | Marathon Petroleum

201 Ashland Rd, Paducah, Kentucky 42003
McCracken County

- Bays: 2
- Gates: 1
- Barge: Tennessee River
- Rail: Illinois Central

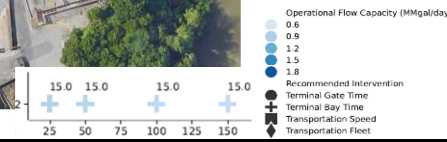


Terminal Group: 490

Paducah | TransMontaigne

233 Elizabeth St, Paducah, Kentucky 42003
McCracken County

- Bays: 2
- Gates: 1
- Barge: Tennessee River
- Rail: Paducah & Louisville Railway

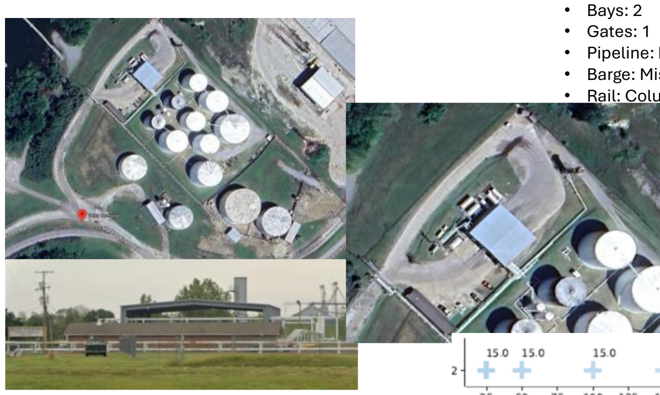


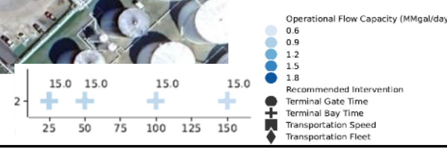
Terminal Group: 655

Greenville | Delta Terminal Inc

2081 Harbor Front Rd, Greenville, Mississippi 38701
Washington County

- Bays: 2
- Gates: 1
- Pipeline: Marathon, Centennial
- Barge: Mississippi River
- Rail: Columbus and Greenville Railway





Terminal Group: 655

Greenville | Scott Petroleum Corp

942 N Broadway St, Greenville, Mississippi 38701
Washington County

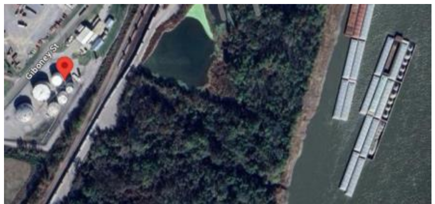
- Bays: 3
- Gates: 1
- Pipeline:
  - Marathon, Centennial
  - Energy Transfer, ETCO
- Barge: Mississippi River
- Rail: Illinois Central

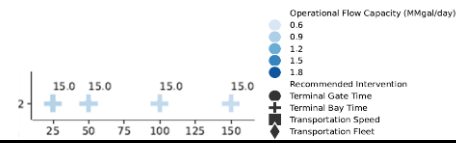
Terminal Group: 275

Cape Girardeau | TransMontaigne

1400 Giboney Street, Cape Girardeau, MO 63703
Cape Girardeau County

- Bays: 2
- Gates: 1
- Pipeline: TEPPCO, Enterprise (outbound)
- Barge: Mississippi River (inbound)
- Rail: BNSF (UP/SP trackage rights)



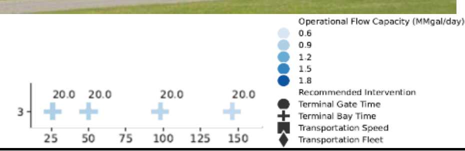


Terminal Group: 418

Hayti (Caruthersville) | OakMar Terminal

2353 State Hwy D, Caruthersville, MO 63830
Pemiscot County

- Bays: 3
- Gates: 1
- Barge: Mississippi River
- Rail: BNSF

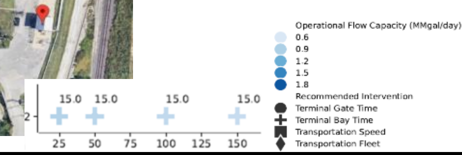


Terminal Group: 540

St Louis (Lemay) | JD Street

1 River Road, St. Louis, MO 63125
St. Louis County

- Bays: 2
- Gates: 1
- Pipeline: Goldline, Phillips 66
- Barge: Mississippi River
- Rail: Missouri Pacific --> UP

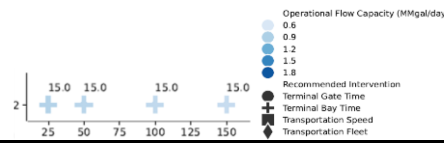


Terminal Group: 540

Saint Peters | Magellan Midstream Partners

4751 Veterans Memorial Parkway, St. Peters, MO 63376
St. Charles County

- Bays: 2
- Gates: 1
- Pipeline: Houston – Woodriver, Explorer
- Rail: Norfolk Southern

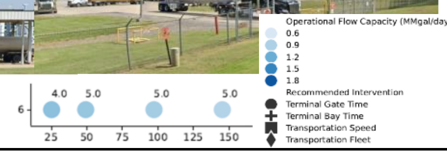


Terminal Group: 275

Scott City | Enterprise Refined Products

10653 State Hwy N, Scott City, MO 63780
Scott County

- Bays: 6
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Rail: Missouri Pacific --> UP

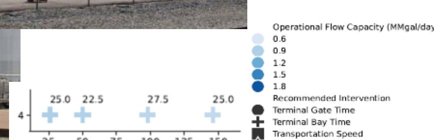


Terminal Group: 540

St Louis | JD Streett & Co

3800 South First Street, St. Louis, MO 63118
St. Louis County

- Bays: 4
- Gates: 1
- Pipeline: Wood River - St. Louis, Explorer
- Barge: Mississippi River
- Rail: Missouri Pacific --> UP



Terminal Group: 540

St Louis | Buckeye Terminals

239 East Prairie Street, St. Louis, MO 63147
St. Louis County

Assumption: able to use secondary gate

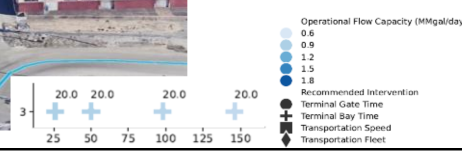
- Bays: 4
- Gates: 2
- Pipeline: Wood River - St. Louis, Explorer
- Barge: Mississippi River
- Rail: Chicago Burlington & Quincy -> BNSF

Terminal Group: 540

St Louis | Kinder Morgan Transmix

4070 South First Street, St. Louis, MO 63118
St. Louis County

- Bays: 3
- Gates: 1
- Pipeline: Wood River - St. Louis, Explorer
- Barge: Mississippi River
- Rail: Union Pacific, TRRA

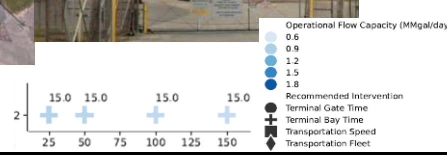


Terminal Group: 435

Memphis | Petroleum Fuel & Terminal Co

1232 Riverside Blvd, Memphis, Tennessee 38106
Shelby County

- Bays: 2
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Barge: Mississippi River
- Rail: BNSF

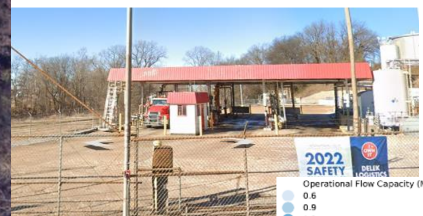


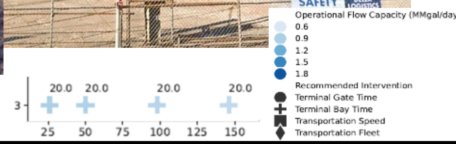
Terminal Group: 435

Memphis | Delek Logistics Operating

1023 Riverside Blvd, Memphis, Tennessee 38106
Shelby County

- Bays: 3
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Barge: Mississippi River
- Rail: BNSF





Terminal Group: 435

Memphis | ExxonMobil Corporation

454 Wisconsin Ave, Memphis, Tennessee 38106
Shelby County

- Bays: 5
- Gates: 1
- Pipeline: TEPPCO, Enterprise
- Barge: Mississippi River
- Rail: BNSF

Terminal Group: 435

Memphis | Valero Energy Corporation

2385 Riverport Rd., Memphis, Tennessee 38109
Shelby County

- Bays: 7
- Gates: 1
- Pipeline: Plains All American, Diamond
- Barge: Mississippi River
- Rail: Illinois Central