Fuel Distribution: Modeling the Operational Flow Capacity in the Middle Mile During Disaster Scenarios

by

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ABSTRACT

Fuel supply disruptions caused by natural disasters can cascade rapidly through regional distribution networks, yet most emergency response models focus on last-mile delivery and overlook the upstream middle-mile segment that connects refineries to distribution terminals. This gap leaves emergency management organizations without tools to evaluate how refinery outages, pipeline failures, or disruptions to waterborne fuel imports via marine terminals propagate through the network.

Using Southern California as a case study, this project extends an existing Operational Flow Capacity (OFC) framework into the middle mile through a discrete-event simulation, built on open-source Python tools, that quantifies fuel flows and identifies throughput bottlenecks under specified disruption conditions.

The model was tested across three scenarios: a refinery fire, a major earthquake, and a 2-week disruption occurring together with the imminent decommissioning of the Phillips 66 refinery. In this last scenario, the combined effect reduced overall network throughput to 68% of its normal value over the duration of the disruption; applying a fuel-blending policy could partially offset this impact, raising throughput to 79.6%.

More broadly, the results reveal that the network is resilient to short, localized disruptions, but that large, multi-asset failures can isolate inland cities like Las Vegas and Phoenix, with recovery taking nearly three months.

Based on these findings, the project recommends pre-authorizing bundled emergency regulatory waivers, establishing minimum safety stock requirements at distribution terminals, and expanding pipeline capacity through targeted federal financial incentives; measures that, if adopted, could reduce supply shortfalls, shorten regional recovery timelines, and maintain critical fuel access during major disaster events.

While Southern California serves as the primary case study, the simulation framework is designed to be transferable to other regional fuel networks, requiring only locally calibrated input parameters, making it a broadly applicable tool for emergency planners across the country.

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1.0 INTRODUCTION

Unexpected disasters can severely disrupt critical infrastructure and create cascading failures across essential supply chains. The mission of the Humanitarian Supply Chain Lab (HSCL) in MIT's Center for Transportation and Logistics (CTL) is to understand and improve the supply chain systems behind public services and private markets to better meet human needs during crises (Humanitarian Supply Chain Lab, n.d.). The lab focuses on a broad range of supply chain-related initiatives that enhance emergency response during crises, including collaboration with the United States Federal Emergency Management Agency (FEMA). Notable recent projects include developing frameworks for evaluating critical commodity stockpiles in the event of disaster scenarios (Seelbach, 2019), developing practical plans to revive supply chain operations after crises (Boutiller et al., 2019), and the Supply Chain Analysis Network (SCAN) study evaluating private sector supply chains that provide commodities in areas of Northern and Southern California that are at risk of earthquakes (Supply Chain Analysis Network, 2025).

1.1 Motivation

One of the key commodities studied in the SCAN study was gasoline and diesel fuel. The U.S. fuel supply chain can be broadly divided into three major segments, as shown in Figure 1:

- **Upstream:** Exploration and production of crude oil
- **Midstream:** Transportation and storage of crude oil before refining
- **Downstream:** Refining and distribution through terminals to end consumption points such as gas stations, airports, and power plants. This segment can be further broken down into the following:
    - **Middle Mile** refers to the movement of fuel from refineries to distribution terminals
    - **Last Mile** refers to the movement of fuel from distribution terminals to end consumption points

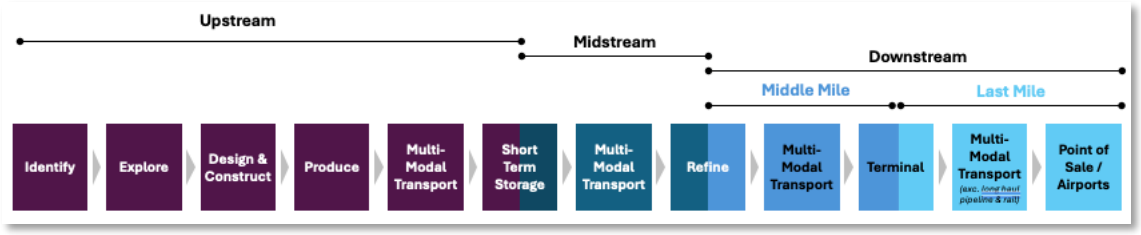


Figure 1. Segments of the Fuel Supply Chain (Source: Adapted from American Petroleum Institute, n.d.)

Several scenarios have been modeled to assess how disruptions from natural disasters affect the downstream sector, particularly at the last mile (i.e., the flow from terminals to service stations and airports). Rana et al. (2024) addressed the last-mile problem associated with retail fuel availability in the state of Florida during a hurricane disruption, concluding that the primary limiting factors were terminal and transportation operations rather than fuel inventory in terminal storage tanks. To conduct this research, they defined an Operational Flow Capacity (OFC) model for the downstream network's fuel capacity. This model focused on last-mile downstream fuel distribution from distribution terminals, delivered by truck within a single day, and concluded that terminal gates and bays, as well as truck drivers, were the limiting factors. The 2024 Rana paper builds on a 2021 SCAN study done by Goentzel et al. that describes the overall US fuel ecosystem. This study highlights

different public policies and business levers that can be activated at each network stage to reduce supply disruptions and assess these levers across disruption scenarios.

Building on these last-mile studies, recent research highlights the importance of extending the analysis to the middle-mile segment, where disruptions can cascade downstream and ultimately affect end consumers. The middle-mile fuel network is built around a set of distinct upstream nodes that differ significantly from those in the last-mile environment. It begins at the refinery, where crude oil is processed into multiple finished products with varying production and storage constraints. These products are primarily injected into pipelines, with additional volumes routed through marine docks for coastal or inland waterborne transport. Pipelines operate either as private assets or regulated common carriers, where access, batching, and tariffs dictate actual flow capacity. Marine transport is entirely privatized and governed by vessel availability, draft limits, berth throughput, and weather-driven variability. The network terminates at bulk distribution terminals, where products are stored, blended, and staged to meet regional demand across gasoline, diesel, and jet fuel.

The Southern California region presents a particularly relevant case for middle-mile disruptions, given the recent refinery closures linked to the state's energy transition (Austin, 2025; Bridges, 2025) and the potential for acute disruptions, such as the fire at El Segundo, California's second-largest refinery (Jiménez et al., 2025). A quantitative tool that models permanent and temporary refinery or pipeline losses in the middle-mile fuel network would help SCAN or FEMA identify effective policies to enhance system resilience in at-risk regions.

1.2 Problem Statement and Key Questions

Because disasters such as earthquakes or hurricanes typically cause localized spikes in fuel demand, there is often an emphasis on servicing last-mile distribution terminals without considering upstream supply. However, if a disaster were to affect supply to terminals or from refineries, the current OFC model developed by Rana (2024) cannot account for such disruptions in sufficient detail to inform potential responses. To make practical recommendations, SCAN or FEMA needs a model that reflects the unique dynamics of middle-mile nodes (refineries, pipelines, marine shipments) and can be applied more generally across at-risk regions. We use Southern California as our test case to evaluate the efficacy of our model.

Therefore, the key questions this paper addresses are:

- What are the physical interfaces and operational constraints that limit the flow of refined product from refineries and through pipeline or marine transport?
- How can the OFC mathematical model be extended upstream to assess the network's aggregated middle-mile capacity?
- How does the extended model support evaluating the middle-mile supply chain resilience in the at-risk Southern California region?

1.3 Project Goals and Outcomes

The project aims to expand the OFC framework upstream to analyze transportation arcs between refineries and distribution terminals. We started by investigating the constraints of the middle-mile network's three main nodes—refineries, pipelines, and marine shipments—through literature reviews and industry interviews. Then, building on Wilson et al. (2015) and Siddiqui et al. (2018), who developed similar flow-capacity models for Southern California as a representative at-risk region,

we created an aggregated OFC model. Finally, we used the OFC model to simulate disruptions and assess various resilience metrics under different disruption scenarios.

The outcomes for this project include the following:

1. Aggregated Operational Flow Capacity (OFC) model using open-source discrete event simulation logic of the middle-mile fuel distribution network for Southern California, incorporating refinery, pipeline, port, and distribution terminal capacities
2. Assessment of Southern California's resilience in the event of disruptions to refinery production, pipeline operations, or ports in the middle-mile network

The findings from this project indicate that Southern California's middle-mile network is already well balanced under normal conditions. While it can handle short, localized disruptions, it is vulnerable to a major loss of refining or pipeline capacity. Using the methodology described in this paper, we go beyond simply identifying supply shortages to analyze how subsequent transportation arcs (pipelines) and demand nodes (terminals) are affected. We can also test operational strategies that are likely to enhance resilience.

For organizations such as FEMA and SCAN, this project provides a tool to assess disruption scenarios and evaluate potential mitigation strategies in advance of a fuel infrastructure crisis. Because this is a generalized, open-source framework, the model could also be adapted by other organizations to evaluate infrastructure constraints for emergency planning and policy decisions.

2.0 STATE OF THE PRACTICE

This capstone aims to develop an Operational Flow Capacity (OFC) model for the middle-mile network to aid federal, state, and local agencies in planning for disruptions. Using Southern California as a case study, it evaluates the model's effectiveness, considering the region's refining, pipeline, marine capabilities, and disaster risks. The model development involved reviewing literature on physical and operational constraints of refineries, pipelines, and marine shipments, the current state of Southern California's middle-mile network, and existing flow-capacity and disruption-planning models.

2.1 Constraints of Middle Mile Components

Each middle-mile component is governed by a different set of physical and operational constraints that together determine how much fuel can move through the network.

Refineries: The middle-mile network starts at refineries, where crude oil is processed into products like gasoline and diesel. Refineries are complex, using various units and conditions to convert crude oil, and they can turn a 42-gallon barrel into about 45 gallons of refined products (U.S. Energy Information Administration, 2024). Their capacity mainly depends on the size of the crude distillation unit (CDU), which separates crude into components based on boiling points. However, as Kaiser (2017) notes, refineries are not uniform; the yield of each product heavily depends on the specific configuration of processing units. More complex, deep conversion refineries have multiple units (fluid catalytic cracker [FCC], hydrocracker [HCU], reformer, coker) to process various crude types into nearly any product. In contrast, simpler hydroskimming refineries produce fewer products. Refinery storage and outbound distribution capacity are generally considered secondary to production capacity, so model levers should focus on refining output rather than outbound handling.

In developing our OFC model, we considered each refinery's characteristics independently when aggregating Southern California's refining capacity. We used the CDU's capacity as the maximum outbound flow and then examined which processing units are available at each refinery to determine each refined product's actual outbound capacity. A more complex refinery will have the flexibility to adjust production during unit disruptions, although the offline status of specific units can disproportionately impact output. Additionally, the time required to restart a refinery after a disruption will depend on its complexity.

Pipelines: Once refined products are produced, they are transported mainly via multi-product pipelines. These pipelines can be privately owned and operated or they can operate as common carriers, like public utilities, offering capacity for a fee. The Federal Energy Regulatory Commission (FERC) ensures these pipelines provide open, nondiscriminatory access, publish rates, and allocate capacity transparently. They use standard nomination cycles in which shippers submit volume and timing requests that are confirmed, scheduled, and (if needed) prorated to assign capacity and deliver products in batches. Unused nominated capacity incurs a fee, encouraging pipelines to operate near full capacity (Tartan Oil, personal communication, October 30, 2025). However, Li et al. (2024) note that operational constraints limit actual flow below maximum capacity due to batch sequencing, interface management, and injection scheduling.

Our model represents pipelines with fixed, cycle-based throughput, preventing flow increases beyond capacity and accounting for transportation lead time. Since multi-product pipelines transport fuels in discrete batches, these serve as the analysis unit for pipeline OFC. Following Li et al. (2024), we incorporate batch sequencing rules and can account for losses from unusable products at the interface between batches (also known as transmix).

Marine Shipments: While pipelines handle most transport from source production to distribution terminals, marine shipments offer flexibility during regional disruptions by delivering refined products from outside areas. Marine shipments operate in contract and spot markets, meaning some ships carry unsold fuel, allowing fuel retailers to buy product “off the water” while in transit, close to points of demand. Marine inflow is primarily constrained by port factors such as berth availability, draft limits, and cargo-handling equipment, not vessel capacity. As Christiansen et al. (2007) note, these factors determine which ships can enter ports and how quickly they unload. Marine operations have long service times and strict requirements governing which ship types can dock at a port, so ports may not be able to easily accommodate additional tankers during disruptions. Marine inflow is thus queue-based and berth-limited, with throughput dependent on unloading rates and berth use, not vessel or fleet size. For simplicity, we incorporate marine transport into the OFC model by estimating port inflow capacity from historical import data and applying the historical gasoline and diesel shares to those inflows.

2.2 Southern California's Fuel Distribution Network

Southern California is useful for testing the extended OFC model because it functions as a regional fuel “island” with no pipelines for refined products entering the state. It relies on two sources: local refineries and marine imports, primarily through the Ports of Los Angeles and Long Beach, which are the only facilities capable of receiving refined cargo. These sources supply Los Angeles, San Diego, Phoenix, and Las Vegas via Kinder Morgan pipelines. The Supply Chain Analysis Network, including emergency agencies, MIT researchers, and industry experts, notes the area's structural fragility, describing it as two isolated fuel systems with no direct pipeline connection, therefore requiring

marine vessels for interregional transfers (SCAN, 2025). Rail is used but plays a limited role, so it is excluded from the model. Figure 2 shows the Southern California region with the relevant components for middle-mile distribution.

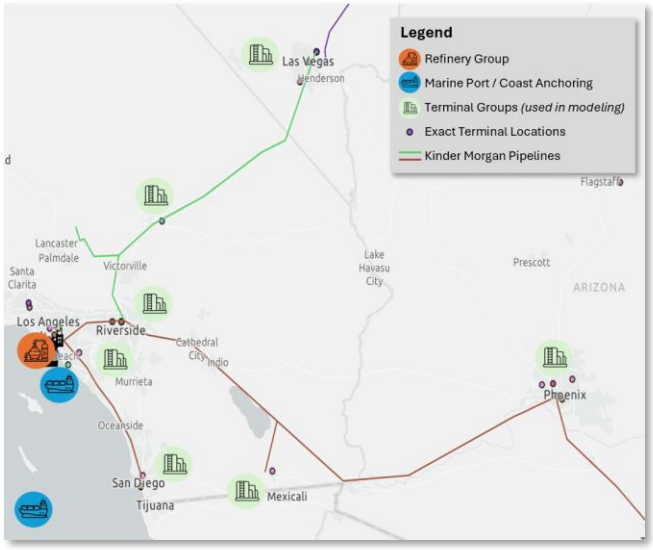


Figure 2. Middle-Mile Fuel Distribution Network for Southern California

The California Energy Commission (CEC) reports that statewide gasoline demand is about 800,000 barrels per day, while peak refining capacity is just below 1 million barrels per day, leaving little flexibility to meet excess demand during a disruption. In Southern California, a temporary refinery shutdown could reduce capacity by up to 35%, and storage covers only about two weeks of demand (CEC, 2024). Due to regional isolation, few refineries, long marine lead times, and out-of-state commitments, Southern California's fuel system is tightly balanced and fragile, making it suitable for testing the extended OFC model.

2.3 Existing Modeling Approaches

Several models analyze disruptions in fuel distribution. We review three approaches relevant to our problem, highlight key details, and discuss how to incorporate them.

Scenario-Based Middle-Mile Simulation: Wilson et al. (2015) simulated disruptions to the US liquid fuel infrastructure, including Southern California, where an earthquake damages refineries, ports, and pipelines, causing shortages in several cities. They simulate fuel consumption over time and the days needed to return to normal operations. While the specific details of their methodology are not shared, the scenarios are well explained, and some general approaches are provided. We used their work as a validation tool and adopted similar aggregation methods for middle-mile components.

Discrete Event Simulation in the Last Mile: Rana et al. (2024) developed the OFC framework to measure downstream flow capacity between distribution terminals and gas stations via truck deliveries. They use a time-limited, multi-server tandem-queue model to represent gates, bays, and driver hours as the primary flow-limiting factors. However, it only considers downstream flow and excludes middle-mile nodes. We extended the OFC framework, which calculates maximum daily volume based on refinery units, pipeline cycles, and port berths, to the middle-mile nodes using a similar queueing approach.

Marine and Pipeline Throughput Modeling: Siddiqui et al. (2018) proposed a mixed-integer programming framework to select between pipeline and marine transport for a refinery-to-distribution-terminal route. The model includes operational details such as batch sequencing and vessel capacity utilization, with the goal of minimizing costs and environmental risk rather than handling disruptions. However, we used the framework as a basis for modeling operational details for pipelines and marine shipments and applied it to potential disruption scenarios.

Together, these three modeling approaches form the foundation for our extension of the OFC framework into the middle mile, allowing us to test disruption scenarios in Southern California.

3.0 METHODOLOGY

To evaluate the resilience of Southern California's fuel supply chain, this study models the network by aggregating supply and demand at the city level and testing disruption scenarios through a discrete-event simulation. The methodology used in this capstone draws directly on the modeling approaches identified in the State of the Practice. Specifically, it applies Wilson et al.'s (2015) network aggregation approach, extends Rana et al.'s (2024) OFC-based discrete-event simulation framework to middle-mile nodes, and uses Siddiqui et al. (2018) to inform the treatment of pipeline batching and marine transport constraints.

3.1 Network Definition and Aggregation

The approach described by Wilson (2015) simplifies the network sufficiently by aggregating both supply capacities and demands. This method makes the modeling more robust, as aggregation reduces parameter variation in demand and supply without sacrificing generality. Considering this approach, we modeled the network as seen in Figure 3.

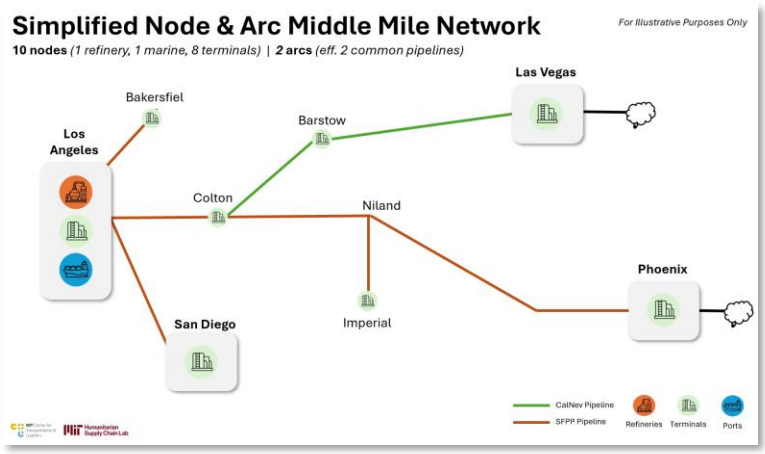


Figure 3. Simplified Middle-Mile Network for Southern California

The components of the network can be grouped into the following:

- Supply nodes: Entities that generate inventory according to the need in the network. This can be a refinery or a port. Their main property is the production rate. There are two supply nodes in total, one refinery node and one marine node.

- Terminal nodes: Clusters representing all the terminals around a city. The two main properties of these nodes are demand and maximum inventory capacity. There are seven terminal nodes in total, four in cities and three along the pipelines.
- Pipelines: Arcs moving inventory between nodes according to First In – First Out (FIFO) queue logic, governed by velocity and batch capacity. Pipelines flow inventory if the terminal nodes have enough available storage capacity.

It is important to note that when calculating supply and demand capacity, we consider only gasoline and diesel fuel and aggregate their capacities into a single value.

3.2 Parameter Estimation and Data Collection

For each network component, we estimated its parameters based on literature and data sources. The stock-and-flow diagram in Figure 4 shows the main nodes to model.

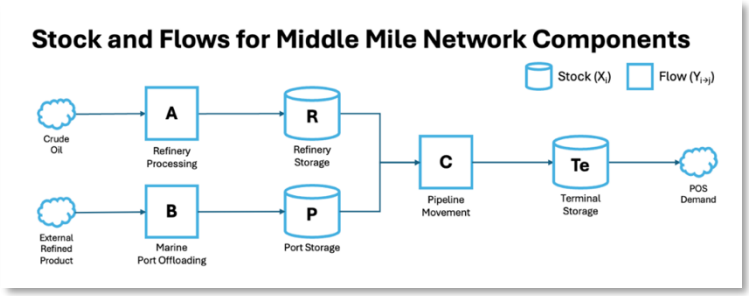


Figure 4. Stocks and Flows Relevant for Middle-Mile Network Modeling

Supply nodes (A, B, R, P)

- Refineries: Data from the Supply Chain Analysis Network (2021) and the Energy Information Administration (EIA, 2025) provide detailed information on both refining capacity and storage capacity at Southern California refineries. This information is sufficient to build an aggregated model focused on the refinery cluster's overall production capacity, using a yield factor based for gasoline and diesel.
- Ports: Data from the Port of Los Angeles and the Port of Long Beach provide historical liquid import volumes, which can be used to estimate the effective capacity of the ports to handle refined fuels (Port of Los Angeles, n.d.; U.S. Army Corps of Engineers, n.d.).

Terminal nodes (Te)

- The demand for each terminal group is estimated using the OFC method described by Rana (2024), based on the number of gates, bays, and delivery radius for each group.
- The storage capacity for each terminal group is estimated using a days-of-supply inventory heuristic based on the OFC, as analyzed by the Supply Chain Analysis Network (2021).

Pipelines (C, Ts)

- The capacity of each pipeline is calculated by summing the OFC for all terminals that use it. This essentially forces each pipeline to operate near 100% capacity, representing how markets work to avoid fees for unused pipeline allocation.

- The lead time for each pipeline segment is calculated as a fraction of the approximate straight-line distance in miles between terminal groups, multiplied by the total pipeline length. This distance is then multiplied by a standard velocity of 70 miles per day to get the segment lead time (U.S. Department of Energy, 2023)

3.3 Discrete Event Simulation Logic

To evaluate the network, the model uses a discrete-event simulation implemented with the SimPy Python library to model the movement of fuel from supply sources to terminals. The model relies on an Excel input file containing node capacities, node hierarchies, schedules for applying disruptions, and levers that affect the percentage of each node's capacity. For simplicity, preprocessing of the input file is handled outside the model's scope. However, the capability to adjust the parameters that influence each input is available separately. See the References section to access the GitHub repository containing both the input files and the simulation model (Cutler & Subercaseaux, 2026).

Using the given inputs, the model creates the supply and demand nodes, the connecting pipeline segments, and an orchestration function to coordinate the network. Specifically, this orchestration function considers the total system demand and allocates available refinery and port supplies proportionally across all terminals.

Once each network element is built, the model follows a daily execution cycle, including:

1. Demand Consumption: At the start of each simulated day, terminals deduct the day's demand from their current on-hand inventory.
2. Order Generation: Each terminal calculates the required order volume to restore its inventory position to its target level (also known as an "order-up-to" policy).
3. Supply Allocation Priority:
    a. Satisfy as much of the total order as possible using refinery capacity.
    b. If a shortfall remains, use the port's capacity to meet the remaining demand.
4. Injection: Fuel is injected into pipelines in batches, with a preset destination at a terminal, and is now considered in-transit inventory and unavailable until the modeled lead time has elapsed.
5. Receipt and Movement: Fuel is added to the terminal's on-hand inventory, and each upstream batch is moved forward according to its specific lead-time delay.

Each terminal group follows a periodic order-up-to policy. At each daily time step, the model calculates the terminal’s inventory position as on-hand inventory plus fuel already assigned to that terminal and moving through the pipeline. The terminal then requests only the volume needed to return to its target inventory level.

The model also checks downstream pipeline capacity before fuel is injected upstream. For example, fuel moving from Los Angeles to Las Vegas must first pass through the shared Los Angeles-to-Colton segment and then through the dedicated Colton-to-Las Vegas segment. The model therefore verifies that capacity will be available on the downstream segment when the batch reaches the junction. This prevents the simulation from injecting fuel into the network when it would later be blocked by the most constrained segment.

Finally, the model outputs several time-series plots, including the following: terminal inventory utilization, percentage of demand satisfied, and refinery and pipeline segment utilization rates.

To make testing scenarios comparable, throughput and utilization metrics are reported relative to the pre-disruption baseline. In this report, "100% of baseline OFC" means the steady-state flow achieved by the model under normal operating conditions before any disruption is applied. Figure 5 identifies the components and major flow and inventory decisions that determine scenario outcomes.

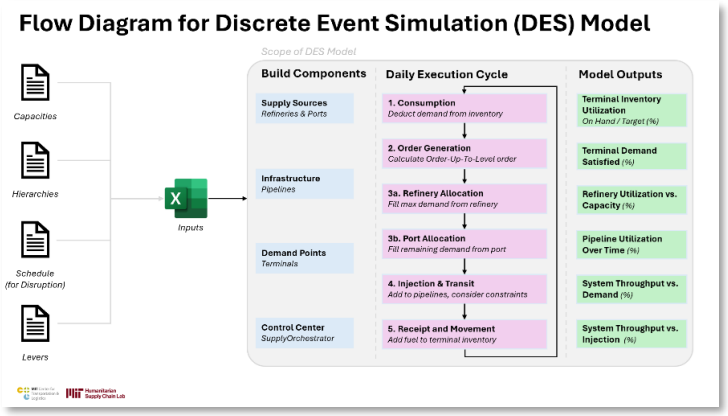


Figure 5. Visualization of Simulation Logic in the Discrete Event Simulation Model

3.4 Assumptions and Model Limitations

Recognizing the limitations of this academic research project and its discrete-event simulation approach is crucial. Fully modeling middle-mile fuel operations would require many contractual, operational, and asset-specific rules, which isn't feasible for two reasons. First, much of the data needed is proprietary and unavailable for academic use. While these characteristics can impact throughput and capacity, capturing them would need extensive research and expert collaboration. Second, modeling each operational rule at refineries, ports, and pipelines would add unnecessary complexity without improving our ability to identify high-level interventions to improve operational flow during disruptions. Since our main goal is to help emergency management organizations identify policy levers, reproducing exact network behavior is not necessary (ExxonMobil, personal communication, February 20, 2026).

While we do simplify the impact of changes to capacities, lead times, and storage using percentages, examples of constraints that we do not explicitly model include:

1. Shipper-specific allocation and trading of pipeline space
2. Berth-level operations at ports and competing berth utilization by non-fuel commodities
3. Refinery unit-level process constraints and regulation relaxation on product specification

By setting up the codebase to support additional parameters, the open-source framework enables future research to explore how refined assumptions may impact throughput.

3.5 Testing Disruption Scenarios

The simulation model is designed to handle a variety of potential disruption scenarios based on the inputs provided. While the method for calculating the magnitude and length of a disruption may vary, fundamentally, disruptions are either a percentage reduction in a node's or an arc's capacity over time. Therefore, the following disruptions were tested in Southern California.

Refinery Fire at El Segundo: In October 2025, a fire at the El Segundo refinery near Los Angeles International Airport resulted from a major explosion in the Isomax unit, producing jet fuel. Flames were visible across the Los Angeles basin. News reports indicated the fire was quickly contained, with limited damage, and operations resumed by October 7. Despite the brief outage, it provides a case for evaluating how refinery disruptions affect regional supply capacity.

Northridge Earthquake (San Andreas Fault Earthquake): In 1994, a magnitude 6.7 earthquake struck beneath the San Fernando Valley, 19 miles northwest of Los Angeles. It lasted 8 seconds and was among the largest in the area. The quake caused widespread power outages, impacting refinery operations (U.S. Geological Survey [USGS], n.d.). Reports documented a crude oil pipeline rupture, leading to shutdowns. Although this model doesn't include crude pipelines, a refined product pipeline would likely fail similarly. Terminal storage tanks were also damaged, with elephant-foot buckling, anchor failure, and roof-to-shell separation, affecting fuel receipt (Haroun & Bhatia, 1995).

Improvements have been made to the aging infrastructure since the 1994 earthquake. The Southern California disruption scenario is based on the USGS's ShakeOut model, simulating a M7.8 earthquake along the San Andreas Fault (2015). We used USGS seismic maps to estimate recent petroleum infrastructure damage.

Phillips 66 Closure: Stress Test Results: Beyond modeling capacity reductions based on historical events, this section evaluates the network's resilience by simulating a severe three-week supply disruption. We apply this to both a baseline and a post-closure setup, simulating the planned Phillips 66 Wilmington closure (Phillips 66, 2024), to compare recovery profiles. Finally, we analyze how oil-blending policy can help counterbalance the disruption post-closure environment.

Applying the described methodology to these three disruption scenarios mentioned above allows us to assess the resilience of the South California middle-mile fuel network under disruption. The next section presents our findings, focusing on structural bottlenecks and the impacts of disruptions on operational flow capacity and system performance.

4.0 RESULTS AND DISCUSSION

This section begins by describing the scale of the network based on our data collection and introducing the key middle-mile metric, Operational Flow Capacity (OFC). It then simulates the two disruption scenarios outlined in Section 3.5. Finally, we perform a network stress test and evaluate a third scenario to determine if specific policy interventions can reduce the severity of disruptions.

4.1 Operational Flow Capacity Model in the Middle Mile

To describe the capacity of the middle-mile fuel network, this study defines Operational Flow Capacity (OFC) as the maximum volume of fuel that can be moved through the aggregated network over a given time period. The OFC of the middle-mile network is simply the lesser of two quantities: how much fuel is available to enter the system, and how much the system's physical infrastructure can actually move, as captured in the equation below.

$$OFC_{Middle\ Mile} = Min(\Phi_{supply}, \Phi_{flow})$$

Here, Φ_{supply} denotes the amount of fuel that can be injected into the network over the relevant time horizon, including refinery production and marine inflows. Φ_{flow} denotes the amount of fuel that can physically move through network nodes and arcs over that same period, subject to constraints such as pipeline throughput, lead times, and terminal receipt limits. This formula is intended to capture

the operational logic of the middle mile, where total throughput is subject to the most limiting interface between supply availability and transportation capacity.

4.2 Size of the Network

Using data from 2021 to 2025 by EIA and the Los Angeles and Long Beach ports, we estimate the flow capacity at source and demand nodes in Table 1. The network is nearly balanced, with the terminal side able to boost OFC through minor gate, bay, and driver adjustments, per Rana et al. (2024).

Source Node	**Operational Flow Capacity *(bbl/day)***		**Demand Node**	**Operational Flow Capacity *(bbl/day)***
Refinery | Carson	292,000		Terminals | Los Angeles	279,330
Refinery | El Segundo	228,000		Terminals | Colton	99,321
Refinery | Torrance	128,000		Terminals | Phoenix	88,685
Refinery | Wilmington (Phillips 66)	110,690		Terminals | Las Vegas	73,997
Refinery | Wilmington (Marathon)	68,000		Terminals | San Diego	65,636
Refinery | Wilmington (Valero)	3,150		Terminals | Bakersfield	62,674
Port | Los Angeles	28,236		Terminals | Imperial	34,200
Port | Long Beach	9,721		Terminals | Barstow	17,151
Total	**868,067**		**Total**	**720,994**

Table 1. Estimation results for Operational Flow Capacity of Southern California Middle Mile Source and Demand Nodes (EIA, Port of Los Angeles, Port of Long Beach)

We do not assign specific capacity values to pipelines, as they are modeled based on the total demand across connected terminals. With supply and demand nearly balanced, pipelines are assumed to operate at full capacity, and their throughput can be approximated by the network's overall flow capacity.

4.3 Scenario 1: A Fire at El Segundo

To model this disruption, we applied a shutdown in the El Segundo refinery's capacity for four days, followed by a gradual recovery over one week to restore full operating capacity. Note that the model considers only gasoline and diesel distribution; jet fuel, despite being the most affected product during the incident, is excluded from the analysis.

In Figure 6, the model illustrates the decline in refining capacity and the corresponding activation of the port as a buffer, reaching 100% utilization.

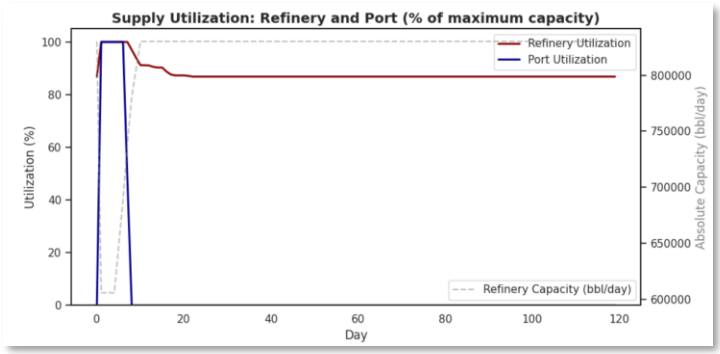


Figure 6. Supply Utilization During a Refinery Fire

Figure 7 shows the delayed effect of the disruption on pipeline utilization, producing a brief tailwhip response as the system works to restore terminal inventory to pre-disruption levels.

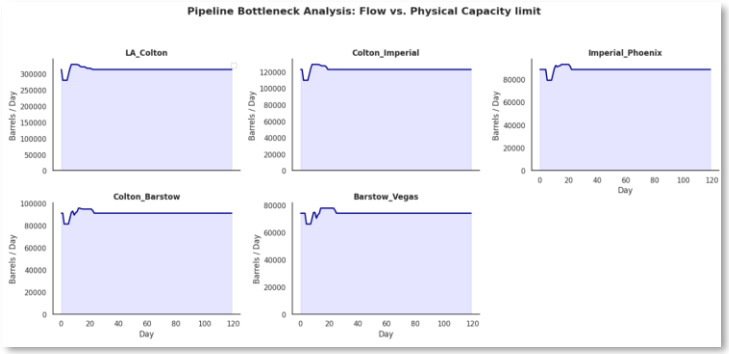


Figure 7. Pipeline Capacity Usage During a Refinery Fire

These results show that the brief, contained disruption did not cause lasting effects on the gasoline and diesel networks, and demand was fully satisfied. This scenario suggests that the Southern California middle-mile network is resilient to a short, localized disruption to its supply, with the ability to absorb the shock through on-hand inventory and increased port utilization. This absorption relies on two key dynamics. First, pipelines, already operating at near-full capacity, must consume the remaining slack to buy time for the primary refinery system to recover. Second, the port must be available to buffer the lost production created by the downed refinery.

4.4 Scenario 2: San Andreas Fault Earthquake

The scenario described by Wilson et al. (2015) presents a cascading failure that includes a three-day regional power outage, the shutdown of all Los Angeles refineries for at least 14 days, and prolonged disruptions to the major transmission pipelines serving Las Vegas and Phoenix.

Because the network spans a large portion of Southern California, it is useful to analyze the Los Angeles area separately from the more distant regions such as Las Vegas and Phoenix. Figure 8 shows the percentage of normal demand each group can meet.

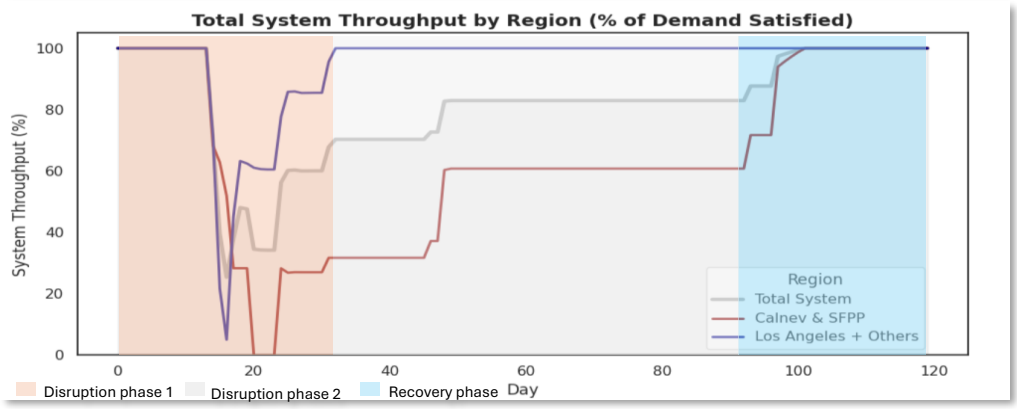


Figure 8. System Throughput for In-State California and Out-of-State Terminals

We observe that the system begins to underperform several days after the disruption, rather than immediately, because the inventory already positioned at the terminals initially buffers the shock. The Los Angeles area holds a smaller inventory position than the more distant regions do. However, its proximity to refineries yields a shorter lead time, allowing for a faster operational response. As a result, Los Angeles exhibits a more responsive recovery profile following the disruption.

By contrast, the CALNEV (California-to-Nevada pipeline) and SFPP (Santa Fe Pacific Pipeline) systems, which serve Las Vegas and Phoenix, are significantly affected by pipeline outages. Service levels return to normal only after nearly three months, with the final pipeline segment resuming standard operations on Day 88.

From a supply-side perspective, the port is activated as a mitigation measure, meaning that supply now also flows through the port, rather than relying solely on refinery capacity. However, as shown in Figure 9, its utilization does not reach 100% because several earthquake-damaged pipelines remain under repair, limiting the system's ability to transport additional volume.

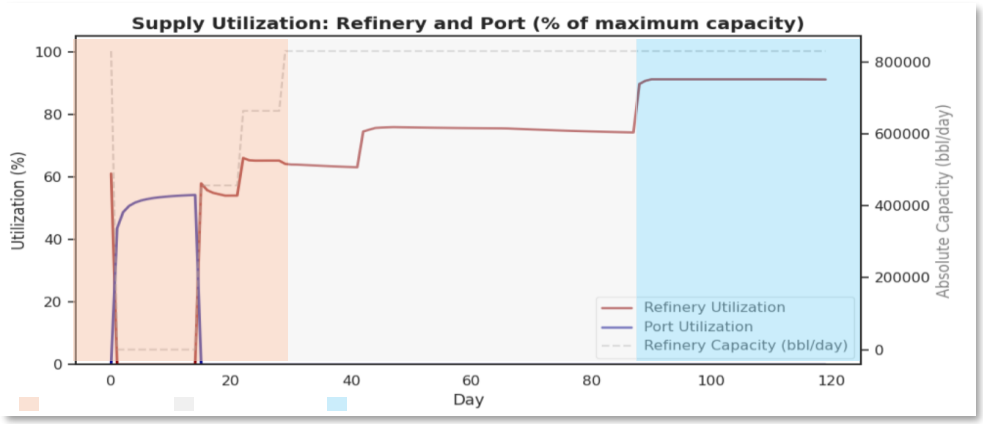


Figure 9. Utilization of Supply Nodes During Earthquake Disruption

Terminal-level results show the difference between last-mile demand served by the terminal and replenishment flow. During the first days of the disruption, terminals can continue to satisfy demand by drawing down on-hand inventory, even though replenishment from upstream assets is

constrained. Once inventories are depleted and the affected pipeline segments remain unavailable, demand satisfaction falls sharply. Recovery is then limited by the rate at which pipelines can refill terminal inventories after service resumes.

Additionally, we observe a slow recovery in terminal inventories, as shown in Figure 10. This is driven by the fact that pipelines typically operate near full capacity under normal conditions, leaving limited room to accelerate flows after a disruption, and therefore resulting in a gradual, prolonged recovery. This dynamic presents a risk that the model currently does not account for: customers' perceptions of fuel scarcity. Such perceptions can trigger demand surges at retail sites, causing recurring inventory shortages and prolonging the overall fuel supply crisis.

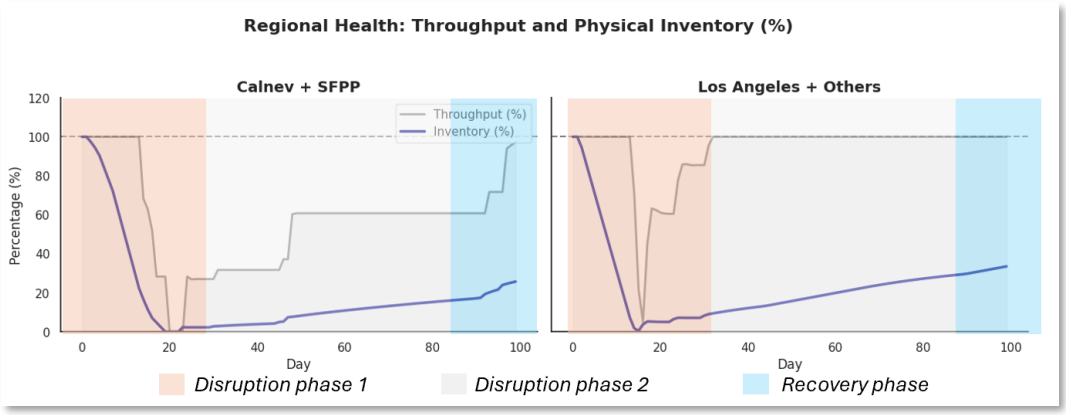


Figure 10. Terminal Throughput and Inventory Availability

This scenario reveals that the middle-mile network is not resilient to a large, multi-asset disruption. The bottleneck is no longer supply availability; instead, it is the transportation infrastructure required to move that supply inland, which is why port utilization never reaches 100%. As transportation becomes the bottleneck, proximity to the source plays a significant role in Los Angeles and San Diego, as their shorter lead times allow them to recover significantly faster than Phoenix and Las Vegas. The transportation issue gets worse when considering inventory recovery, which relies on pipelines already heavily utilized under normal conditions, leaving little capacity to quickly refill terminals after service resumes.

4.5 Phillips 66 Wilmington Refinery Closure: Stress Test Results

To model an extreme stress test, we simulated a disruption scenario that combines the imminent decommissioning of the Phillips 66 Wilmington refinery (which removes approximately 110,960 bbl/day from regional capacity) with a 20-day recovery period. Resilience is assessed using a regulatory waiver that permits the immediate distribution of sub-octane fuel by increased ethanol blending to E15, boosting fuel supply by up to 15% (Oil industry expert, personal communication, February 20, 2026).

The baseline analysis in Figure 11 indicates that over a 14-day total supply outage, the system satisfies 75% of the cumulative demand in the first month of recovery. This shortfall implies that, once terminal inventories are exhausted, major metropolitan areas could face periods in which no fuel is available to meet demand until inbound supply resumes. Additionally, the permanent

shutdown of the Phillips 66 refinery acts as a stress multiplier for the region. Removing this refinery causes a 6% decrease in cumulative throughput, dropping it to 69%.

By applying regulatory flexibility, specifically E15 blending and sub-octane distribution, the system is capable of partially offsetting the throughput drop during the recovery phase. In the simulated "Phillips66 Closure + Lever" scenario, cumulative throughput reaches almost 80%, effectively neutralizing the structural loss caused by the Phillips 66 closure and even outperforming the baseline of 75% of demand satisfied.

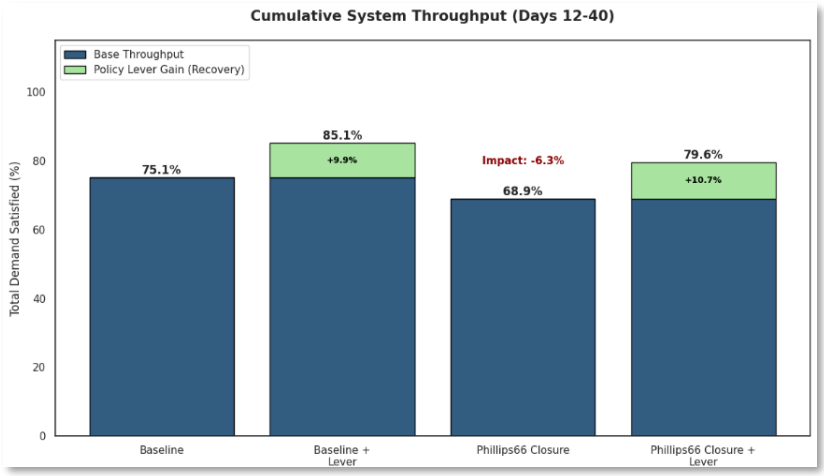


Figure 11. System Cumulative Throughput for Different Configurations on a Two-Week Supply Outage

The results demonstrate that regulatory intervention is an immediate tool for crisis management; however, it only addresses a small part of the overall demand. Although policy measures boost supply, the system still falls about 20 points short of fully meeting demand. This gap shows that while policy can temporarily increase supply, it cannot compensate for the total production lost during the 14-day outage.

5.0 RECOMMENDATIONS

Southern California's fuel network seems resilient to small disruptions, but only because it uses nearly all its spare capacity to maintain that resilience. Our scenarios reveal three structural vulnerabilities: slow activation of emergency supply levers, insufficient terminal inventory buffers, and inadequate pipeline redundancy, each of which calls for a distinct policy response.

Pre-Authorize Conditional Emergency Supply Waivers: Our Phillips 66 stress test demonstrates that regulatory flexibility is one of the most effective and immediate tools available during a fuel supply crisis: applying fuel-blending and distribution waivers during the recovery phase increased cumulative throughput from 69% to nearly 80%, and waivers eliminate the typical 3- to 5-day delay in the high-heat ramp-up period following a refinery restart. Rather than activating these measures reactively, policymakers should pre-authorize a bundled emergency waiver package that triggers automatically when defined conditions are met, such as regional refining capacity falling below a set threshold for a specified number of days.

The package may contain EPA Reid Vapor Pressure (RVP) waivers that facilitate the entry of higher-volatility winter-blend and non-reformulated gasoline into summer markets. It may also include

Reformulated Gasoline (RFG) waivers, which temporarily allow the sale of conventional gasoline in cities that usually require reformulated blends. Furthermore, conditional Jones Act waivers (generally mandating that goods transported between U.S. ports be carried on U.S.-flag vessels) may be issued to speed the movement of domestic supplies from outside the region by permitting foreign vessels to operate on these routes. An IRS dyed-diesel waiver allows red dyed diesel, typically used for tax-exempt off-road purposes, to be used in on-road vehicles during declared emergencies. Participants should receive liability protections and streamlined approval, which accelerate the process, especially during emergencies. Regulators should ensure these waivers are issued only temporarily and strictly in disaster situations to prevent long-term effects on the original regulation intent.

Establish Minimum Safety Stock Requirements at Distribution Terminals: Since pipelines in Southern California operate near full capacity under normal conditions, terminals have limited ability to quickly replenish inventory once stocks run out. The earthquake scenario clearly shows that terminals begin to run low within days of disruption, and the long pipeline lead times prolong shortages. In 2024, the California Energy Commission (CEC) passed policy ABX2-1, which gives the commission the authority to mandate minimum inventory levels at in-state refineries and to impose up to $1 million in daily fines for non-compliance. The CEC's Vice Chair is quoted as saying that 15 days of inventory is the critical threshold (California Senate Appropriations Committee, 2024). Extending this policy to include minimum safety stock levels at distribution terminals would create a crucial buffer during the early stages of any disruption, providing time for emergency responses to take effect. This is a short-term regulatory step that requires no new infrastructure and could be coordinated through FEMA or the CEC.

Provide Financial Incentives for Pipeline Capacity Expansion: When pipelines become inoperable, geographically distant cities are disproportionately affected. For example, our earthquake scenario indicates that Las Vegas and Phoenix, which are located hundreds of miles from the Los Angeles-area refineries that serve them, took nearly 88 days to return to normal service levels, while Los Angeles recovered much faster due to its proximity to refineries. Since pipelines operate near capacity, there is little room to accelerate inventory recovery, even if refineries increase production beyond normal levels. Interest in this area is already evident, with Kinder Morgan announcing the Western Gateway Pipeline in October 2025, which will transport product from Texas to California and connect to Las Vegas via the CALNEV pipeline (Kinder Morgan, 2026). Policymakers should expand such investments by providing financial guarantees and tax incentives, such as accelerated depreciation schedules for qualifying pipeline infrastructure. Notably, the Department of Energy already supports the Energy Infrastructure Reinvestment subprogram, which issues conditional loans to qualifying infrastructure projects, with over $250 billion under its purview (U.S. Department of Energy, Loan Programs Office, n.d.). Besides potential cost savings during a crisis, the public benefit case for these incentives is strong.

This project demonstrates that discrete-event simulation can be applied to middle-mile fuel distribution networks, filling a gap left by existing emergency response models, which primarily focus on last-mile distribution. The Southern California case study produces a framework that FEMA, SCAN, and state energy agencies can adapt for other at-risk regions with minimal reconfiguration. For policymakers, the recommendations offer concrete, simulation-backed interventions that can be implemented without new legislative authority in most cases. For the public, these recommendations mean shorter outages, more stable prices, and a fuel network ready for the disruptions Southern California will inevitably face. The question is not *if*, but *when*.

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