Assessing Freight Network Performance and Resilience in Relation to Terminal Wholesale Produce Markets

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14. ABSTRACT
This white paper presents findings from a multi-year effort sponsored by the U.S. Department of Agriculture (USDA) to investigate the relationship between regional wholesale terminal produce markets and the transportation networks that serve them. It draws upon modeled freight flows to and from the Los Angeles Produce Market to demonstrate an analysis of how various hazard occurrences might affect fresh produce freight patterns to estimate regional network resiliency.

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Introduction

This white paper presents findings from a multi-year effort sponsored by the U.S. Department of Agriculture (USDA) to investigate the relationship between regional wholesale terminal produce markets ("terminal markets") and the transportation networks that serve them. Wholesale produce markets remain a vital component of regional food systems, functioning as aggregation points where products from growers are distributed to retailers, institutions, and other buyers. Despite their importance, these facilities are seldom examined in the context of regional transportation planning, even though they can produce and attract significant volumes of perishable and time-sensitive freight.

To place this work in context, it is important to note that terminal markets themselves have changed considerably over the past several decades. A parallel research effort by Cornell University provided a broad descriptive assessment of how terminal markets operate as businesses in the 21st century, filling a gap in scholarship that had not been revisited in nearly 50 years.[1] Their study identified pressing infrastructure and operational concerns within markets' gates, such as dock space, building maintenance, and utility upgrades. By contrast, this study was designed to assess the extent to which these markets perceive regional transportation networks – the highways, arterials, and intermodal connections that link them to farms and customers – as critical to their operations.

The central finding of this study is that regional transportation access does not rank as a priority for most terminal market managers, who are primarily tasked with filling leases, maintaining facilities, and ensuring day-to-day viability of the market as business entities. Responsibility for freight transportation beyond the facility's gates typically rests with decisionmakers several steps removed: tenants contract with freight brokers, who in turn arrange trucking services to reach customers. As a result, terminal market managers rarely see themselves as stakeholders in regional transportation planning processes, even when nearby infrastructure changes could directly affect market access.

This disconnect creates an opportunity. Regional and local transportation agencies make long-term infrastructure decisions that can affect access to food distribution hubs, while terminal market operators and their tenants have insights into supply chain vulnerabilities that are not commonly communicated to the public sector. Strengthening these connections could allow terminal markets to highlight the unique needs of perishable supply chains, such as the importance of reliable highway access or the consequences of disruptions to refrigerated freight and help planners to better understand how public projects influence regional food distribution.

[1] Park, Kristen; Abigail B. Long; Miguel I. Gómez, (2024). Whole Produce Markets: An On-Site Infrastructure Assessment. Cornell University extension bulletin. https://dyson.cornell.edu/wp-content/uploads/sites/5/2025/05/Wholesale_Produce_Markets_Infrastructure_FINAL__VD_.pdf

Project Insights to Consider

For Terminal Markets:

- Even if transportation is delegated to tenants and brokers, facility performance and competitiveness are directly shaped by regional access conditions.
- Delays or detours have disproportionate impacts on refrigerated and perishable products, increasing costs and food loss.
- Many of the most important transportation issues like interchange redesigns, signal timing, or congestion on key corridors, are not easily observed from within the market gates, but still affect operations.

For Transportation Planning Agencies:

- Wholesale terminal produce markets are rarely acknowledged in transportation plans, yet they handle substantial volumes of time-sensitive freight.
- Market supply often depends on a small number of regional corridors, creating potential single points of failure – particularly risky in hazard-prone regions.
- Analysis shows that strengthening specific routes or bridges can deliver outsized benefits to perishable supply chains. Agencies should consider replicating similar analyses during their regional programming and prioritization processes.
- Market operators may not have the bandwidth to proactively participate in planning processes, but their insights (often transmitted through tenants or brokers), can help agencies design projects that support both economic and community goals.

Why Transportation Matters

Terminal markets function as aggregation hubs that link farms, import points, and regional buyers. The continuity and cost of these flows are strongly influenced by regional infrastructure reliability, congestion, and accessibility. Although day-to-day market operations are not centered on transportation planning, the broader supply chain context makes transportation analysis essential for understanding market viability and resilience.

Recent research by Cornell University and the USDA illustrates how regional transportation conditions directly shape the economics of terminal markets.[2] Using a computational model applied to Boston and Detroit, the study found that markets tend to operate most efficiently at two 'sweet spots' in size – roughly the equivalent of handling 3,000 or 5,740 truckloads of produce per month. At those levels, costs per pound of produce are lowest because facilities can take advantage of scale without having to

[2] Xu, Jiaming, H. Ge, Miguel I. Gomez, K. Park, and A. Long (2025), Modeling Strategies to Improve the Terminal Market Operational Efficiency. Selected paper prepared for presentation at the 2025 AAEA & WAEA Joint Annual Meeting. Denver, Colorado, July 27-29, 2025.

source products from excessively distant regions. When markets try to grow larger than those thresholds, efficiency gains disappear since produce must be trucked from farther away. The longer hauls add cost and increase the risk of spoilage, outweighing the benefits of scale.

The comparison of Boston and Detroit highlights one way that differences in regional networks affect market performance. At the same operating size, Boston's costs were 19-22 percent higher than Detroit's. This gap was linked to heavy congestion on Northeast highways and fragmented structures of nearby farms, which makes it harder and more expensive to assemble product flows. The finding demonstrates that two facilities performing the same function can experience very different outcomes depending on the condition and reliability of the transportation networks around them.

The type of freight moving through terminal markets intensifies this vulnerability. Unlike dry goods, produce is perishable and often refrigerated, making it far more sensitive to disruption. Even modest delays caused by congestion detours or infrastructure outages can result in lost produce and significant cost escalation. For instance, a substantial share of Los Angeles terminal market's inbound volumes originate in Southern California, Arizona, and Texas counties, much of which is likely Mexican imports. This concentration means that regional disruptions affecting a small number of corridors or gateways could have a disproportionate impact on the availability and price of produce across entire markets.

These findings illustrate that regional transportation analysis offers value and has direct impact on the concerns of terminal market managers, even if the responsibility to conduct those analyses may not lie with the market itself. Quantifying how congestion, access constraints, and sourcing distances shape the efficiency of market produce flows can reveal supply chain vulnerabilities and inform planning decisions. The sensitivity of perishable and refrigerated commodities and the unique perspective of terminal markets underscore the need for public agencies to look beyond aggregated freight volumes and account for unique characteristics of food distribution.

Market Perspectives

As part of this study, the project team conducted interviews and site visits with a range of terminal markets across the United States. These facilities varied in size and organizational structure, but their operators expressed strikingly consistent views: regional transportation networks were not part of their core responsibilities. One manager summarized this perspective candidly:

> *"If I can see it from my building, I might worry about it. Otherwise, that's not my job."*
>
> \- Market manager of a large terminal market

This sentiment reflects both the organization structure of these markets and the limited capacity of their staff. In many cases, a market employs just one or two full-time employees with duties encompassing marketing, leasing, finances, operations and maintenance, and tenant relations. With such lean staffing, attention is focused almost entirely on keeping facilities functional and financially viable, rather than on monitoring broader freight transportation systems.

Transportation typically only rises to the level of concern under two circumstances. First, when developments such as roadway construction, right-of-way changes, or signal timing adjustments directly affect access at the market's gates. Second, when market activities spill onto surrounding public roads, such as trucks queuing for entry to the terminal market site or maneuvering into nearby docks, which can create conflicts with other roadway users. Beyond these visible, site-specific issues, market managers rarely engage with questions of regional mobility or infrastructure planning.

This perspective is also reinforced by the way transportation responsibilities are distributed. Market managers lease space to tenants; tenants arrange their own supply chain operations; freight brokers hired by tenants secure carriers and manage routing. As a result, the question of "how produce gets in and out of the market" is often several steps removed from the market manager's responsibilities. This delegation chain effectively insulates managers from regional transportation concerns, even though the market's success ultimately depends on the reliability of those same networks.

Findings from Cornell's *On-Site Infrastructure Assessment* lends further support. Respondents highlighted issues such as dock capacity, backing space, and on-site circulation as immediate priorities – concerns that are largely contained within the gates of the market. Far fewer respondents identified regional freight access or congestion as pressing issues. This alignment across both studies suggests that wholesale market operators view transportation primarily through the lens of site operations, not their facility's regional connectivity.

The combined effect is that terminal market managers generally do not participate in regional or state transportation planning processes. None of the managers interviewed for this project saw clear value in proactively engaging with public agencies on roadway development or freight planning.

Public Sector Perspectives

The perspective of public transportation agencies is similarly unaware of the importance of terminal markets to their planning efforts. While terminal markets remain critical nodes in the regional food distribution, they are rarely acknowledged as such in the documents and processes that guide regional and state transportation investment.

A review of a sample of metropolitan planning organization (MPO) and state freight plans suggests that wholesale markets are seldom named as key freight generators or stakeholders. Instead, most plans focus on traditional freight facilities like corridors, ports, and intermodal connectors. The omission of terminal markets and other large freight generators and attractors reflects both institutional practices and data limitations. Freight planning has historically relied on national datasets such as the Freight Analysis Framework (FAF) and the Commodity Flow Survey, which capture broad commodity flows but not site-level dependence on any particular facilities or sites. As a result, planners have limited visibility into how terminal markets affect or depend on specific access roads, signalized intersections, or local interchanges. Academic research provides additional evidence: Castillo et al.[3] note that local governments often rely on aggregate freight data while failing to involve site-specific actors in land or transportation planning. Similarly, Baker[4] finds that urban freight planning struggles to incorporate smaller but critical distribution facilities into long-range strategies.

Institutional silos are also likely to play a role. Economic development offices may recognize the contribution of wholesale markets to regional food supply, but transportation planners focus on congestion, safety, and throughput along corridors. Land use planners, meanwhile, are often more concerned with mitigating conflicts between industrial areas and nearby residential or mixed-use development. This fragmentation means that even when terminal markets are recognized as economically important facilities for a region, their transportation access needs may not be recognized or prioritized to ensure preserved freight accessibility or upgrades.

The absence of terminal markets from planning processes has practical consequences. Infrastructure decisions made without market input, such as reconfigured interchanges, modified signal timing, or added pedestrian or bicycle facilities, can inadvertently create new barriers for truck access. The study team for this project observed instances where such changes conflicted with the operational realities of freight vehicles entering and exiting wholesale market sites. These blind spots reinforce the broader finding: while terminal markets depend on regional transportation networks, they are not seen as stakeholders in shaping those networks, and planners often overlook them when making long-term infrastructure decisions.

Transportation Vulnerability and Resiliency Analyses

To further illustrate the benefits of considering the perspectives of both the terminal market and public sector together, the second part of this study demonstrates how freight planning analysis can be applied in practice using supply chain and transportation infrastructure data. While terminal market managers may not frame regional access as a priority, the resilience of surrounding networks is nonetheless one of several critical factors for maintaining efficient and affordable food flows.

The Volpe Center undertook several transportation vulnerability and resiliency analyses to demonstrate how robust network and hazard analysis tools can be used to explore transportation infrastructure needs specific to a terminal market and how those might intersect with transportation infrastructure investment decision-making. Understanding which routes and assets the regional terminal market relies on can help transportation planners make more robust transportation decisions.

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[3] Castillo, C., Marta Viu-Roig, Marc Nicolàs, Eduard J. Alvarez-Palau (2024). Tackling urban freight distribution: a public-private partnership. Research in Transportation Business & Management, Volume 53. https://www.sciencedirect.com/science/article/pii/S2210539524000075

[4] Baker, D., S. Briant, A. Hajirasouli, T. Yigitcanlar, A. Paz, A. Bhaskar, P. Corry, K. Whelan, P. Donehue (2023). Urban freight logistics and land use planning education: trends and gaps through the lends of literature. Transportation Research Interdisciplinary Perspectives, Volume 17. https://www.sciencedirect.com/science/article/pii/S2590198222001919?via%3Dihub

Terminal market managers can play a key role in communicating transportation needs to public sector agencies by serving as a conduit for information from their tenants and their tenants' logistics providers to the public agencies. They can help identify where key routes, bottlenecks, and critical infrastructure exist for their supply chains and relay this information to the public sector as part of the transportation planning process. Conversely, there is a role for public sector agencies (cities, MPO governments) to proactively identify significant freight attractors in their region and make an active effort to engage them.

Terminal markets and public sector agencies can leverage existing tools to help explore potential scenarios for disruption and resilience investment. These tools provide a shared forum for all stakeholders to identify critical assets for supply chains and project prioritization, and work through scenario planning variations to identify those that are jointly beneficial. In this study, the Volpe team used two publicly available tools to demonstrate such an analysis:

1) The Freight and Fuel Transportation Optimization Tool (FTOT)[5] – a geospatially-explicit tool that optimizes routing and flow of material over a multimodal transportation network to maximize delivery and minimize costs and other factors. FTOT is designed for regional/corridor analyses and focuses on freight and supply chain movements and therefore is well-suited to analyze regional flows to the terminal market and the associated transportation costs and disruption impacts.
2) The Resilience and Disaster Recovery Tool Suite (RDR)[6] – a geospatially-explicit tool that provides an estimate of return on investment for resilient transportation infrastructure investments under a range of hazard severities. RDR is designed to support transportation agencies' decision-making and can address all trips in a region or a subset of trips for a particular supply chain and is well-suited to analyze more local flows near the terminal markets and the associated risk and resilience of the network conditions under hazards.

Case Study: The Los Angeles Terminal Market

The Los Angeles Wholesale Produce Market has been serving the Los Angeles (LA) region for over 100 years and is located on East Olympic Avenue in downtown LA (1601 E Olympic Blvd, Los Angeles, CA 90021). It distributes a range of organic and conventional herbs, fruits, and vegetables. Agricultural produce is delivered to the market for distribution from farms and warehouses throughout the U.S. and abroad.

For this study, the Volpe Center mapped Transearch trucking freight flow data[7] of agricultural materials transported into Los Angeles County from counties across the U.S. The data, which had already been

[5] Volpe National Transportation Systems Center. (2025). Freight and Fuel Transportation Optimization Tool. https://volpeusdot.github.io/FTOT-Public/

[6] Volpe National Transportation Systems Center. (2025). Resilience and Disaster Recovery (RDR) Tool Suite. https://volpeusdot.github.io/RDR-Public/

[7] S&P Global. (2021). Transearch – Freight Transportation Research. https://www.spglobal.com/market-intelligence/en/solutions/products/transearch-freight-transportation-research

subset to truck freight flows, were mapped and routed using the Freight and Fuel Transportation Optimization Tool (FTOT) (see Figure 1).

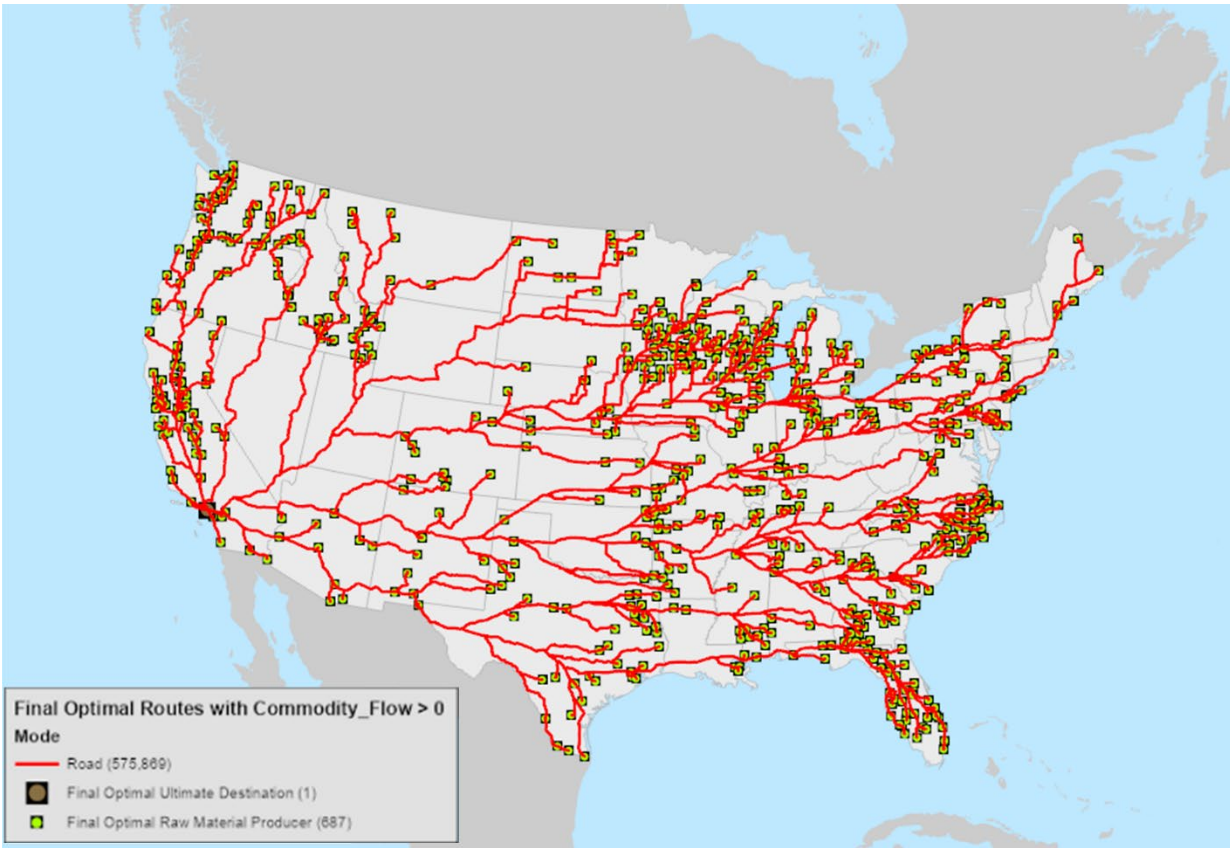

Figure 1: Baseline scenario showing optimal routing of produce to the LA terminal market from national sources. Routing executed using FTOT based on Transearch data. Source: Volpe Center analysis of S&P Global's Transearch Data using FTOT.

According to the Transearch dataset, 706 counties supply agricultural products to the Los Angeles area. For the purposes of this analysis, these flows were assumed to be destined for the Los Angeles Wholesale Produce Market. Collectively, these origins deliver over five million tons of agricultural goods annually. The largest county contributors by tonnage are primarily located within California, as shown in Table 1. In the FTOT routing analysis, 687 of the 706 counties were successfully modeled in the final optimal routing solution. Nineteen county origins did not route due to unresolved model constraints; while their exclusion has minimal effect on the overall results, it may slightly alter certain detailed values and graphics.

Full details of the FTOT data preparation and methodology are included in the Appendix.

Table 1: Top 10 Transearch Origin Counties for Tonnage Delivered to LA County

Rank	County	Annual Tonnage
1	Fresno County, CA	766,177
2	San Diego County, CA	560,952
3	Ventura County, CA	539,344
4	Kern County, CA	470,357
5	Monterey County, CA	389,354
6	Imperial County, CA	285,808
7	Santa Cruz County, AZ	211,656
8	Hidalgo County, TX	199,773
9	Tulare County, CA	125,662
10	Riverside County, CA	125,195

Analysis: Los Angeles Terminal Market Supply Chain Vulnerability

The Los Angeles region is subject to a range of potential natural hazards, including earthquakes, wildfires, and land slips. The effects of these hazards are likely to impact produce transportation patterns for the LA Wholesale Produce Market.

From the baseline FTOT analysis with Transearch data, the Volpe Center team identified eight roadways within 90 miles of LA that optimally carry all of the produce into the city, including I-5, State Route 99, CA-1/Pacific Coast Highway, I-15, I-40, I-10, US-101, and Freeway 14 with only five optimal roadways within 25 miles of the Wholesale Produce Market: I-5, I-10, US-101, and CA-1/Pacific Coast Highway (Figure 2). Starting with that baseline, Volpe analyzed two hazard types and three scenarios for their potential to disrupt regional entry of produce into LA: a historical fire, a hypothetical fire expansion, and a historical earthquake scenario.

Los Angeles Terminal Market Disruption – January 2025 Canyon Fires

In early 2025, the Los Angeles region experienced a series of highly destructive wildfires. The three largest wildfires during this period – Palisades, Eaton, and Hughes – burned a collective 47,894 acres, destroyed 16,188 structures, and resulted in widespread disruption including the closure of major highways.[8] [9] [10] The locations of these three fires are displayed in Figure 3.

[8] State of California. (2025). 2025 Fire Season Incident Archive. https://www.fire.ca.gov/incidents/2025
[9] LA County. (2025, January 23). Media Update: Eaton and Palisades Fires 1/23/25. https://recovery.lacounty.gov/2025/01/23/media-update-eaton-and-palisades-fires-1-23-25/
[10] Los Angeles Times. (2025, January 22). What happened on Wednesday, Jan. 22 as the Hughes fire broke out north of Castaic. https://www.latimes.com/california/live/la-southern-california-fire-weather-rain-wind

Figure 2: Baseline FTOT routing of produce into the LA terminal market showing that produce is routed on only eight major roadways within 90 miles and five within 25 miles. Source: Esri, FTOT, OpenStreetMap.

Los Angeles Terminal Market: Baseline vs. 2025 Wildfire Scenario

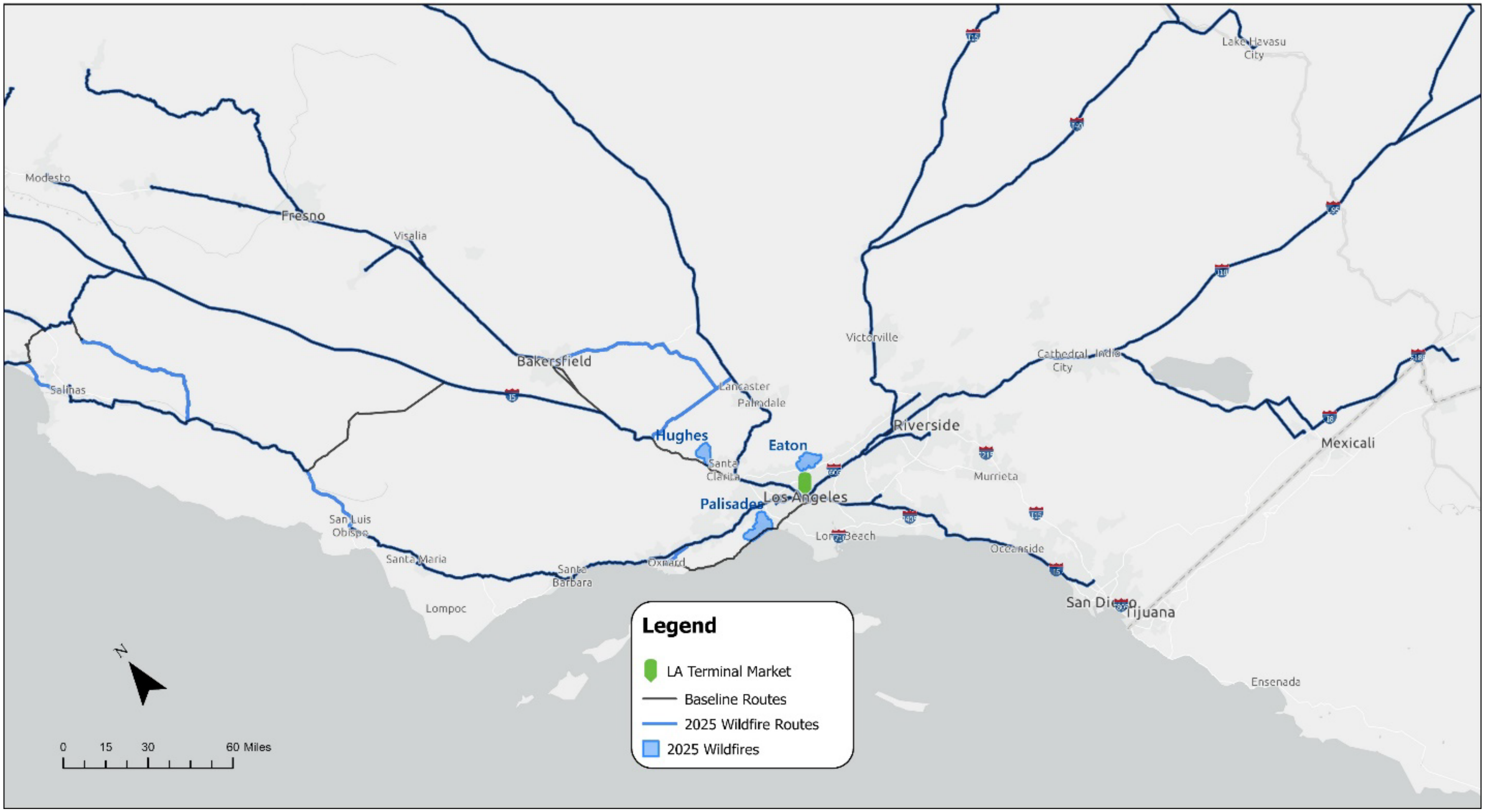

Figure 3: Baseline optimal routing vs. 2025 Wildfire Scenario showing the adjusted FTOT routing due to the fires in light blue. Source: California Department of Forestry & Fire Protection, Esri, FTOT, OpenStreetMap.

Using FTOT, the Volpe Center team analyzed how these real-world fires would have impacted optimal freight flows into the Los Angeles Wholesale Produce Market. Impacted roads include I-5, I-210, and the CA-1/Pacific Coast Highway. These disruptions were passed into FTOT as road closures, which permitted the team to quantify their impact on freight travelling to the Los Angeles Wholesale Produce Market. Further details on the data and methods of this disruption overlay analysis are available in the Appendix.

Figure 3 overlays optimal freight routing into the market with and without the historic wildfire disruptions, demonstrating how the fires would have forced freight vehicles to deviate from the most efficient routing into the market. All of the incoming produce on disrupted routes was able to be rerouted, resulting in a 4.3 percent increase in total transportation cost (see Table 2) from origins to the terminal market and indicating that even very localized rerouting around the market could have a significant impact on LA Wholesale Produce Market produce transportation costs. Perishability could add to these costs due to the potential for increased spoilage in transit, as total travel time also increased by 6.4 percent (see Table 2).

Table 2: FTOT Wildfire Scenarios Summary

	Optimal Baseline	January 2025 Canyon Fires	Hypothetical Expanded Fire Scenario
Demand Fulfilled (tons)	5,087,277.18	5,087,277.18	4,526,325.41
Truck Loads	195,664.51	195,664.51	174,089.44
Transport Cost (USD)	$383,767,173.39	$400,141,802.76	$408,137,872.10
Vehicle Miles Travelled (VMT)	77,478,186.08	80,784,035.74	82,398,350.34
Travel Time (hrs)	1,293,399.87	1,375,199.91	1,406,565.93

Source: FTOT.

While the local fires had significant impact on specific origin-destination pairs, all rerouting of freight to the terminal market due to the fires increased the individual routes by less than 50 miles, and over 85 percent of routes experienced no shift in routing (Figure 4). The most disrupted corridor in terms of aggregate travel time increase in the 2025 fire scenario is the Fresno County to Los Angeles route for agricultural commodities, as shown in Figure 5. This route represents the largest origin-destination flow in the model, handling over 766,177 tons annually under the optimal baseline. Fire-induced disruptions force trucks to reroute east of I-5, adding approximately 57 minutes of additional travel time per driver for the duration of the disruption and rerouting.

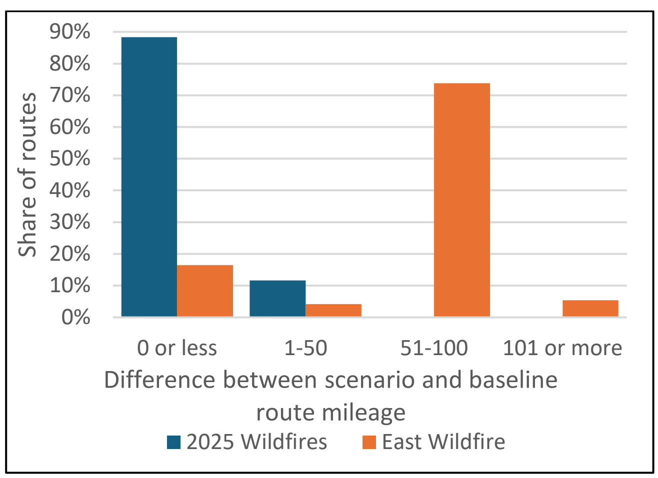

Figure 4: Mileage associated with rerouting needed for the 2025 Wildfire and East Wildfire scenarios. Source: FTOT.

Los Angeles Terminal Market: Most Disrupted Route with 2025 Wildfires

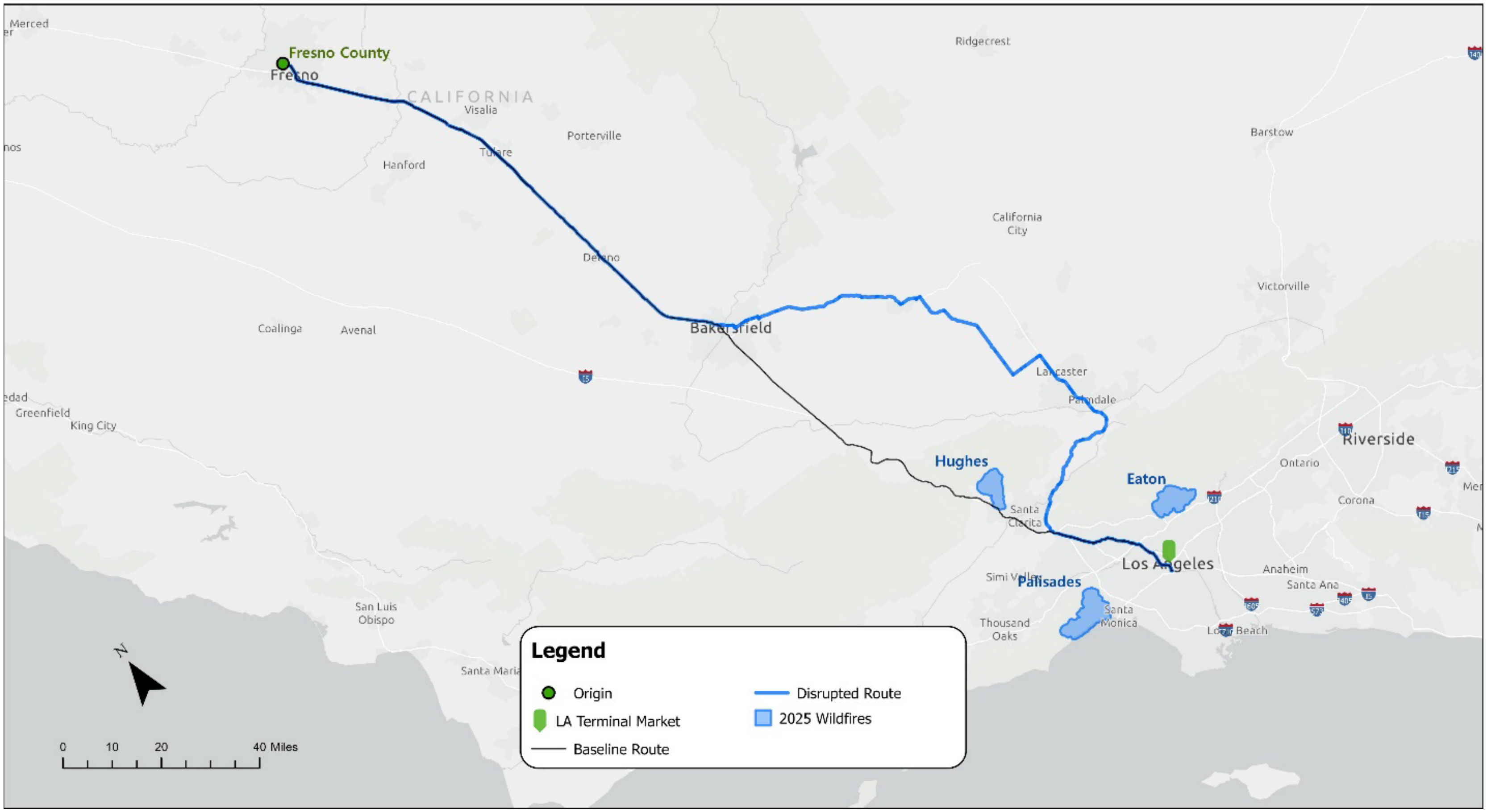

Figure 5: Most disrupted route relative to baseline resulting from the 2025 wildfires scenario. Source: California Department of Forestry & Fire Protection, Esri, FTOT, OpenStreetMap.

Los Angeles Terminal Market Disruption – Hypothetical Expanded Fire Scenario

Fortunately, the 2025 wildfires were contained, preventing further disruption to the freight transportation system's ability to deliver agricultural commodities to the market and its consumers. However, this might not always be the case. To extend the analysis to consider the impacts of a more severe wildfire, the Volpe Center team considered a scenario in which significant fires occur on the eastern side of LA County and explored how a much greater area of fire impact would affect freight transportation to the Los Angeles terminal market and how mitigation of such hazards would improve performance.

To gauge this worst-case scenario, the team used Fire Hazard Severity Zone (FHSZ) data[11] from the California Department of Forestry and Fire Protection and clipped the FHSZ raster along a natural break produced by the San Gabriel River and Little Rock Creek systems, as shown in Figure 6.

Any areas located within a FHSZ east of the highlighted break were considered at risk, meaning roads in these areas were closed in the scenario. Figure 7 highlights the extent of this potential disruption and the associated rerouting of produce headed to the LA Terminal Market.

[11] California Department of Forestry & Fire Protection. (2025). Fire Hazard Severity Zones. https://osfm.fire.ca.gov/what-we-do/community-wildfire-preparedness-and-mitigation/fire-hazard-severity-zones

Los Angeles Terminal Market: Fire Severity Break

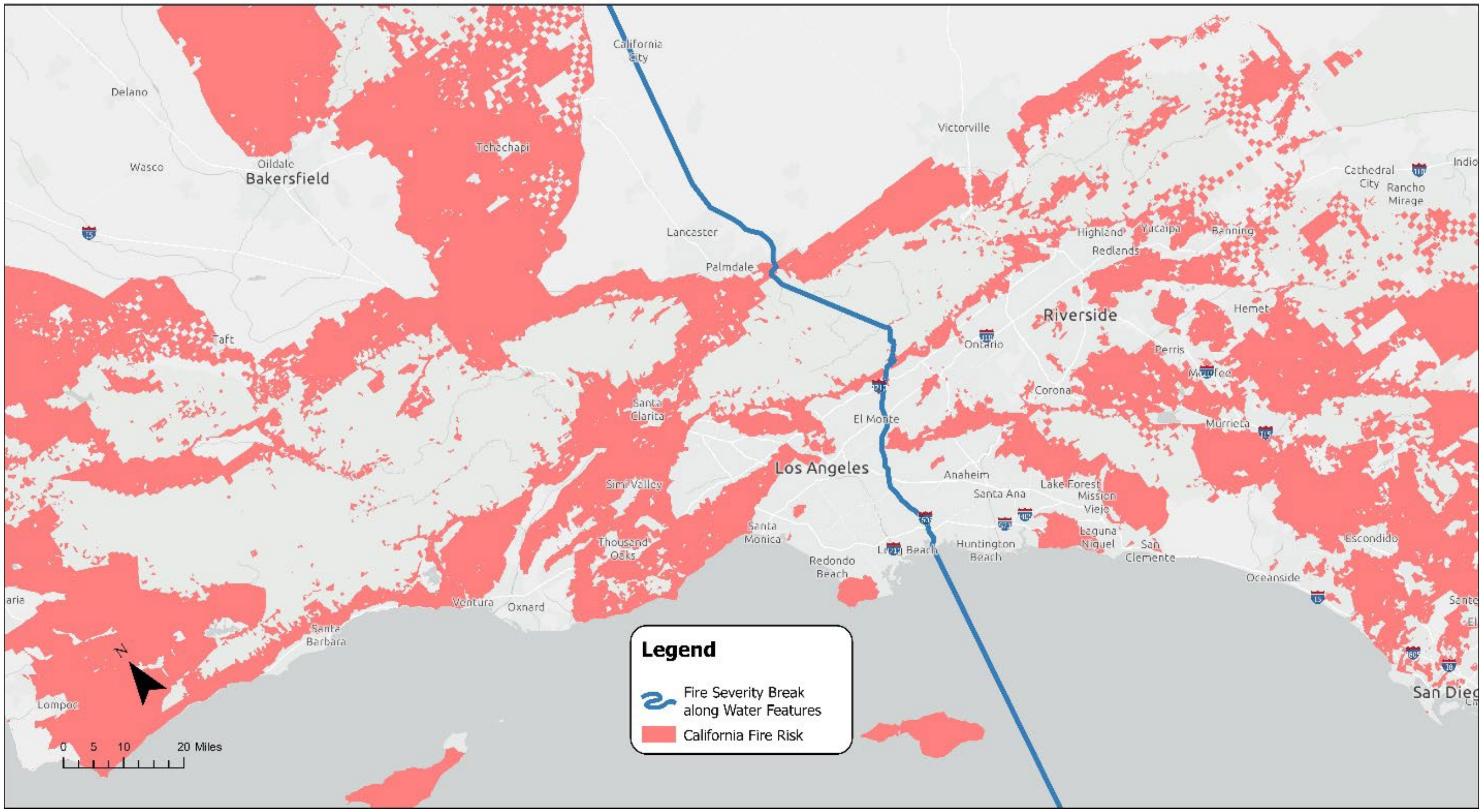

Figure 6: Map showing Fire Hazard Severity Zone data for the Los Angeles region, with a blue vertical line indicating the break in fire severity along the San Gabriel River and Little Rock Creek systems used to delineate the hypothetical East Fire in the FTOT scenarios for this study. Source: California Department of Forestry & Fire Protection, Esri, OpenStreetMap.

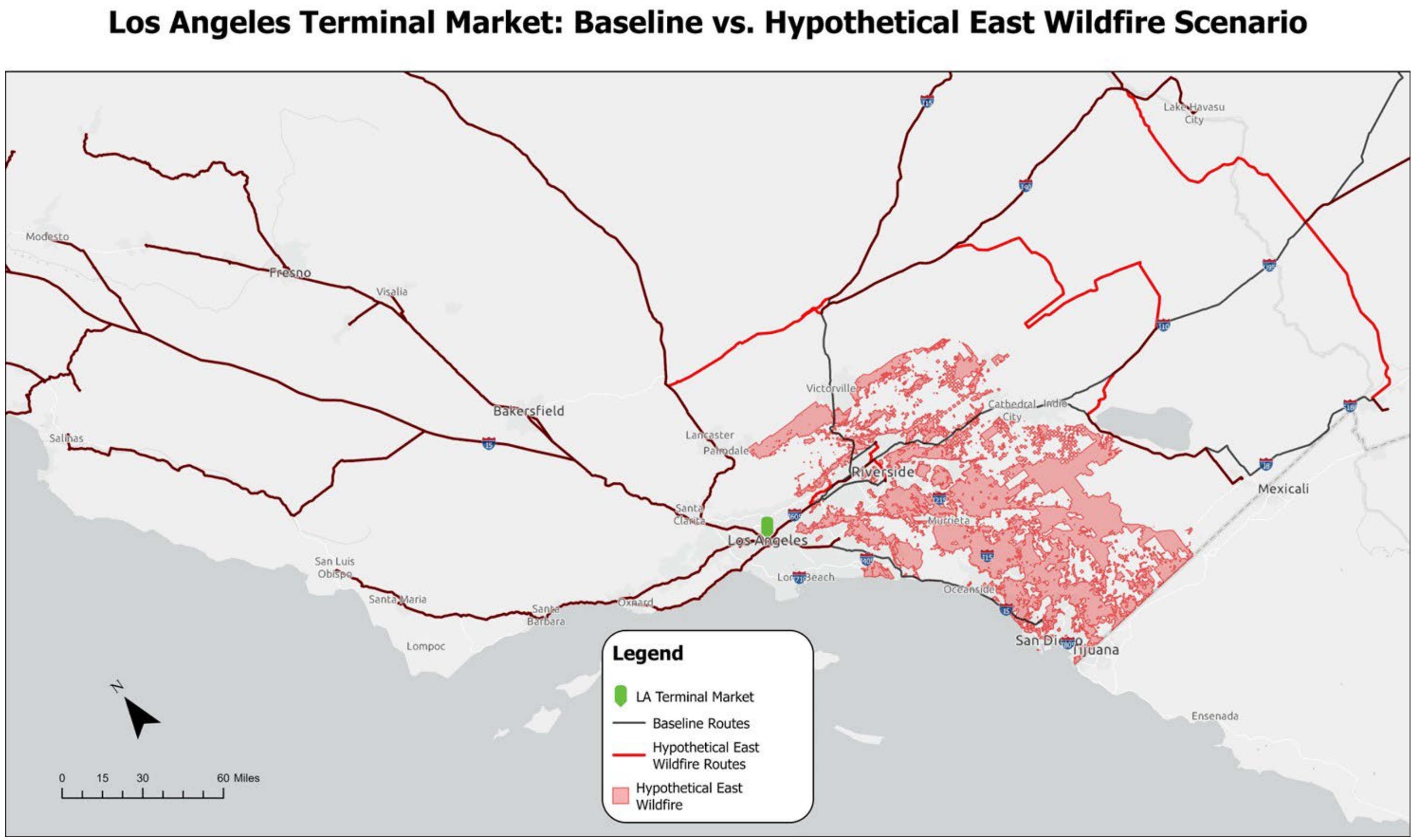

Figure 7: Hypothetical LA East extensive wildfire scenario showing baseline routes in black and wildfire routes in red. Where wildfire routes match baseline routes, the red is shown overlain on black. Source: California Department of Forestry & Fire Protection, Esri, FTOT, OpenStreetMap.

Approximately 15 percent of baseline routes suffered no rerouting in this East Wildfire scenario. Most disrupted routes (over 70 percent) required a detour that added 50-100 miles to the original routing, and approximately 5 percent of routes were rerouted by over 100 miles (Figure 4). The rerouting around this larger, hypothetical fire led to a transportation cost increase of 6.4 percent nationally for produce coming into the LA terminal market, while also reducing the number of truckloads of produce coming into the market by 11 percent (Table 2). Spoilage and other factors could reduce the amount of successful deliveries even further, as total travel time was increased by 8.75 percent (Table 2).

The corridor that experienced the greatest disruption in this hypothetical fire scenario as measured by increased travel time is the Imperial County CA to Los Angeles route for agricultural commodities, as shown in Figure 8. This route represents the 6th largest origin-destination flow in the model, handling over 285,807 tons annually under the optimal baseline. Fire-induced disruptions force trucks to reroute north of I-10, adding approximately 5 hours and 25 minutes of additional travel time per driver. The significant travel time impact of these disruptions may also contribute to truck driver hours of service limitations and more involved labor considerations, which can compound delays.

A summary of the FTOT results for each wildfire scenario is presented in Table 2. More severe wildfires resulted in less demand fulfilled, fewer truck loads, higher transport costs, increased VMT, and elevated travel times. Overall, these fire disruption analyses provide insight into the critical routes the LA terminal market is likely to rely on and the impacts of their potential disruption, providing a basis for engagement with the regional transportation agencies regarding the protection and repair prioritization of these roadways under hazard conditions.

Los Angeles Terminal Market: Most Disrupted Route with Hypothetical East Wildfire

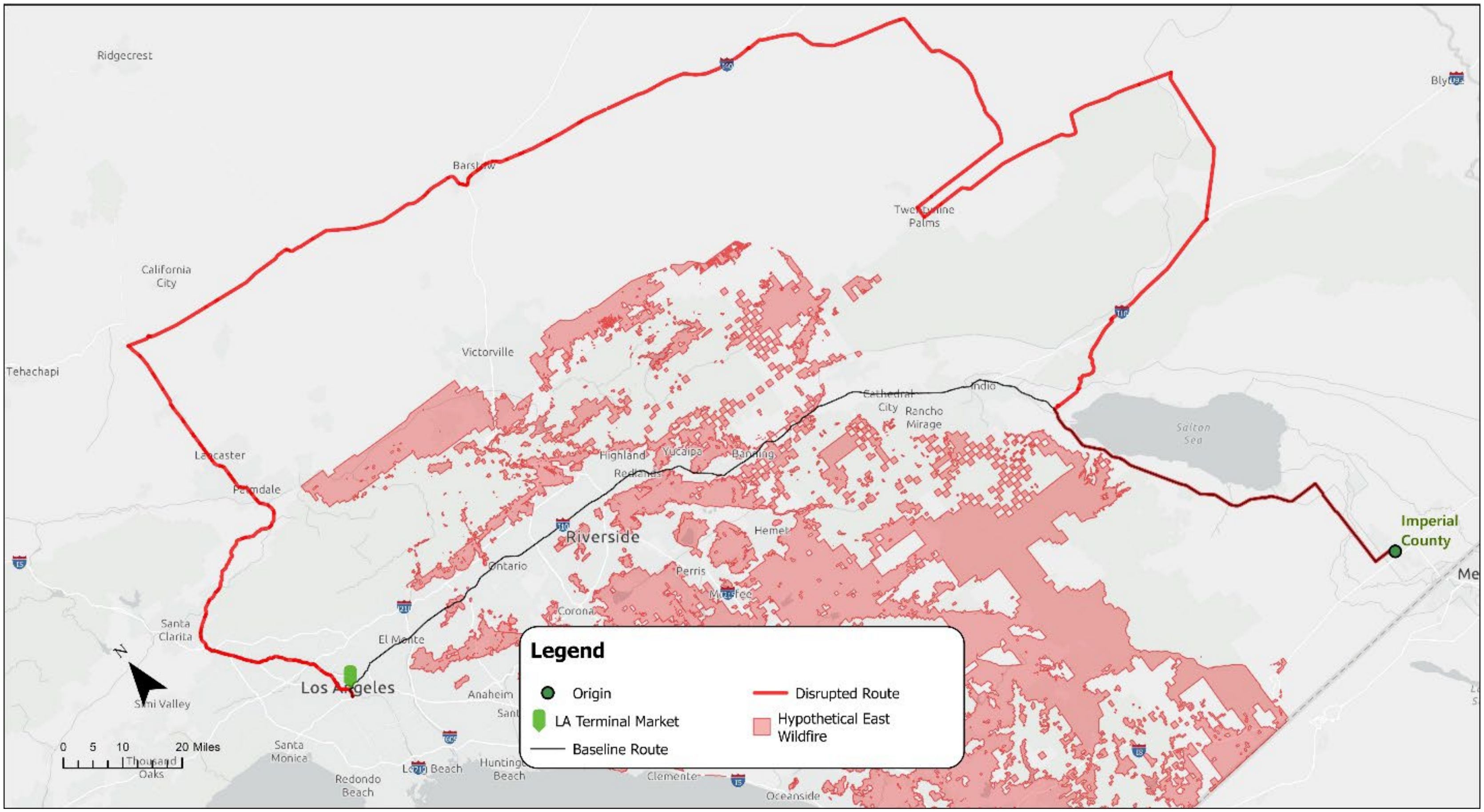

Figure 8: Most disrupted route relative to baseline resulting from the hypothetical east wildfire scenario. Source: California Department of Forestry & Fire Protection, Esri, FTOT, OpenStreetMap.

Los Angeles Terminal Market Disruption – Historical Earthquake

Multiple geological faults are located under and around Los Angeles, leading to frequent and at times significant earthquakes in the region. The U.S. Geological Survey (USGS) estimates that within the next 30 years, there is a 60 percent probability of Los Angeles experiencing an earthquake of 6.7 magnitude or greater, and a 31 percent probability of an earthquake of 7.5 magnitude or greater on the Richter scale.[12] Given the high likelihood of this hazard, the Volpe Center team modeled a historical earthquake in the region and the potential impacts on LA terminal market produce routing based on bridge fragility. Terminal markets are often identified as critical distribution points in emergency plans, as it's assumed they are one of many facility types that have optimized distribution into the city (and therefore have some perceived advantages of distributing emergency supplies such as food, water, or medicine). Therefore, the resilience of the LA terminal market deliveries in the event of a significant earthquake is a high priority.

For this analysis, the Volpe Center team used the Resilience and Disaster Recovery (RDR) Tool Suite to explore the potential disruption to LA terminal market produce arrival during and immediately after a significant earthquake event where critical corridors would be disrupted. The team assumed a magnitude M6.7 earthquake with an epicenter at 34.213°N 118.537°W (Northridge, CA).[13] The Volpe Center team developed an LA region road network using OpenStreetMap (see Figure 9) and identified bridges within this network using the FHWA National Bridge Inventory.[14] The road network was developed such that the granularity gradually decreases with increasing distance from the terminal market. The full data preparation details can be found in the Appendix.

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[12] U.S. Geological Survey. (2025). What is the probability that an earthquake will occur in the Los Angeles Area? In the San Francisco Bay area? https://www.usgs.gov/faqs/what-probability-earthquake-will-occur-los-angeles-area-san-francisco-bay-area

[13] U.S. Geological Survey. (2020, July 7). M 6.7 – Northridge, California, earthquake. https://earthquake.usgs.gov/earthquakes/eventpage/ci3144585/shakemap/intensity

[14] Federal Highway Administration. (2023). National Bridge Inventory (NBI). https://www.fhwa.dot.gov/bridge/nbi.cfm

Los Angeles Terminal Market: Road Network for RDR

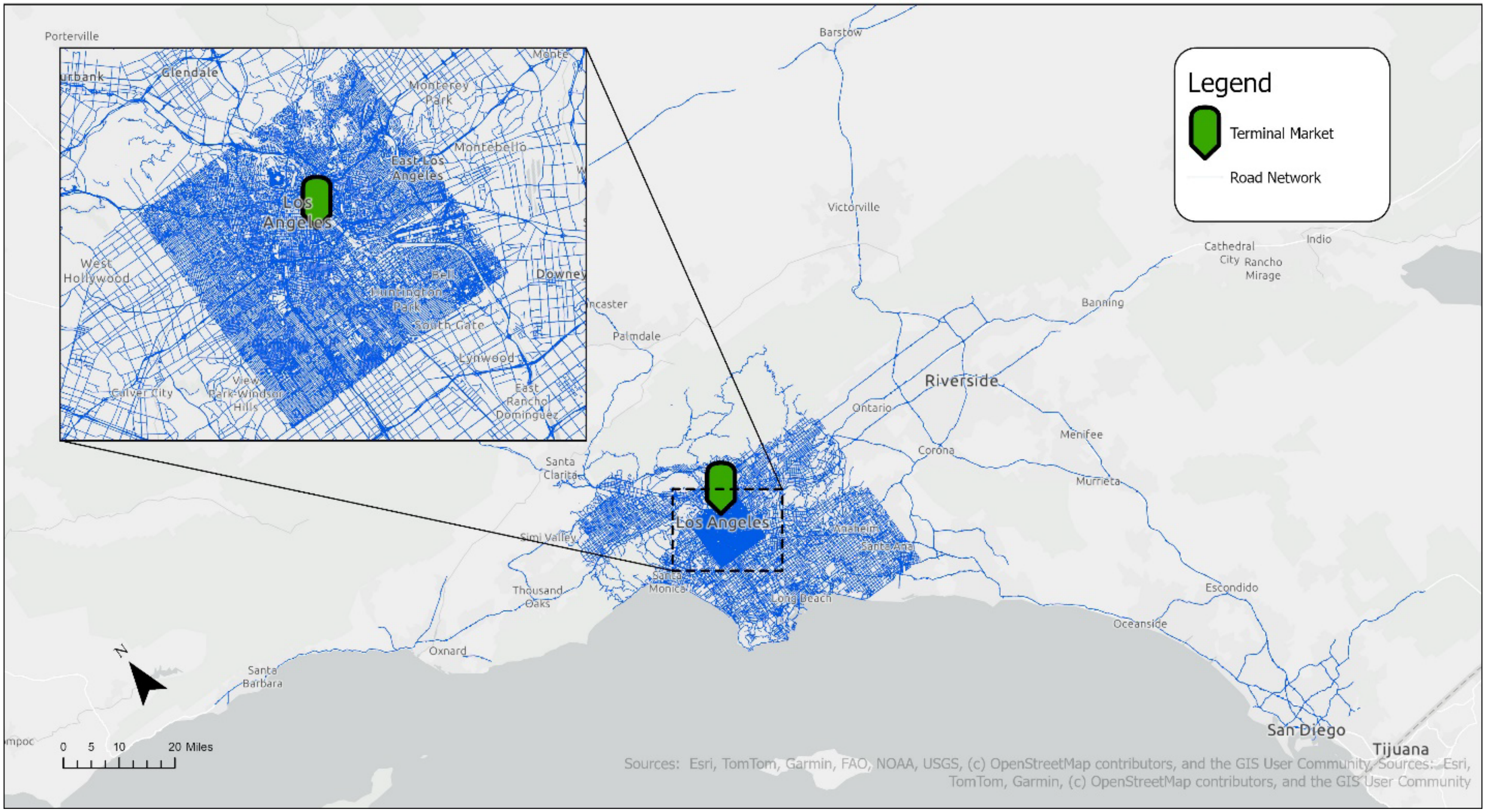

Figure 9: Los Angeles regional road network developed from OpenStreetMap for the LA terminal market analysis. Source: Esri, OpenStreetMap.

Using the "RDR Hazard Exposure Generation from Public Data" methodology (See Section 5.5 of the RDR User Guide),[15] the team applied the peak spectral acceleration (PSA; a measure of maximum force applied from a vibration) in the LA region to the road network to identify the extent of shaking experienced by bridges and translated this to expected bridge damage, which was then used to constrain capacity on the bridge links (Figure 10, Figure 11, Figure 12). The analysis indicated that out of 4,337 bridges identified in the LA road network, 527 bridges would be entirely lost (over 70 percent probability of extensive damage or over 25 percent probability of collapse) and 293 bridges would be partially affected (over 70 percent probability of moderate damage or over 25 percent probability of extensive damage) by the earthquake (Table 3). The damage to these bridges is likely to disrupt traffic flow for a substantial period while inspections, repairs, and replacements occur.

Table 3: Estimated number of bridges experiencing disruption in the LA region of interest during an earthquake similar to the historical Northridge earthquake with magnitude M6.7 and epicenter in North Ridge.

Bridge Condition	**Number of Bridges**
Unavailable (>70% probably of extensive damage or >25% probability of collapse)	527
Partially available (>70% probability moderate damage or >25% probability of extensive damage)	293
Unaffected	3,520
Total	4,337

[15] Volpe National Transportation Systems Center. (2025). RDR User Guide. https://github.com/VolpeUSDOT/RDR-Public/blob/main/documentation/RDR_UserGuide_final.pdf

Los Angeles Terminal Market: Northridge Earthquake Intensity

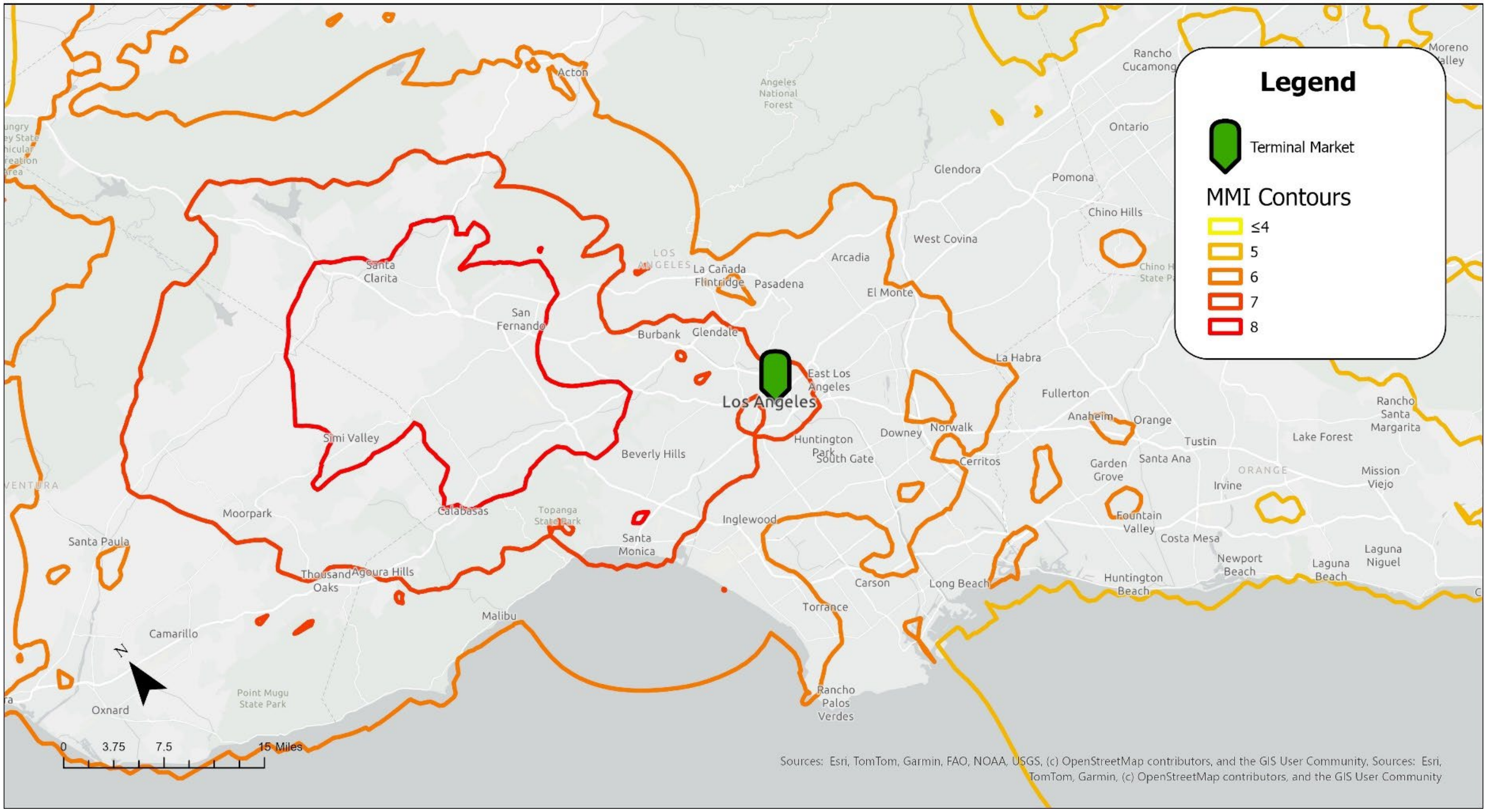

Figure 10: Modified Mercalli Intensity (MMI) contours for an earthquake of magnitude 6.7 with an epicenter in Northridge, CA. Source: OpenStreetMap, USGS ShakeMap, Esri.

Los Angeles Terminal Market: Vibration Maximum Force on Road Network at 0.3s

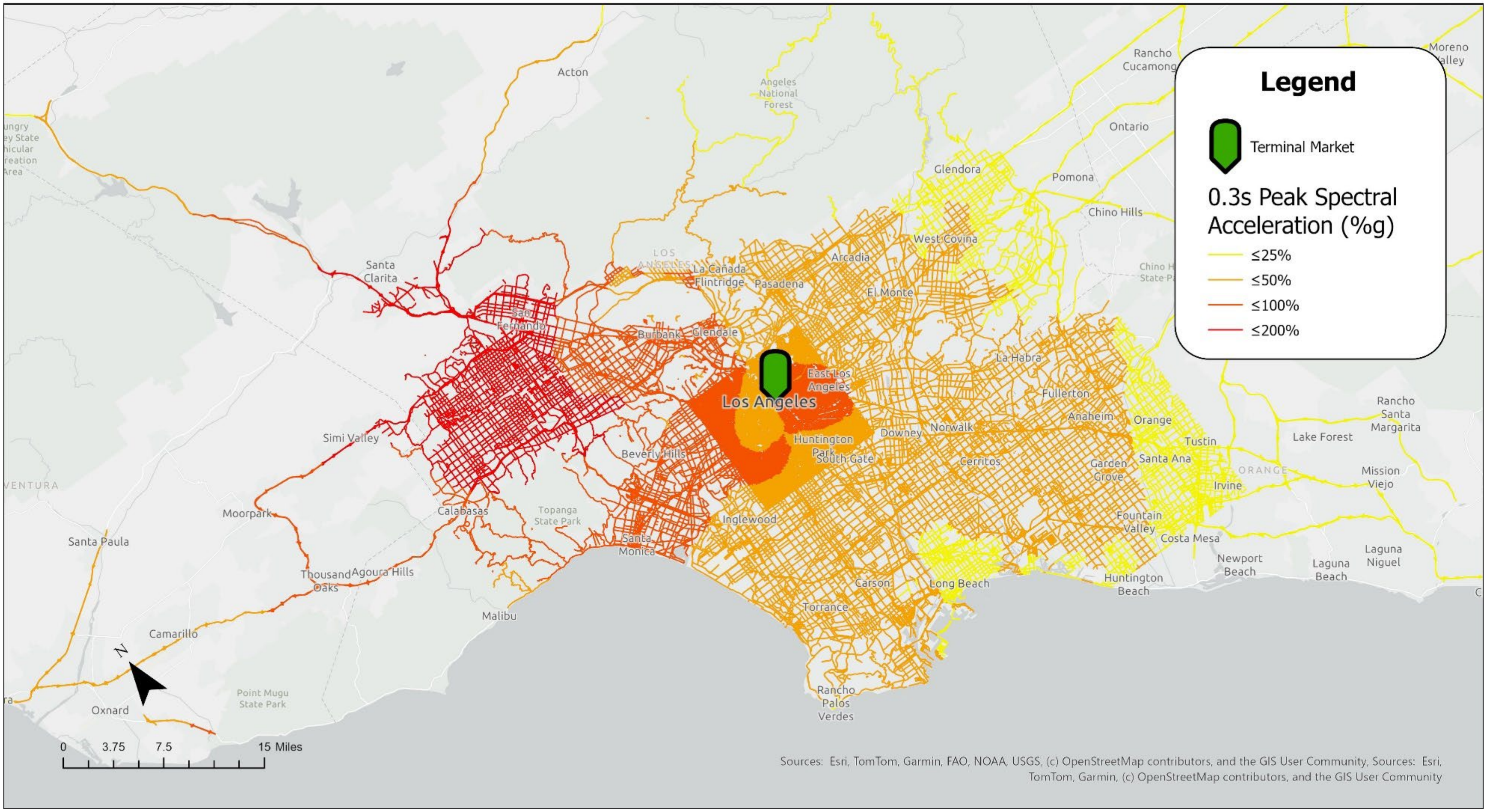

Figure 11: Vibrational maximum force for roadway links based on 1.0s Peak Spectral Acceleration. Source: OpenStreetMap, USGS ShakeMap, Esri.

Los Angeles Terminal Market: Northridge Earthquake Bridge Capacity

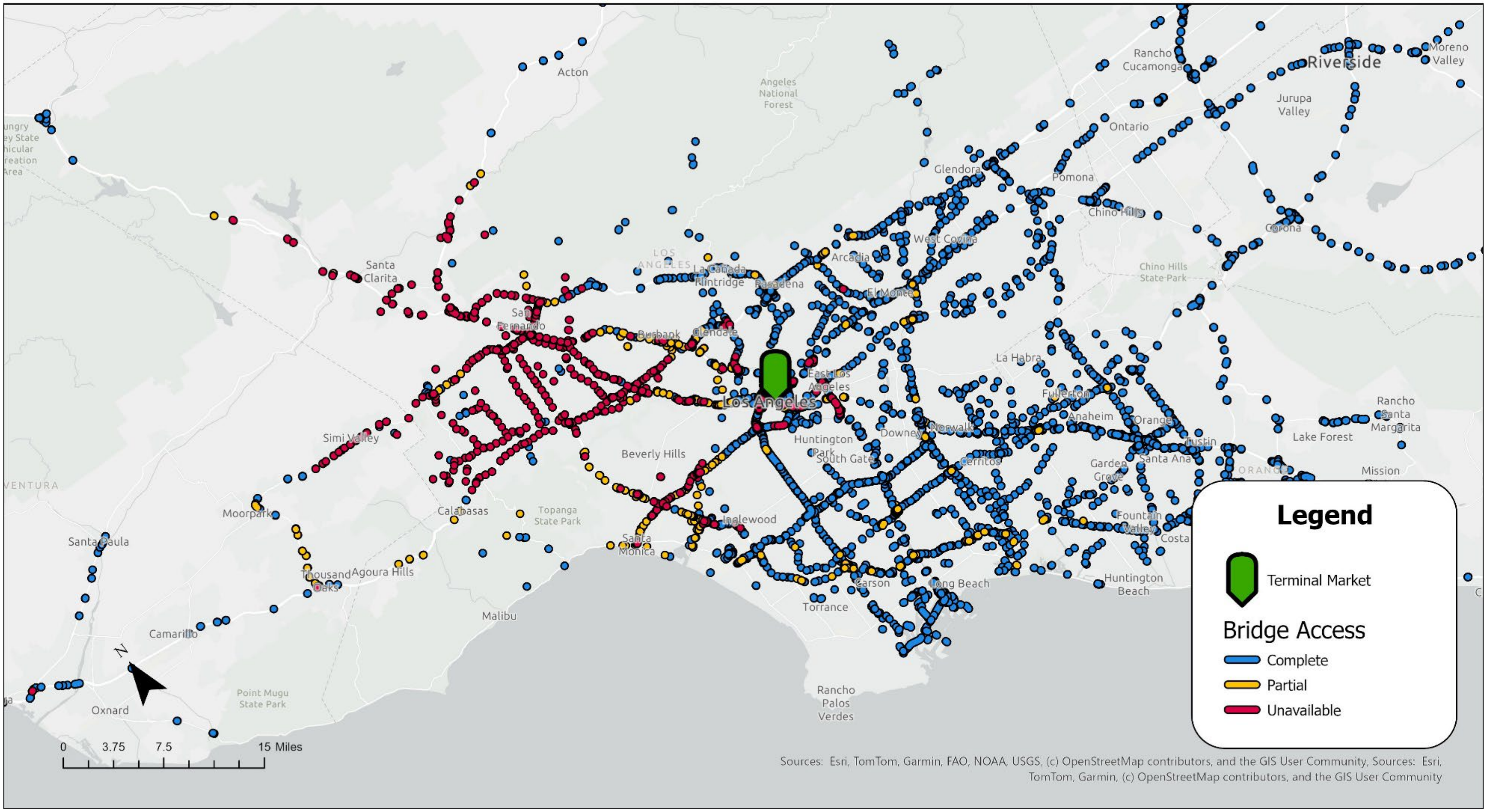

Figure 12: Pattern of bridge capacity loss based on roadway exposure from the Northridge earthquake. Source: OpenStreetMap, USGS ShakeMap, FHWA National Bridge Index, RDR, FEMA HAZUS, Esri.

The impact of the earthquake on network performance was measured in two distinct settings: from the point-of-view of the terminal market manager and the point-of-view of the local public agency. For the RDR analyses, the team generated trip tables from two sources: inbound terminal market trips were generated from the baseline FTOT run, and total freight trip tables for the LA region were generated from experimental county-level Freight Analysis Framework (FAF) flows.[16] These trips were then used to run baseline and disruption scenarios using the RDR Tool Suite. Results are summarized in Table 4. The disruption of flow resulting from the earthquake scenario led to the loss of over 62 percent of the trips leading to the terminal market and 17 percent of overall freight trips within the region, equivalent to a daily loss of 29.1 US tons for the terminal market and 962.9 US tons for the region, respectively (Figure 13, Figure 14).[17] Trip losses may be artificially increased due to the level of detail in the road network developed for this analysis, which limits re-routing opportunities further than 25 miles from the terminal market. Additionally, the impact of the disruption on terminal market trip loss is potentially overstated due to the terminal market trips all originating from external zones. This type of supply chain-specific analysis can highlight key vulnerabilities of critical industries that might not be reflected in a more generalized analysis. Due to the extensive bridge failure in the scenario, trip loss dominated the results because detour routes were equally unavailable.

Table 4: Effect of earthquake scenarios and mitigation corridors on the trips made for produce and for freight overall in the LA region.

Scenario	Produce Trips	Produce Percent Change vs. Baseline	Freight trips	Freight Percent Change vs. Baseline
Baseline	700.8	--	66,199.4	--
Northridge Earthquake	264.3	-62%	51,755.8	-22%
Northridge Earthquake with I-5 Corridor Project	603.8	-14%	63,035.5	-5%
Northridge Earthquake with Route 101 Corridor Project	355.5	-49%	54,850.8	-17%

The team used the Resilience and Disaster Recovery (RDR) Tool Suite to explore what would be needed to mitigate these impacts along two specific corridors (I-5 and Route 101) that are highly disrupted in the earthquake scenario and are critical to the LA terminal market, supplying 63 percent (49 percent from North and 14 percent from South of LA) and 13 percent of inbound produce flows, respectively. In this analysis, the team used the RDR Tool Suite to estimate performance when the entire corridors of bridges are suitably hardened to prevent damage and capacity loss under the earthquake scenario.

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[16] Bureau of Transportation Statistics. (2025, August 18). Freight Analysis Framework Version 5 (FAF5): Experimental County-Level Estimates. https://www.bts.gov/faf/county

[17] Daily produce loss calculation assumes capacity of 22 US ton per truck with only weekday operations (260 days per year), and does not account for seasonal variation.

If the I-5 corridor impacts are mitigated, only 14 percent of inbound terminal market trips are lost, compared to over 60 percent without mitigation; for overall freight trips, only 5 percent would be lost if I-5 were mitigated compared to 17 percent without mitigation. If the Route 101 corridor impacts were mitigated, 49 percent of inbound terminal market trips were lost instead of 60 percent, and 17 percent of overall trips compared to 22 percent in the baseline. Therefore, the hardening of I-5 bridges against earthquakes would have a proportionally greater benefit for inbound produce going to the LA terminal market than for freight as whole. Analyses like this can inform the need for hardening of key vulnerable infrastructure in order to maintain the critical role of terminal markets like the LA terminal market for food and supply receipt and distribution under emergency conditions.

Los Angeles Terminal Market: Northridge Earthquake Impact on Terminal Market Flow

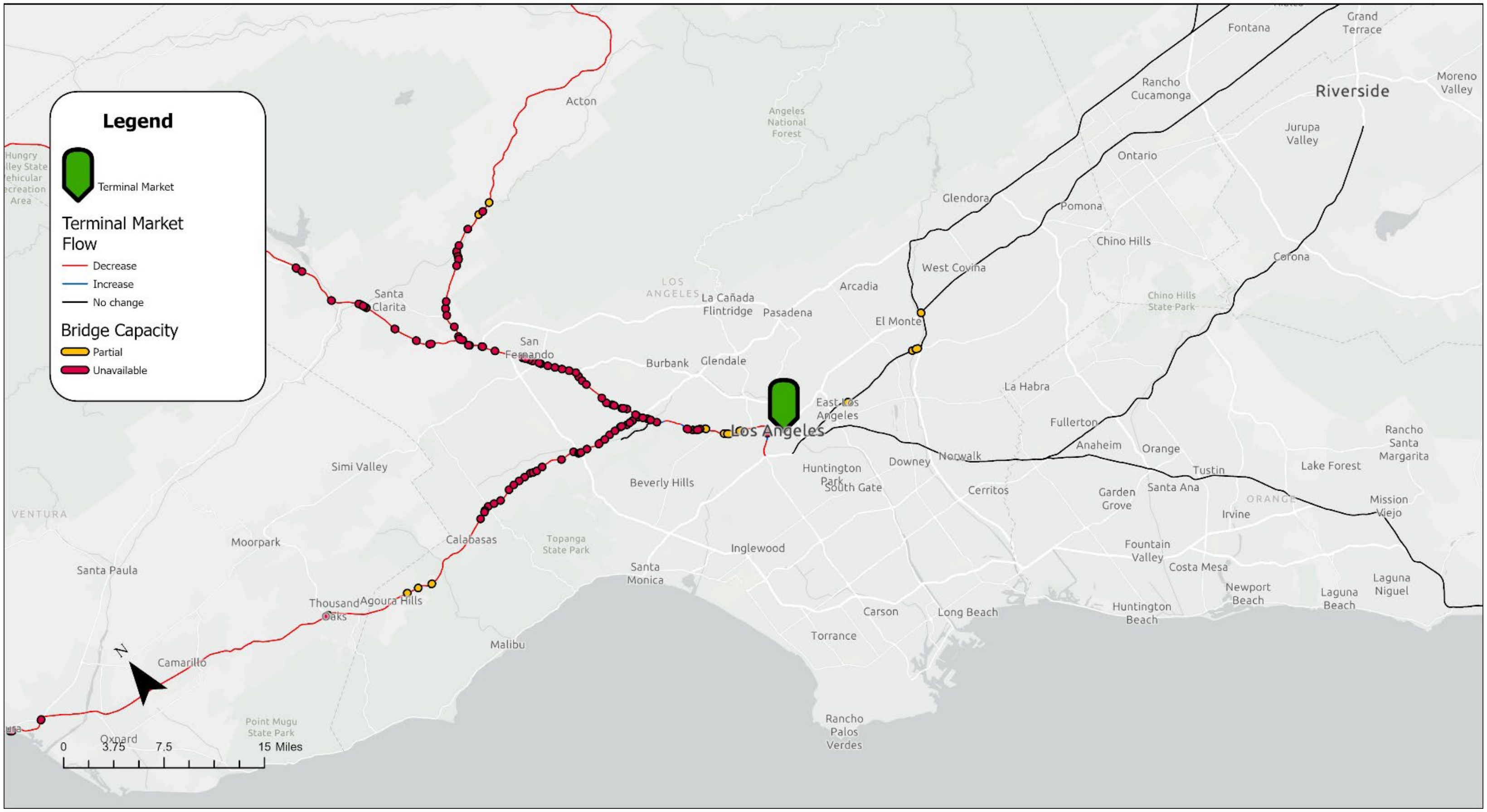

Figure 13: Terminal market change in flow and bridge capacity due to Northridge Earthquake. Source: OpenStreetMap, USGS ShakeMap, FHWA National Bridge Index, RDR, FEMA HAZUS, Esri.

Los Angeles Terminal Market: Northridge Earthquake Impact on All Freight Flows

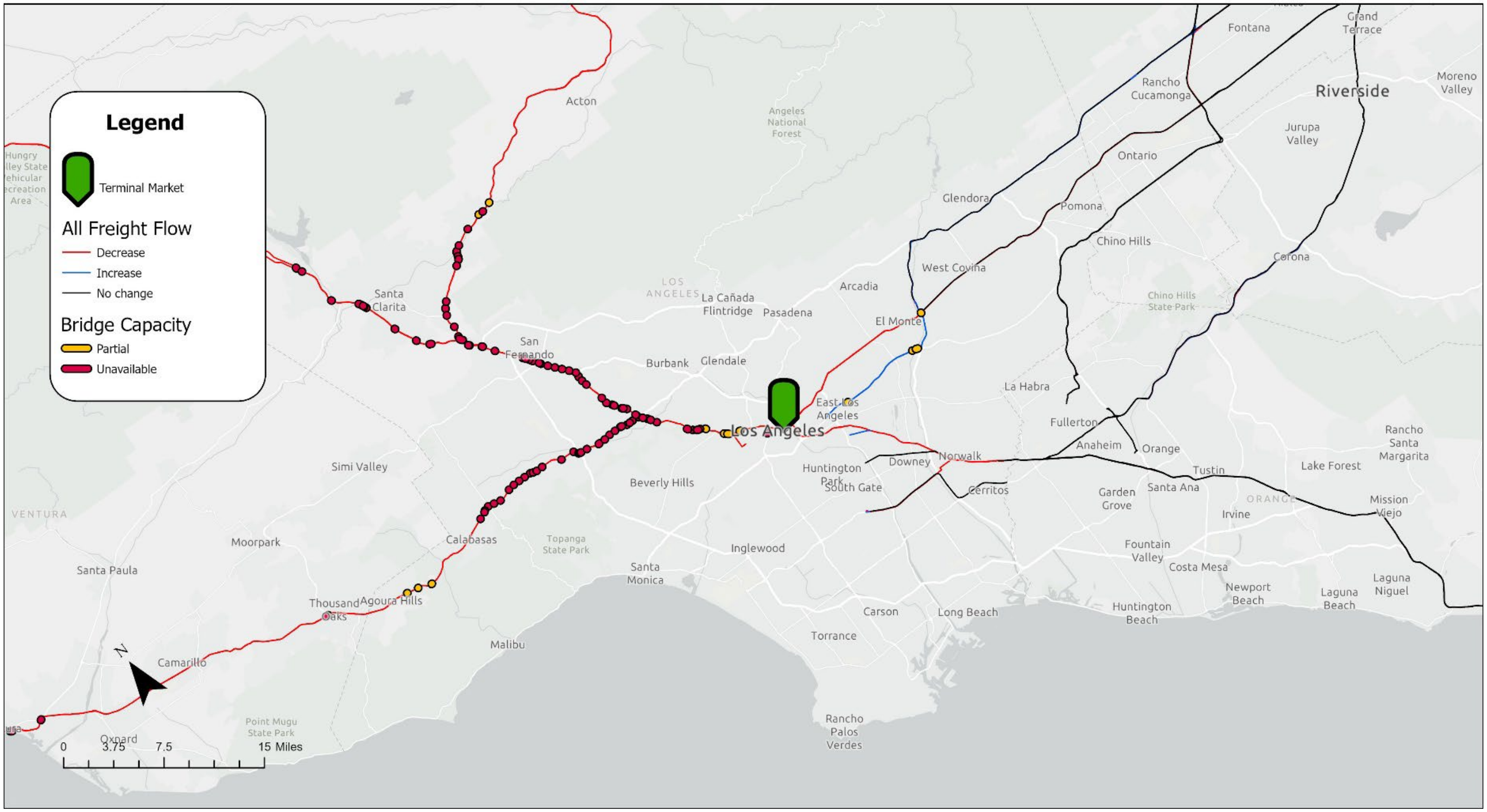

Figure 14: Overall freight change in flow and bridge capacity due to Northridge Earthquake. Source: OpenStreetMap, USGS ShakeMap, FHWA National Bridge Index, RDR, FEMA HAZUS, Esri.

This “first pass” analysis focused on a large earthquake and associated massive bridge loss to demonstrate the approach and ensure a perceivable impact on the transportation network. However, more nuanced future analyses focused on much more frequent but smaller earthquake patterns (e.g., some aggregated hazard representing the most frequent small earthquakes historically) could help identify priority locations where a few infrastructure projects might make a significant difference in inbound produce travel and overall freight trips.

Case Study: St. Louis, MO Flooding – Data Availability Limitations

The previous analyses are made possible by the availability of granular, geospatially-explicit, and easily accessible data on the region of interest, its freight flows, and the potential disruptions that inform a resilience analysis. The Volpe Center team attempted to run a similar vulnerability analysis for the terminal market in St. Louis, MO. St. Louis is situated on the border of Missouri and Illinois, thus requiring any geospatial analysis to incorporate data from both states. After reviewing likely hazards in the region, the Volpe team identified riverine flooding as the key hazard for analysis. However, in this instance, data inconsistencies or lack of availability prevented the analysis from being completed.

The Volpe Center team reviewed Federal Emergency Management Agency (FEMA) National Risk Index (NRI) to assess flooding likelihood.[18] However, while this dataset provides annualized frequencies of flooding, it does not provide flood depth, which is necessary to distinguish among road links to be eliminated during a flooding event. The team considered an approach to remove road links with high annualized frequencies. While NRI provided data by census tract, the riverine flooding annualized frequency is either 0 or equivalent to the riverine flooding annualized frequency of the county (see Figure 15). The low level of detail made it difficult to assess potential flooding impact on individual roads in the road network in St. Louis. Without more granular hazard data, the geospatial difference in disruption on the network is not possible to model, precluding a more nuanced supply chain resilience analysis.

[18] Federal Emergency Management Agency. (2025). The National Risk Index. https://hazards.fema.gov/nri/

St. Louis Terminal Market: National Risk Index Riverine Flooding Annualized Frequency

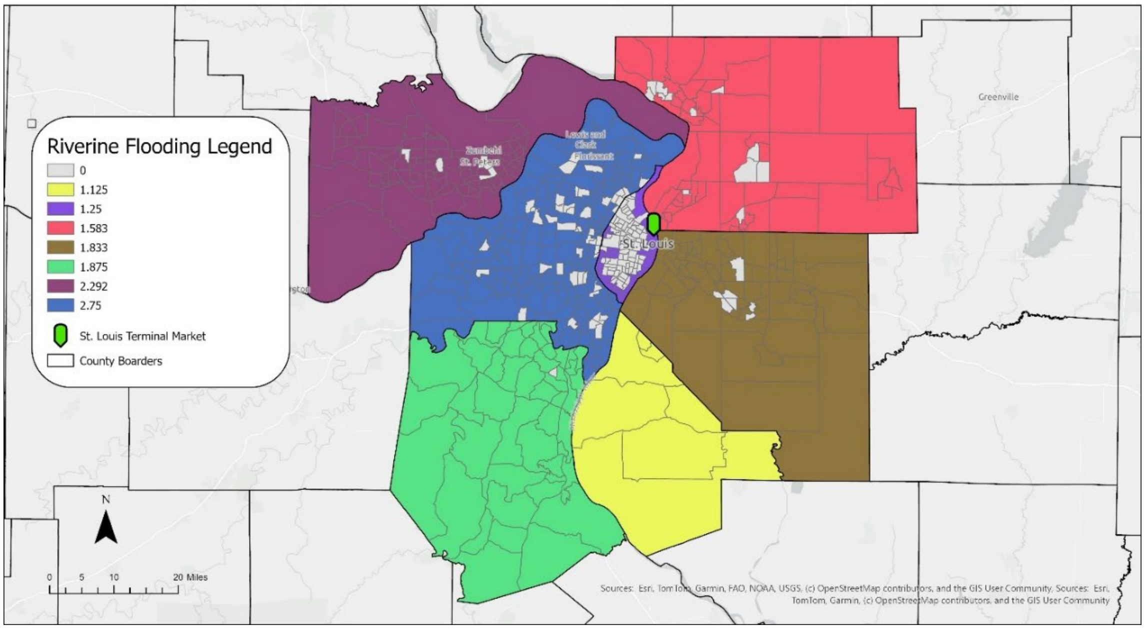

Figure 15: FEMA National Risk Index riverine flooding annualized frequency for St. Louis Area counties. The annualized frequency for each census tract is either 0 or the one common value within each county. Source: FEMA National Risk Index, Esri.

The Volpe Center team then reviewed the FEMA Flood Map Service Center's flood risk database.[19] Data are available for counties in Missouri but only preliminary data (prepared in 2022) are available for two of the three Illinois counties near St. Louis (St. Clair and Madison). No FEMA flood data exists for Monroe County, IL.

Data availability is a common problem in freight transportation planning. If there are concerns from the market that access to/from their facilities is impeded or inefficient, there may be an opportunity for the public sector to collaborate with the market to complete a data study.

Conclusion

This paper examined the relationship between regional terminal produce markets and the transportation networks that serve them. Field observations showed that market managers focus their limited capacity on business-related tasks such as leasing, maintenance, and facility operations, leaving freight transportation responsibilities to tenants, brokers, and carriers. As a result, terminal markets are seldom active participants in regional or state planning processes, and public agencies rarely consider them explicitly in long-range freight or infrastructure strategies.

Despite this disconnect, modeling demonstrates that regional transportation networks are central to the efficiency and resiliency of produce flows. Cost-effective throughput levels depend on sourcing distances

[19] Federal Emergency Management Agency. (2025). FEMA Flood Map Service Center: Welcome! https://msc.fema.gov/portal/home

and congestion, while the perishable nature of commodities magnifies the consequences of even modest delays or disruptions. Vulnerability assessments for markets in Los Angeles and other regions highlight how concentrated dependence on a handful of highways can expose supply chains to risk from hazards, closures or bridge postings, or other causes.

Together, these findings suggest that wholesale produce markets and public agencies share an interest in maintaining reliable regional transportation access, even if this alignment is not always apparent. Strengthening this connection through targeted analysis, improved communication, and recognition of market-specific supply chain needs can preserve the resilience and competitiveness of regional food systems.

Appendix: Resilience Analyses Data and Methods

FTOT Scenarios Data Preparation

The main data sources for the FTOT analysis were Transearch, for commodity flow data, and the California Department of Forestry and Fire Protection, for wildfire disruption areas.

1. Baseline FTOT scenario
    a. Filter Transearch data to destination of choice (e.g., Los Angeles County).
    b. Aggregate Transearch data across agricultural commodities for each origin county, and associate with origin county FIPS code.
    c. Add terminal market to FTOT facilities geodatabase. (Note lat/lon for creating a centroid later.)
    d. Create dest.csv input table that identifies the total tonnage of agricultural commodities flowing to the destination.
    e. Create rmp.csv input table that identifies the total tonnage of agricultural commodities flowing to the selected destination from each origin. Ensure that the origin region from Transearch is converted to an RMP facility name in rmp.csv.
2. Disruption FTOT scenario
    a. Create a hazard raster and then use run_ftot_tools.bat to develop hazard exposure disruption.csv file.
    b. For historical wildfires in CA, use Fire Hazard Severity Zones provided by the California Department of Forestry and Fire Protection: https://calfire-forestry.maps.arcgis.com/home/item.html?id=ac8ed44d76ed4988bceb07d35d80f4cb#overview.
    c. For hypothetical wildfire, used Fire Hazard severity Zones from the California Department of Forestry & Fire Protection: https://osfm.fire.ca.gov/what-we-do/community-wildfire-preparedness-and-mitigation/fire-hazard-severity-zones
    d. Raster data should be exported in ArcGIS Pro using Export Raster to GRID.
3. Run scenarios in FTOT and save optimal_route_segments feature class from the output main.gdb for use in additional analysis and visualizations.

RDR Scenarios Data Preparation

The main data sources for the RDR analysis were OpenStreetMap, for network data, the Freight Analysis Framework, for trip table data, and USGS, for earthquake data.

1. Pulling network data from OpenStreetMap
    a. Use OSMNx package to query OpenStreetMap data around the terminal market on network size, network type, functional class, etc. Use windowing such that the network's granularity gradually decreases with increasing distance from the terminal market.
        i. Include service and residential roads to connect the market to through roads.

    ii. Include ~10 mile radius of trunk, primary, secondary, tertiary, and unclassified roads.
    iii. Include regional motorways at a larger radius large enough to allow RDR to redirect to other motorways if there are disruptions.
  b. Use NetworkX methods to compose network graphs generated by OSMNx, to simplify and clean the resulting graph, and to ensure that the output is compatible with the General Modeling Network Specification (i.e., unique node IDs and separate features for each direction of travel).
    i. Renumber node IDs starting at a higher offset value (e.g., 100), since the centroid nodes will need to be added and must have the smaller ID values. Use NetworkX method convert_node_labels_to_integers() with first_label parameter.
    ii. **Note:** If you are planning to use bridge information to model earthquake hazards using the National Bridge Inventory (NBI), retain the "bridge" tag from OSM and incorporate it into the facility_type field for RDR.
  c. Save as geopackage and load into ArcGIS Pro to create separate node and edge feature classes. Save node and edge feature classes.
2. Preparing RDR Network Files
  a. Node table
    i. Calculate XY coordinates on nodes feature class. Export attribute table for non-centroid nodes, indicate these as "not_centroid".
    ii. Add centroid nodes.
      1. Create a feature class to keep centroid points with field "Node ID".
      2. For each FTOT flow coming into the RDR network, add a point to define the origin centroid of the flow close to where it enters the network. Give it a node ID starting from 1.
      3. Note the nearest network node(s) and their OSMID for creating centroid connector links. Unless there is a straightforward re-routing available, only note the nearest network node.
      4. Add a point for the terminal market. Note all potential entry point network nodes and their OSMIDs.
      5. Calculate XY coordinates for all points in the feature class.
  b. Link table
    i. Export attribute table for OSM network links. Use ArcGIS methods, Python methods, and/or Excel manipulations to calculate fields required by RDR:
      1. Link ID can be the FID from the feature class – confirm this is unique
      2. From/to nodes are the OSMID of network nodes
      3. Length – use Calculate Geometry and select statute miles to get miles
      4. Facility Type – create a lookup of OSM highway tags to RDR default facility types

5. Capacity – create a lookup of facility types to approximate capacities
6. Max speed – create a lookup of facility types to approximate maximum speeds
7. Lanes – use OSM value (divided by 2 and rounded if needed)
8. Toll – set to 0
9. Travel time – calculate from Length and Max speed then convert hours to minutes

ii. Add centroid connectors
   1. Create a new link(s) for every centroid node created above tying this into an existing network node using the OSMID noted above. Add one centroid connector in each direction (flipping the node_ids).
   2. Fields: link_id, length = 0.5 miles, speed = 5 mph, facility_type = 901, capacity = 10000, lanes = 1

3. Preparing RDR Trip Table for Terminal Market Trips
   a. Given initial RDR network from OSM, clip optimal_route_segments from FTOT baseline scenario to RDR network bounding box to calculate commodity flow amounts entering from each external zone centroid.
      i. Determine number of centroids based on number of intersections of optimal_route_segments with the boundary of the bounding box.
      ii. For each centroid created, note the FTOT flow volume (in tons per year) coming into the RDR network from that centroid.
      iii. Convert volumes from tons per year to trucks per day.
         1. Assumptions: 22 tons per truck (https://otrsolutions.com/what-is-a-reefer-truck-a-complete-guide-otr-solutions/) and 330 days per year (operating at ~90%)
      iv. Create CSV file with ”orig_node”, “dest_node”, and “trips” columns with rows summarizing the FTOT flows originating at external zone centroids and ending at the terminal market centroid.
         1. Note that every centroid-centroid pair must be included in the CSV file in order for the OMX file to be generated correctly using the below helper tool. Assign zero trips when necessary.
      v. Run RDR’s convert_trip_table.bat to create an OMX file needed for an RDR run.
4. Preparing RDR Trip Table for Regional Freight Trips
   a. Several types of trips should be modeled for the region: internal-internal, external-internal, internal-external, external-external (ignored). Model these at the county level.
   b. Determine how many internal centroids are needed. Only include internal centroids for county destinations where there is a robust network.
      i. Create centroids and add to node files.

   ii. Build out new centroid connectors for these county centroids – build centroid connectors to and from the internal centroids to all motorway junctions within 5 miles.

c. Continue to use the same external centroids from the terminal market trip table method.
   i. For counties adjacent to the internal county centroids selected in Step b.ii. above, use an existing centroid as the origin centroid.
   ii. For all other counties, assign flows to a few reasonable external centroids for entry into RDR network.

d. Use experimental FAF county flows (https://www.bts.gov/faf/county) to approximate I-I, I-E, E-I daily trips.
   i. Internal-internal trips will be between county FIPS that correspond to the internal centroids (County-to-County).
   ii. External-internal trips will come from FAF-to-County and County-to-County files. Trips within the market's multi-state area will only come from the county-to-county file. In other words, trips coming from outside of the multi-state area will use FAF zones, but trips coming from within the multi-state area will use county data.
   iii. Internal to External trips will come from County-to-FAF and County-to-County files. Trips within the market's multi-State area will only come from the county-to-county file. In other words, trips going out of the multi-state area will use FAF zones, but trips travelling within the multi-state area will use county data.

e. Generate a lookup table that relates each FAF zone and county in the datasets to an entry/exit centroid. FAF zones corresponding to the market's state should be labeled "NA." Similarly, the lookup table should only include counties within the market's state.

f. FAF experimental county-level estimates data processing
   i. To open the county-to-county file in Excel, it may be necessary to use pandas to pre-filter the table down by setting dms_mode = 11.
   ii. For external to internal trips, relate each origin FAF zone to a centroid. Pivot the table, filtering for just truck trips (dms_mode = 11) and summing on tons_2022. This will yield annual truck volumes from each centroid of entry to the selected destination county centroids. Summarize this data with "from" and "to" centroids, making sure to remove tonnage travelling exclusively between origin/destination county centroids as these are internal-internal trips. Convert to trips, assuming 22 tons per truck and 330 travel days per year; FAF tonnage is in thousands of tons.
   iii. For internal to external trips, relate each destination FAF zone to a centroid. Pivot the table, filtering for just truck trips and summing tons. This will yield annual truck volumes from each origin county centroid to the centroid of exit. Summarize this data with "from" and "to" centroids, making sure to remove

tonnage travelling exclusively between origin/destination county centroids as these are internal-internal trips. Convert to trips, assuming 22 tons per truck and 330 travel days per year; FAF tonnage is in thousands of tons.

iv. Finalize the internal-to-internal trip table, with from and to centroids. Convert to trips, assuming 22 tons per truck and 330 travel days per year; FAF tonnage is in thousands of tons. Note that internal-to-internal trips originating and ending in the same county will not be explicitly flowed in RDR.

v. Make sure to rename from and to centroids to the values used in the node file.

g. Update the demand.csv input file with the new flows generated from the FAF data.

h. Update the baseline run file with centroid connectors. Buffer the county centroids at around 5 miles. Near the edge of this buffer, select a reasonable sample of nodes in the network from which to generate connectors.

5. Preparing RDR Hazard Data
    a. Select a historical earthquake from USGS (see https://earthquake.usgs.gov/earthquakes/search/) and download the 'ShakeMap Shape Files' from the Downloads section of the ShakeMap page.
    b. Follow methodology from the RDR Public Data Prep Jupyter Notebook to develop the RDR Hazard Data. Update bridge to road link matching methodology:
        i. Select all road links identified as a bridge by OSM.
        ii. Match each bridge road link to the nearest bridge (within 200 meters) from the National Bridge Inventory (NBI) using the ArcPy Near (Analysis) tool.
6. Creating RDR Projects
    a. Identify vulnerable highway corridors based on the preliminary bridge vulnerability analysis.
    b. Identify all bridge links for the corridor and assign to the same "corridor improvement" project.