Generating Reliable Freight Disruption Measures with Freight Telematics Data

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Project Partners: Oregon DOT, Robinsight (EROAD)

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16. Abstract
This report explores the use of telematics data to assess freight network resilience during significant disruptions, such as natural disasters and infrastructure failures. Focusing on case studies including the Oregon Forest Fires, Hurricane Florence, and the I-55 Mississippi River Bridge closure, the research analyzes freight movements before, during, and after these events. The findings highlight key patterns in route adaptations and recovery, providing valuable insights for transportation planners. The study emphasizes the importance of real-time data in developing reliable freight performance measures and improving infrastructure planning to enhance network resilience.

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Executive Summary

This report, titled **"Generating Reliable Freight Disruption Measures with Freight Telematics Data,"** presents a framework for evaluating freight network resilience using telematics data provided by EROAD through Robinsight. The primary goal of the research is to address challenges faced by state agencies in understanding freight movements, particularly during disruption scenarios such as natural disasters or infrastructure failures.

The research utilizes telematics data to gain a deeper understanding, which will aid in the development of reliable freight performance measures later on (Year 2). This study focuses on three significant case studies: the Oregon Forest Fires of 2020, Hurricane Florence in North Carolina, and the I-55 Mississippi River Bridge closure in Tennessee. By analyzing freight movement data before, during, and after these events, the research assesses how networks recover from disruptions and proposes metrics for evaluating resilience.

Key findings include the identification of bottlenecks, changes in traffic patterns, and route adaptations during disruptions. Additionally, the study highlights the value of real-time and historical telematics data in informing state transportation agencies on infrastructure investments to enhance network resilience. The report provides a foundation for future studies, suggesting the integration of additional datasets to refine the assessment of freight performance and resilience across multiple jurisdictions.

In conclusion, this research highlights the importance of using advanced telematics data to improve transportation resilience metrics, providing actionable insights for decision-makers to enhance freight network performance during and after major disruptions.

Problem Description

Disasters on the transportation network raise awareness of the need to plan for quick mobility and recovery whether they are due to human error, human intent, or nature. Therefore, understanding how resilient a network is to such events provides opportunities for transportation agencies to better prepare. Resilience measures then become a useful tool to evaluate and predict impacts of disruptions and recovery to guide investment decisions to protect against these events. When it comes to freight network system measurements there are two major challenges the states and other agencies face: (1) the absence of data and (2) the lack of methods of analysis. There are **robust** data for the movement of people and passenger vehicles but understanding the way freight moves presents different types of challenges to decision-makers especially under disruptions scenarios. These movements are based upon supply chain decisions made by individual corporations, which quite often change over time due to various economic conditions. Freight often moves across numerous jurisdictions and by multiple modes of transport (e.g., air, rail, water/marine, and truck). Data that captures origins and destinations, as well as methodologies of collecting and utilizing data across multiple jurisdictions and modes, are extremely limited for freight. Currently, decision-makers are only able to use a few data sources that help in identifying freight movements among States and regions, commodities, tonnage, and value.

With this in mind, this research presents a framework based on telematics technology from EROAD[1] (and already collected data) to evaluate this data source for generating reliable freight network resiliency measures. EROAD is a company that develops and implements technology to modernize traditional paper-based systems within the trucking industry. As part of this modernization, EROAD collects the data used for generating reliable freight performance measures. Still, EROAD data has yet to be used for such an application. This research utilizes the Pacific Northwest (specifically Oregon), the I-55 Mississippi River Bridge Closure, and the impacts of Hurricane Florence as case studies which will allows to us evaluate freight movements over various jurisdictions (e.g., within state and state-to-state) and assess EROAD data in the development of reliable freight network resiliency measures. Given that EROAD data captures freight telematic data for truck movements, this study focuses on the trucking mode. The findings of this study have the potential to lead to the generation of new and reliable freight network resiliency measures utilizing a new source of data for state transportation planners.

[1] EROAD is a regulatory telematics technology company from New Zealand. Over the last 10 years EROAD has provided telematics services to over 69,000 vehicles.

Literature Review

In today's world of growing global freight demands and increasingly complex supply chains, assessing the reliability and resilience of transportation networks has become critical. The ability to predict and evaluate both natural and man-made disruptions to freight systems is essential for maintaining economic stability and efficiency. Leveraging freight telematics data, which provides real-time and historical insights into freight movements across U.S. networks, can significantly improve our ability to accurately measure freight disruptions. This, in turn, leads to more informed decision-making. While several efforts have been made to address this issue, there remains a need for more accurate and actionable metrics, which depend on the availability of reliable data.

The aim of this literature review is to explore recent contributions in this area and utilize advanced telematics data to offer deeper insights into freight network disruptions, ultimately enhancing resilience and overall network performance.

Freight Network Resiliency and Telematics Data

Freight network resiliency is becoming an increasingly important area of study as disruptions, both natural and man-made, can have wide-reaching impacts on transportation systems and economic stability. Numerous studies have explored the reliability and resilience of freight networks, leveraging diverse data sources, including telematics, to develop more accurate metrics for resiliency assessment. This review highlights key contributions to this field, with a focus on how telematics data has been used to understand and improve network resilience.

Morshed et al., (2021) introduced the “8R RESILIENCE” model, which identifies eight key resilience concepts: ‘Redundancy,’ ‘Resourcefulness,’ ‘Reliability,’ ‘Robustness,’ ‘Responsiveness,’ ‘Recoverability,’ ‘Replacement,’ and ‘Rendition.’ This model, aimed at evaluating transportation network resilience from the user’s perspective during both natural and man-made disasters, integrates a multi-criteria decision analysis process that includes survey data and social media reactions (e.g., Twitter). By dynamically involving stakeholders, the model provides a comprehensive framework for assessing infrastructure resilience.

Building on this, Wang et al., (2023) focused on the resilience of urban multi-modal transportation systems (UMTS), considering both passenger demand and infrastructure supply. Their findings underscored the vulnerability of highly connected and central transportation nodes. They concluded that stations with high node degree and centrality are more critical to system resilience, and simply increasing capacity beyond a certain threshold has minimal impact on resilience. This study provides insights into how network topology and station connectivity affect overall transportation network resilience.

Telematics data has emerged as a viable source of data in understanding freight movements and assessing network resilience. Liao,(2014) exemplifies this by analyzing twelve months of truck GPS data to generate performance measures like truck mobility, delay, and reliability. His work demonstrates that telematics data can support large-scale initiatives, such as the U.S. Department of Transportation’s performance measure initiative, and help planners identify freight bottlenecks across metropolitan networks.

Kurth et al., (2020) emphasized that disruptions in U.S. freight networks can lead to delays that outweigh the original disturbance. Their study highlighted the critical need for resilience to ensure rapid recovery in the face of both predictable and unforeseen events. This aligns with Xu et al., (2024), who developed a resilience assessment model for interdependent transit networks. They demonstrated that network interdependencies significantly affect resilience, particularly when node heterogeneity is considered. The more heterogeneous the nodes, the higher the resilience, showing how varying levels of interconnection can shape recovery efforts.

The application of resilience principles is not limited to urban or transit systems. Potter et al., (2022) applied resilience concepts to the rail freight industry, revealing that long-term disturbances have more profound effects than previously considered. Their six-year study on the Cardiff Capital Region's rail network found a 30% decrease in the number of trains operated, highlighting the need for long-term resiliency planning in freight industries.

In contrast, Chen et al., (2023) explored natural disruptions in public transportation systems, presenting a model that mathematically quantifies both structural and functional resilience under different disruption scenarios. They assessed six key abilities, including structural resistance and recoverability, underscoring how varying levels of equipment failure affect overall system resilience.

Zhang et al., (2024) further explored resilience in the context of seismic disruptions, particularly the interdependencies between transportation and electric power systems. Their work highlights how integrating uncertainty factors can improve network recovery strategies, while their proposed enhancement strategy—such as seismic retrofitting—serves as a practical solution for increasing resilience in earthquake-prone areas.

Blake et al., (2019) shifted the focus to data exchange, which plays a crucial role in disaster recovery. Their post-earthquake assessment found that effective information exchange among 35 stakeholder groups significantly enhanced the transportation system's ability to respond and adapt. This aligns with Serdar et al., (2022), who underscored the importance of resilience-based thinking, particularly in response to global challenges like COVID-19. Their review highlighted that identifying key resilience metrics is fundamental to sustaining long-term development.

The potential of big data, including telematics, to improve resilience has been explored in several studies. Foltin et al., (2023) examined the socio-economic impacts of transportation disruptions, showing that delays in transportation infrastructure have significant, time-lagged effects on economic indicators. They utilized cluster analysis to reveal that transport infrastructure resilience is crucial for maintaining socio-economic stability.

Baroud et al., (2014)examined inland waterway networks, focusing on how these systems "bounce back" from disruptions. Their study introduced methods to quantify both vulnerability and recoverability, presenting a novel approach to assessing network components based on their contribution to overall resilience.

More specifically, Ghasemi and Lee, (2021)proposed the "instantaneous resilience" metric to evaluate the seismic resistance of highway bridges, combining robustness and redundancy measures. Their approach offers a fast and efficient way to assess post-earthquake impacts on transportation infrastructure, allowing for timely recovery actions.

Telematics data, particularly GPS data, has proven to be indispensable for understanding freight networks. Demissie and Kattan, (2022)used truck GPS data to model origin-destination choices and analyze shifts in truck travel patterns, while (Akter and Hernandez, 2023) used mobile sensor data to improve freight forecasting models, employing machine learning techniques like K-means clustering to better capture freight activities.

Yanhong and Xiaofa, (2013) highlighted how GPS data can map freight truck utilization and spatial-temporal features, providing real-time insights into freight corridors and traffic patterns. Their study showed the reliability of GPS-based models in understanding truck operations.

Further advancing telematics applications, Ghaffarpasand and Pope, (2024) introduced geospatial and temporal (GeoST) mapping, a technique that translates vehicle GPS data into detailed speed acceleration profiles. This technique not only improves vehicle emissions estimates but also offers valuable insights into travel behaviors and urban mobility patterns.

Lastly, Hu et al., (2022) demonstrated how telematics data can aid in assessing the impacts of urban freight transport, particularly in terms of fuel economy and traffic speeds. Their study on the London Lorry Control Scheme (LLCS) found that certain policies could lead to a 15% increase in vehicle kilometers traveled and a 12% increase in fuel consumption, underscoring the importance of telematics in evaluating the broader impacts of transportation policies. Gao et al., (2022) examined telematics data in the context of actuarial science, revealing how convolutional neural networks can analyze driving styles to improve claims prediction. Their study highlights the potential for telematics to enhance transparency and accuracy in transportation-related risk assessments.

Transportation System Resilience Metrics and Measures

Understanding and measuring transportation system resilience is critical for ensuring the ability of networks to recover from disruptions and continue to function efficiently. Resilience metrics provide a framework for evaluating how transportation systems respond to both natural and man-made disruptions, guiding the development of more robust and adaptable infrastructures. This section reviews key contributions to the field, highlighting various approaches to quantifying resilience, including robustness, redundancy, rapidity, and adaptability, along with specific metrics for different transportation networks.

Hosseini et al. (2016) reviewed system resilience, defining it as the ability to maintain or recover a steady state in the face of external stresses, whether social, political, environmental, or economic. They highlighted key resilience measures, including robustness (the system's ability to prevent damage propagation) and rapidity (the speed of recovery), along with probabilistic approaches that assess performance loss and recovery duration.

Trucco et al. (2023) introduced resilience metrics such as robustness, measured by operational capacity post-disruption and system load thresholds. They also emphasized redundancy (alternative routes in transportation networks), resourcefulness (speed and efficiency of resource mobilization), rapidity (recovery time and rate), and adaptability (the ability to learn and implement improvements from past disruptions).

Misra et al. (2022) focused on resilience in rail-truck intermodal freight networks. Their key metrics included network functionality, throughput during recovery, and restoration assessment, emphasizing that improving intermodal terminal resilience and highway-railway connections significantly boosts overall system resilience.

Finally, Garrido et al. (2023) highlighted the role of flexibility in resilience, demonstrating that incorporating alternative transport modes, such as multimodal transport, can reduce costs and enhance system adaptability during disruptions.

Section Summary

The literature on freight network resiliency and transportation system resilience metrics highlights the critical importance of understanding and quantifying resilience to improve network performance under disruptions. Studies on freight network resiliency emphasize the use of telematics data, such as GPS, to provide real-time insights into freight movements, enabling more accurate disruption modeling and resilience assessments. Key models like the 8R RESILIENCE framework and assessments of interdependent transit networks underscore the need for robust, adaptable systems that can quickly recover from disruptions.

On the metrics side, researchers have introduced various methods to quantify resilience, focusing on core measures like robustness, redundancy, rapidity, and adaptability. These metrics are crucial for assessing how systems withstand and recover from disruptions, whether through alternative routes, resource allocation, or learning from past disturbances. The integration of telematics data into these resilience models enhances the ability to simulate real-world scenarios, providing a deeper understanding of system vulnerabilities and improving recovery strategies.

Approach

Each of the specific tasks to be performed in the project is described in the following section.

Task 1: Comprehensive Literature Review

The research team began by conducting a thorough review of key studies on transportation network resilience, focusing on both natural and man-made disruptions in the freight sector. The review examined the challenges in freight data collection compared to passenger data, with particular emphasis on the role of telematics, such as EROAD, in modernizing data collection. Special attention was given to freight movements in the Pacific Northwest, with other regions explored as data allowed. The review also covered methodologies for freight data analysis and ethical considerations in the use of telematics data.

Task 2: Data Mining and Analysis

The team analyzed the latest EROAD dataset provided to us by Robinsight, focusing on freight movement patterns across 3 distinct case studies, the Pacific Northwest (specifically Oregon), the I-55 Mississippi River Bridge Closure, and the impacts of Hurricane Florence. Using GIS tools and statistical methods, they identified trends and anomalies, which provided information that can lead to the development of preliminary freight performance measures in phase 2. Visual aids, such as charts and graphs, were created to represent the findings, and a detailed report documented the methodologies, results, and implications.

Task 3: Development of Freight Performance Measures

Building on the findings from Tasks 1 and 2, the team assessed the data to identify its potential use in developing and enhancing existing freight performance measures. The potential identified measures included:

- **Freight Travel Time Reliability:** Using EROAD data to assess how predictably freight moves within the study area. This measure can highlight congested corridors or timeframes.
- **Cross-Jurisdictional Freight Flow:** Utilizing EROAD data to quantify and evaluate freight movements across different jurisdictions within the study area.
- **Freight Carbon Footprint Estimation:** Using EROAD data on freight movement distances and frequencies to estimate environmental impact.
- **Route Preference Index:** A metric that quantifies the frequency or preference of certain routes over others.
- **Route Efficiency Ratio:** Evaluates the time taken or distance traveled on chosen routes relative to the optimal or shortest path.

These measures can provide insights into network resilience and potential infrastructure investments and will be addressed in phase 2.

Task 4: Documentation of Findings

The project concluded with the preparation of two scholarly manuscripts detailing the methodologies and findings. The research outcomes provided valuable insights for state transportation planners, offering new tools to improve freight network resilience and performance.

Methodology

Building on the insights from the literature review, which highlighted the importance of telematics data in understanding freight network resilience, this section outlines the methods used to process and analyze the EROAD dataset to assess freight movements before, during, and after disruptions. The analysis focuses on unpacking visit data, segmenting it into key time periods, and applying spatial tools to visualize changes in traffic patterns. By leveraging advanced data processing techniques and Geographic Information Systems (GIS), we developed a comprehensive approach to evaluate the resilience of freight networks, providing crucial insights into route efficiency, network vulnerabilities, and recovery patterns.

Data processing and Analysis

The goal of Task 2 was to process and analyze the EROAD dataset provided by Robinsight to uncover patterns in freight movements before, during, and after disruptions. The EROAD dataset consisted of three datasets structured with key variables, including:

- **node_ids**: OpenStreetMap (OSM) node IDs identifying specific points on the road network.
- **node_tuple_id**: IDs representing segments between two OSM nodes.
- **way_ids**: OSM way IDs that define the road segments.
- **coordinates**: Start and end coordinates for each road segment.
- **highway**: A designator indicating road type.
- **maxspeed**: The speed limit for each road segment (many entries were NULL).
- **data**: The visit data by date for each node tuple, stored as a compressed string to reduce file size.
- **trip_date**: The date of each recorded trip.
- **visits**: The number of trips on each node tuple, rounded to the nearest 50.

```
Rows: 587,264
Columns: 13
$ node_id1      <chr> "6086322776", "6086322702", "6281992738", "195685964", "7025354953", "1956…
$ node_id2      <chr> "6086322702", "3843894466", "195685964", "7025354953", "195685966", "91563…
$ way_id        <dbl> 130125601, 130125601, 130125611, 130125611, 130125611, 130125611, 13012561…
$ point_1_lon   <dbl> -78.68403, -78.68404, -78.48723, -78.48701, -78.48686, -78.48482, -78.4827…
$ point_1_lat   <dbl> 35.79324, 35.79325, 35.79823, 35.79824, 35.79825, 35.79837, 35.79849, 35.7…
$ point_2_lon   <dbl> -78.68404, -78.68406, -78.48701, -78.48686, -78.48632, -78.48270, -78.4825…
$ point_2_lat   <dbl> 35.79325, 35.79326, 35.79824, 35.79825, 35.79828, 35.79849, 35.79850, 35.7…
$ node_tuple_id <dbl> 7, 8, 3, 4, 5, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 2…
$ highway       <chr> "primary", "primary", "primary", "primary", "primary", "primary", "primary…
$ data          <chr> "trip_date:2018-09-05, visits:50", "trip_date:2018-09-05, visits:50", "tri…
$ direction_for <chr> "NW", "NW", "E", "E", "E", "E", "E", "E", "E", "E", "E", "E", "E", "E", "E…
$ direction_rev <chr> "SE", "SE", "W", "W", "W", "W", "W", "W", "W", "W", "W", "W", "W", "W", "W…
$ geom          <LINESTRING [°]> LINESTRING (-78.68403 35.79..., LINESTRING (-78.68404 35.79...,…
```

Figure 1: EROAD Raw Data Snapshot of Hurricane Florence through North Carolina from September 05, 2018 to September 25, 2018.

The primary focus of the analysis was on unpacking the data column, which contained critical visit information, to analyze freight movement trends across different periods.

Further, the dataset used for this analysis represents an immense volume of data, with over 1.3 million features captured for Oregon, 587,000 for Hurricane Florence in North Carolina, and 464,000 for the I-55 Mississippi River Bridge closure. This wealth of information highlights the vast scale of freight movements tracked through the EROAD system, providing a great level of detail for analyzing disruptions and network resilience. The size and granularity of the data highlights its capacity to reveal critical patterns in freight behavior before, during, and after significant disruptions.
Below is the step-by-step methodology applied for Task 2.

Data Preparation

We began by preparing the EROAD dataset using a custom R function called process_visits() we developed (see appendix). This function was specifically developed to:

1. **Unpack the visit data**: The data column, which was stored as a compressed string, was parsed to separate trip dates and the number of visits per node tuple. Each entry in this column was unpacked into individual records for further analysis.
2. **Extract the trip date and visit information**: The extracted data included:
    - **trip_date**: The date of each recorded freight trip.
    - **visits**: The number of visits to the node tuple on that date.
3. **Data filtering and cleaning**: The visit data was filtered by date to focus on the period of interest for the analysis, which included three distinct phases:
    - **Before**: The time period leading up to a disruption.
    - **During**: The disruption period.
    - **After**: The recovery phase following the disruption.

To facilitate this, the code allowed the selection of a start and end date for each period, ensuring that only relevant data was analyzed. Any missing or incomplete data was excluded to maintain the integrity of the analysis.

Data Segmentation

Once the data was cleaned, it was segmented into three periods for analysis:

1. **Before period**: This covered freight movements prior to the disruption.
2. **During period**: This examined freight movements during the disruption.
3. **After period**: This explored the recovery phase, where the system returned to normal operation.

The segmentation was critical to understand how the freight network responded to disruptions and to identify key changes in traffic patterns. This would provide opportunities in phase two in the potential development of Freight Travel Time Reliability.

Aggregation and Summarization

After the data was segmented into periods, we aggregated the number of visits (freight trips) by node tuple and road segment (way_id) for each of the three periods. This aggregation allowed us to quantify the total freight activity during each phase of the disruption.
The R function calculated the following:

- **Total visits per node tuple** for each time period (before, during, and after).
- **Sum of visits** to highlight the intensity of freight traffic through specific segments.

This aggregation step has the potential to provide the basis for generating performance measures related to network usage and resilience during disruptions.

Spatial Analysis

Using **Geographic Information Systems (GIS)** tools (specifically QGIS[2]) , the summarized visit data was joined back to the original spatial dataset. This step allowed us to spatially map freight movements on the road network. Key GIS steps included:

- **Joining aggregated data**: The aggregated visit data was joined to the road network's geometry based on node_tuple_id and way_id.
- **Mapping freight movement density**: The freight movement density was visualized on a map, where line thickness and color intensity represented the volume of freight traffic on specific road segments. This provided a clear visual representation of how freight flows changed over time and space (see results and discussion)

We produced maps that illustrated:

- **Before the disruption**: Normal freight traffic patterns.
- **During the disruption**: Disruption-induced traffic changes and route shifts.
- **After the disruption**: Recovery and return to normal traffic flow.

Identifying Patterns and Trends

By comparing the maps and aggregated visit data, the research team identified key patterns and trends, including:

- **Shifts in freight routes**: Changes in route preference and the use of alternative routes during disruptions.
- **Changes in traffic density**: Increased or decreased traffic on specific road segments, indicating network bottlenecks or underutilized links.
- **Resilience indicators**: Insights into how quickly certain routes or areas recovered after disruptions, providing a measure of the network's resilience.

Reporting and Visualization

To effectively communicate the findings, several visualization tools were employed:

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[2] QGIS is an open-source geographic information system (GIS) software used for spatial data visualization, analysis, and management (https://qgis.org/)

- **Charts and graphs**: These were used to show the overall trends in visit data, illustrating the total number of visits before, during, and after disruptions.
- **Heatmaps and density maps**: Visual aids that highlighted high-traffic areas and key disruptions across the network.

A detailed report was generated at the conclusion of this task, documenting:

- **Methodologies**: A full description of the data processing and analysis steps.
- **Findings**: The identified patterns and trends in freight movement, including areas of high traffic volume, route shifts, and bottlenecks.
- **Implications**: Insights into network resilience and opportunities for improving infrastructure to better accommodate freight traffic during future disruptions.

Section Summary

The methodology employed in this study focused on processing and analyzing the EROAD dataset to assess freight movements before, during, and after significant disruptions. The dataset, which includes detailed trip information such as node IDs, way IDs, coordinates, trip dates, and the number of visits per road segment, was segmented into three key periods: before the disruption, during the disruption, and after the disruption. By using a custom R function, the data was filtered, cleaned, and unpacked to extract valuable information about freight movements across various road segments. This process allowed for the aggregation of visits to quantify freight activity during each phase, laying the groundwork for evaluating route efficiency and network resilience.

Additionally, Geographic Information Systems (GIS) were used to map freight movement density, providing visual representations of how traffic patterns shifted during disruptions. The spatial analysis enabled the identification of critical trends, including shifts in freight routes, changes in traffic density, and the resilience of specific road segments during and after disruptions. The methodology also included creating visual aids such as heatmaps and charts to effectively communicate the patterns and trends in freight movement. These findings are essential for understanding how freight networks adapt and recover from disruptions, and they offer insights that can guide infrastructure improvements and enhance decision-making processes for transportation planners.

Findings

Data documentation

This section provides an overview of the EROAD dataset used to analyze freight movements during significant events, including the Oregon Forest Fires of 2020, Hurricane Florence in North Carolina (2018), and the I-55 Mississippi River Bridge closure in Tennessee (2024). The EROAD dataset includes detailed information on freight traffic, such as node_ids (representing specific points on the road network), way_ids (identifying road segments), trip_date, and visits (the number of trips per road segment). Although, due to budget limitations, we were only able to obtain one to two months of data for each case study, the data received was sufficient to assess the viability of this dataset for analyzing the impact of such disruptions. These variables allowed for an in-depth analysis of how freight routes were impacted and adapted during and after these events. Each case study offers a unique perspective on the resilience of transportation networks under various stressors, whether natural disasters or infrastructure maintenance.

Oregon Forest Fires of 2020

The EROAD dataset used in this study provides a comprehensive view of freight movements across Oregon, focusing on the period surrounding the 2020 wildfires. This dataset includes key variables such as node_ids, which represent specific points on the road network, and way_ids, which correspond to road segments between these points. Additionally, it contains trip_date, marking when trips occurred, and visits, which quantify the number of trips over specific road segments. The dataset is particularly valuable for its granularity, capturing vehicle movements across major highways impacted by the wildfires, including Highway 22 (near the Santiam Fire), Highway 126 (Holiday Farm Fire), Highway 224 (Riverside Fire), and portions of Interstate 5, which experienced significant disruptions due to closures in September and October 2020. The following figure illustrates the raw dataset for the impacted freight routes in the state of Oregon.

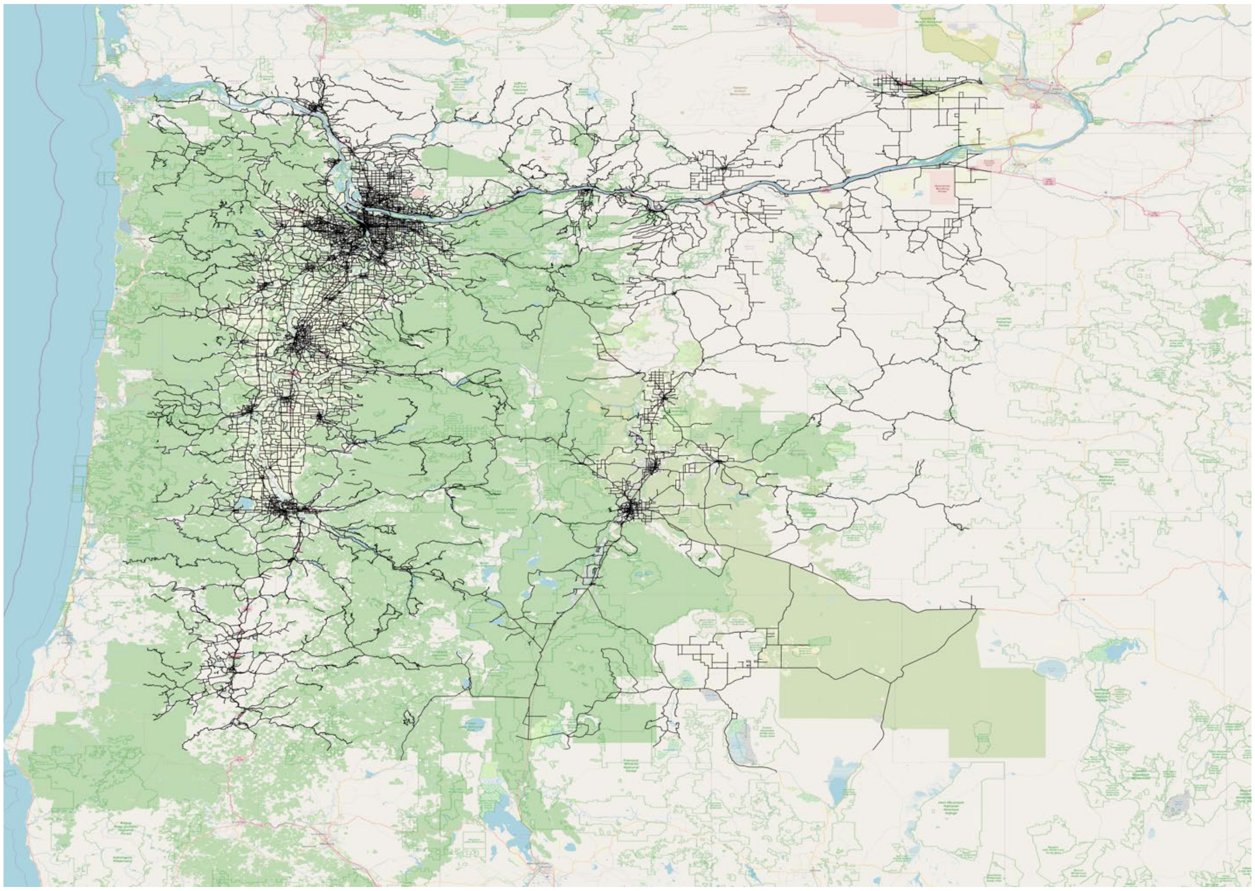

Figure 2: EROAD Raw data of the Oregon Forest Fires from September 28, 2020 to November 2, 2020

During the Oregon wildfires, many major highways were closed due to fire damage, high winds, and safety concerns, impacting both passenger and freight traffic. The closures began on September 7, 2020, and continued into late October, with phased reopenings as fire containment efforts progressed. By analyzing the trip data in the EROAD dataset, we can track how freight traffic was rerouted or delayed during these closures and measure the network's recovery in the following weeks. The data allows for the segmentation of trips into critical periods: pre-disruption, during the wildfire-related road closures, and the post-disruption recovery phase. This segmentation enables the identification of key trends in freight traffic patterns, highlighting which routes were most affected, how quickly traffic returned to normal levels, and the overall resilience of Oregon's transportation network during this natural disaster. The detailed trip data provides essential insights into freight mobility during the wildfires, offering a case study for understanding the impacts of large-scale disruptions on supply chains and infrastructure.

Hurricane Florence

In addition to the Oregon Data, here also the EROAD dataset used for this analysis focuses on freight movements in North Carolina during and after Hurricane Florence in September 2018. The dataset provides detailed trip and visit data for vehicles traveling across key highways and road segments, including major routes such as Interstate 40 (I-40), Interstate 95 (I-95), and U.S. Highways 17 and 70, all of which were heavily impacted by the storm. The variables in the dataset include node_ids (representing specific points on the road network), way_ids (identifying road segments), trip_date (indicating when trips occurred), and visits (the number of trips along each road segment). This data allows for the tracking of freight movement patterns before, during, and after the storm, providing critical insights into how Hurricane Florence disrupted the transportation network. The following figure shows the raw dataset for the impacted freight routes in the state of North Carolina.

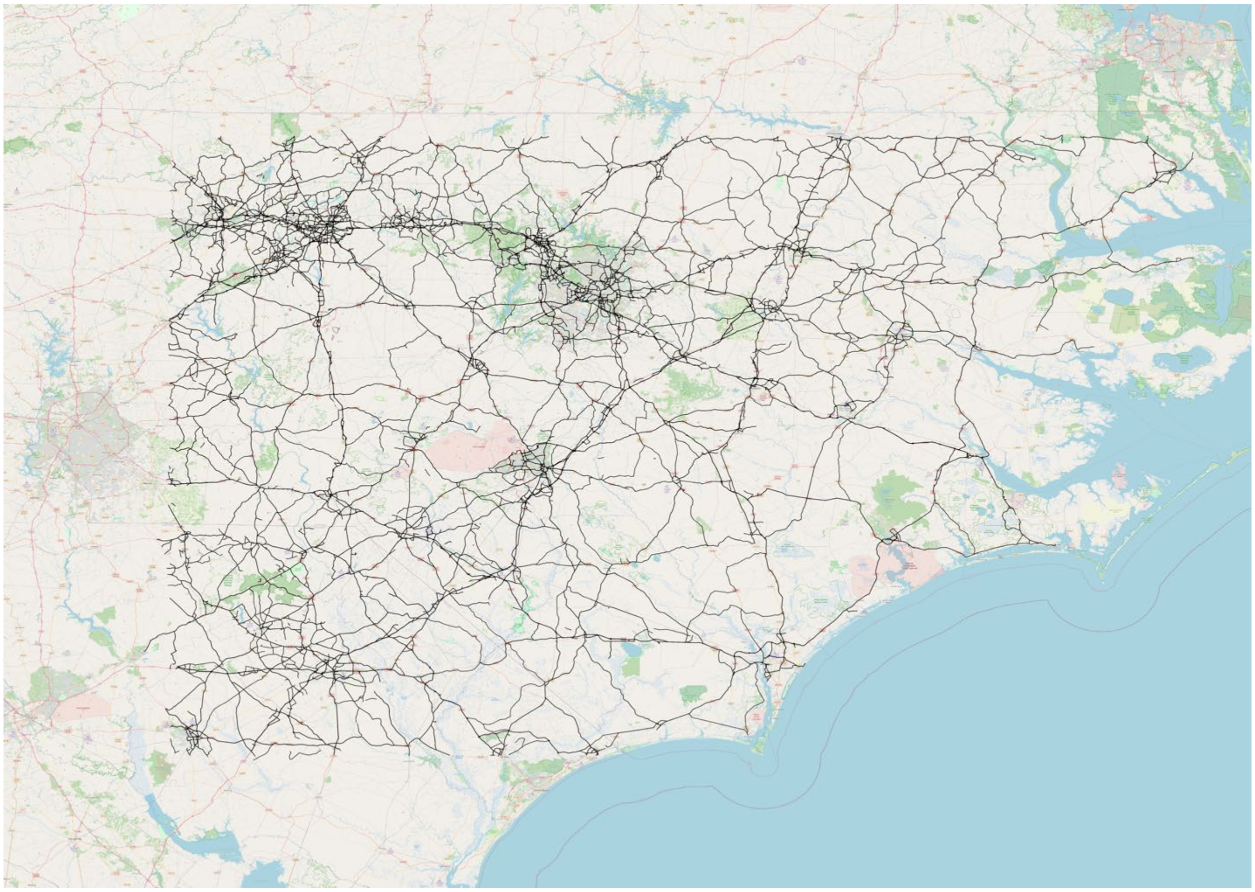

Figure 3: EROAD Raw data of Hurricane Florence Impacts on North Carolina from September 5, 2018 to September 25, 2018

Hurricane Florence, which made landfall on September 14, 2018, brought widespread flooding and road closures across eastern and central North Carolina. Key highways, such as I-40 and I-95, were closed for extended periods due to floodwaters and storm damage, significantly affecting freight routes. The EROAD dataset captures these disruptions in detail, allowing for the analysis of changes in freight traffic flow as roads were closed and reopened. The dataset also enables segmentation of trip data into distinct time periods: pre-storm, during the hurricane-related closures, and the post-recovery phase. This analysis helps to identify the extent of freight traffic rerouting, the resilience of the network, and how quickly freight movements returned to normal. By examining the temporal and spatial distribution of freight trips during this natural disaster, we can assess the network's capacity to withstand and recover from large-scale disruptions.

I-55 Mississippi River Bridge Closure

Although recent, we collected data from EROAD to better understand the impact of the I-55 Mississippi River Bridge closure, which occurred from June 9 to June 23, 2024, as part of construction activities on the I-55 and Crump interchange. The following figure illustrates the routes affected by the closure and its impact on freight networks.

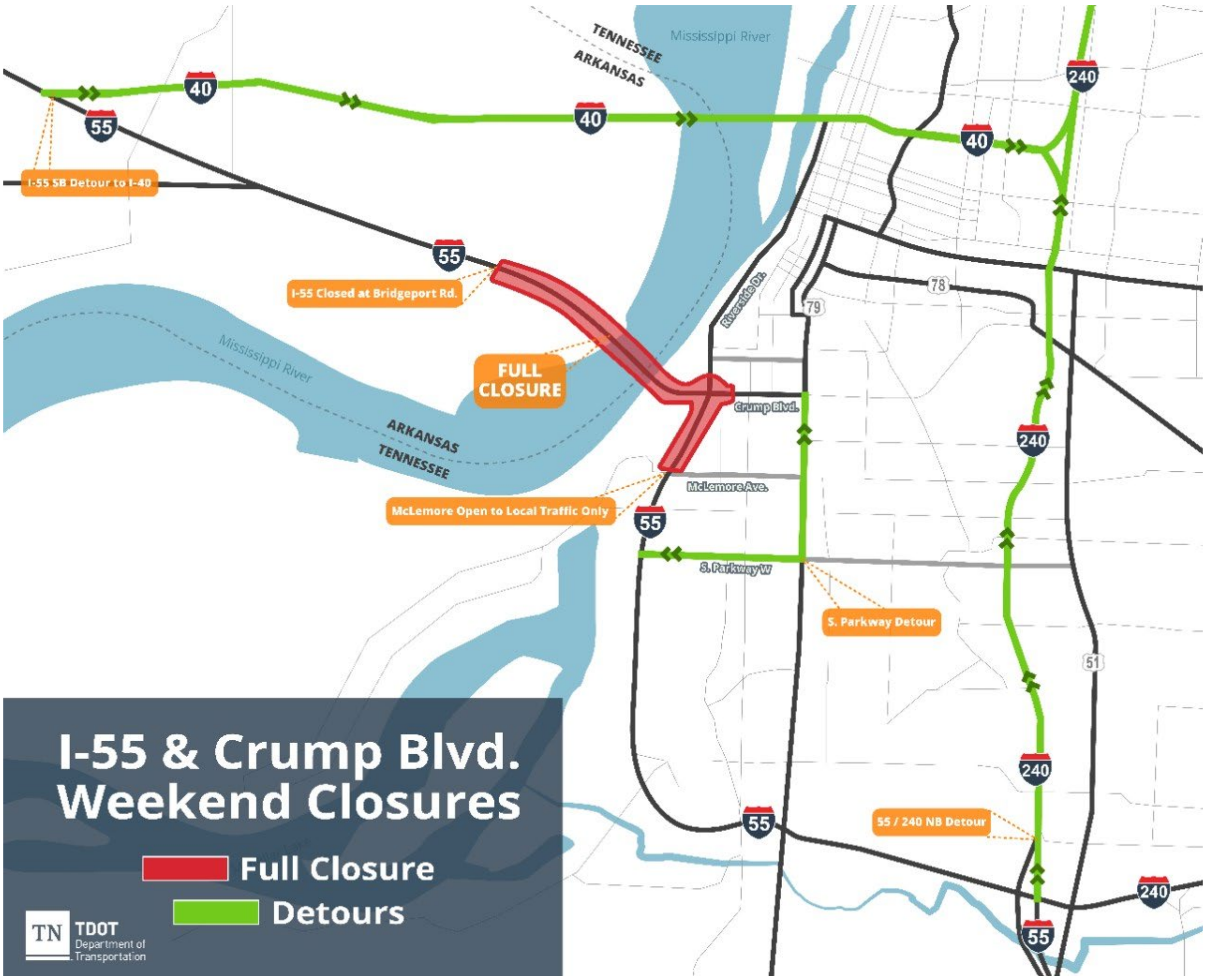

Figure 4: Location of the I-55 Mississippi River Bridge Closure in Tennessee (source: https://www.tn.gov/tdot/news/2024/6/4/i-55-mississippi-river-bridge-closing-for-two-weeks.html)

Moreover the EROAD dataset contains key variables such as node_ids (representing specific points on the road network), way_ids (identifying road segments), trip_date (indicating when trips occurred), and visits (the number of freight trips across each segment). This data allows for the tracking of freight traffic patterns on the I-55 bridge and surrounding roadways before, during, and after the two-week closure. The closure affected both northbound and southbound traffic, with local traffic restrictions and detours in place, impacting freight routes and rerouting patterns. The following figure shows the raw dataset for the impacted freight routes in the state of Tennessee and neighboring Arkansas.

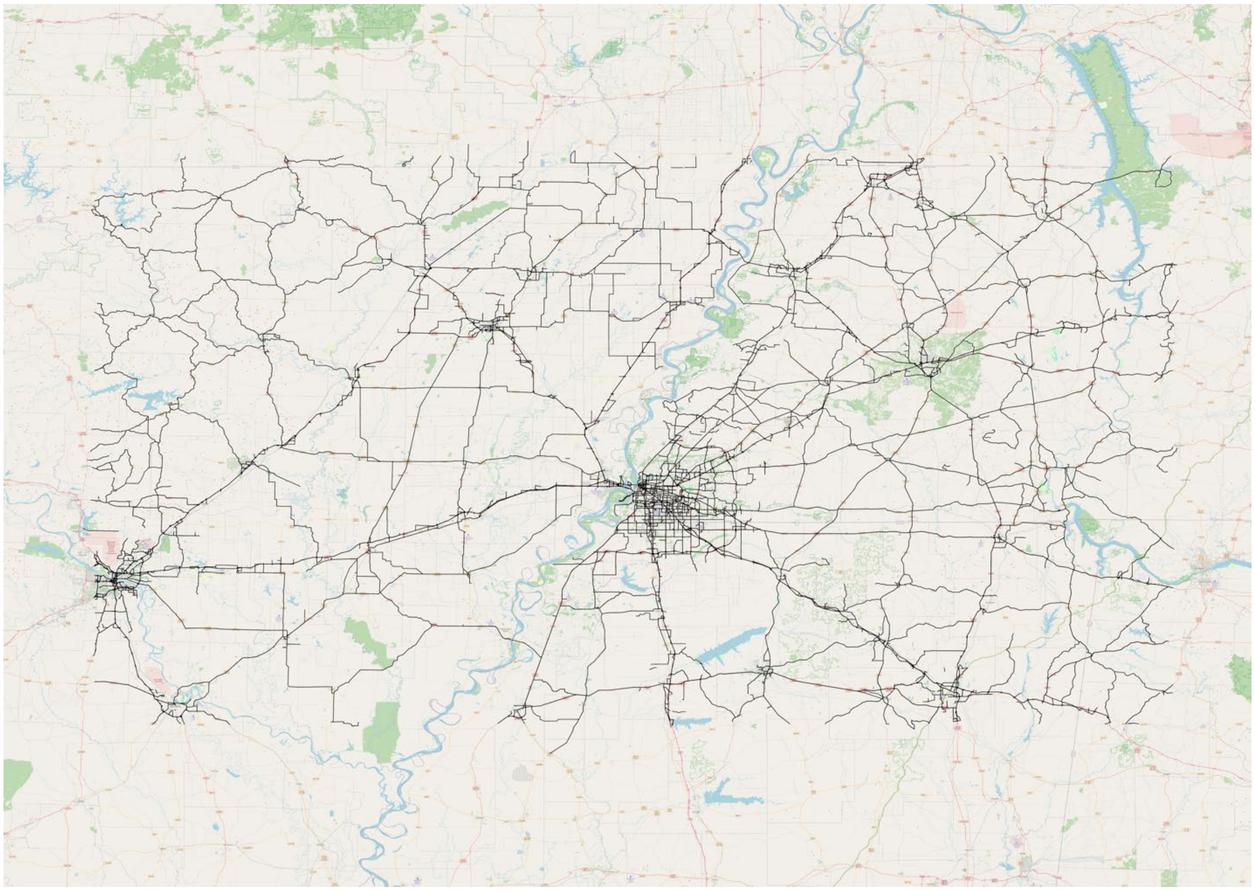

Figure 5: EROAD Raw data of I-55 Mississippi River Bridge Closure from May 26, 2024 to July 7, 2024

The closure of the I-55 Mississippi River Bridge in June 2024 was significant due to the rerouting of freight traffic across alternative bridges and roadways (see Figure 4), notably affecting key corridors for interstate freight. The dataset enables the segmentation of freight trips into pre-closure, during-closure, and post-closure periods, offering insights into how freight routes adapted to the detours. The analysis of this data highlights how the temporary closure influenced traffic volumes on alternative routes, including Bridgeport Road in Arkansas and South Parkway in Tennessee, where detours were posted. By examining the changes in freight patterns, this study aims to evaluate the resilience of the regional freight network during infrastructure-related disruptions and the efficiency of rerouted traffic flows. The data also provides a foundation for understanding the impact of future closures, as this was the first of two planned closures under the TDOT contract.

Section Summary

The EROAD dataset provided valuable insights into how freight movement behaved during significant disruptions, including the Oregon Forest Fires of 2020, Hurricane Florence in 2018, and the I-55 Mississippi River Bridge closure in 2024. By analyzing freight traffic before, during, and after each event, the data revealed important trends in how routes were affected, detours were implemented, and how traffic flows recovered over time. During the Oregon wildfires, the dataset demonstrated how major highways closed due to fire damage impacted freight routes, while freight traffic patterns adjusted to alternate roads. In North Carolina, Hurricane Florence caused widespread road closures due to flooding, particularly affecting critical freight corridors like I-40 and I-95, and the data showed how freight movement adapted to these challenges. The I-55 bridge closure data further illustrated how freight traffic rerouted across alternative paths during the construction period, offering insights into the temporary impact on freight mobility. Overall, the data helped assess the resilience of freight networks, providing a comprehensive visual understanding of how quickly freight movement could return to normal following these disruptions.

Analyses performed

To assess the impact of major disruptions on freight movements, a comprehensive analysis was conducted using the EROAD dataset provided to us by Robinsight. The analysis focused on key events, including the Oregon Forest Fires of 2020, Hurricane Florence in North Carolina (2018), and the I-55 Mississippi River Bridge closure in Tennessee (2024). The dataset, which provided detailed trip and visit data for specific road segments, was processed to track freight movements before, during, and after each disruption. Using custom data processing techniques, the trip data was segmented into distinct time periods and analyzed for trends in traffic rerouting, traffic density changes, and network resilience. Spatial mapping tools were employed to visualize and quantify the impact of road closures and detours on freight traffic, offering a detailed understanding of how freight networks adapted and recovered during these events.

Results

Oregon Case Study

The Oregon forest fires of 2020 had a significant impact on the state’s transportation infrastructure, particularly on freight networks that rely heavily on key highways for the movement of goods. Using the EROAD dataset, we analyzed the freight traffic patterns before, during, and after the fires to assess how freight routes adapted to the disruptions caused by the wildfires. This analysis focuses on how freight traffic shifted across Oregon's highways, the effectiveness of rerouted traffic, and the recovery of the network once the fires were contained. By examining the data in these three distinct phases, we gain insight into the resilience of the freight network and its ability to recover after a major natural disaster.

Before the Fires

Before the Oregon forest fires of 2020, freight routes across the state operated normally, with major highways such as Highway 22, Highway 126, and Interstate 5 experiencing consistent traffic flow. The EROAD data shows that freight traffic was evenly distributed across key roadways, with no significant disruptions. Freight movement patterns indicate that routes through the wildfire-affected areas were heavily utilized, as they are essential for both intra- and interstate commerce. The "before" figure illustrates a network with clear, uninterrupted freight flow, highlighting the importance of these routes for regional supply chains, see the following Figure.

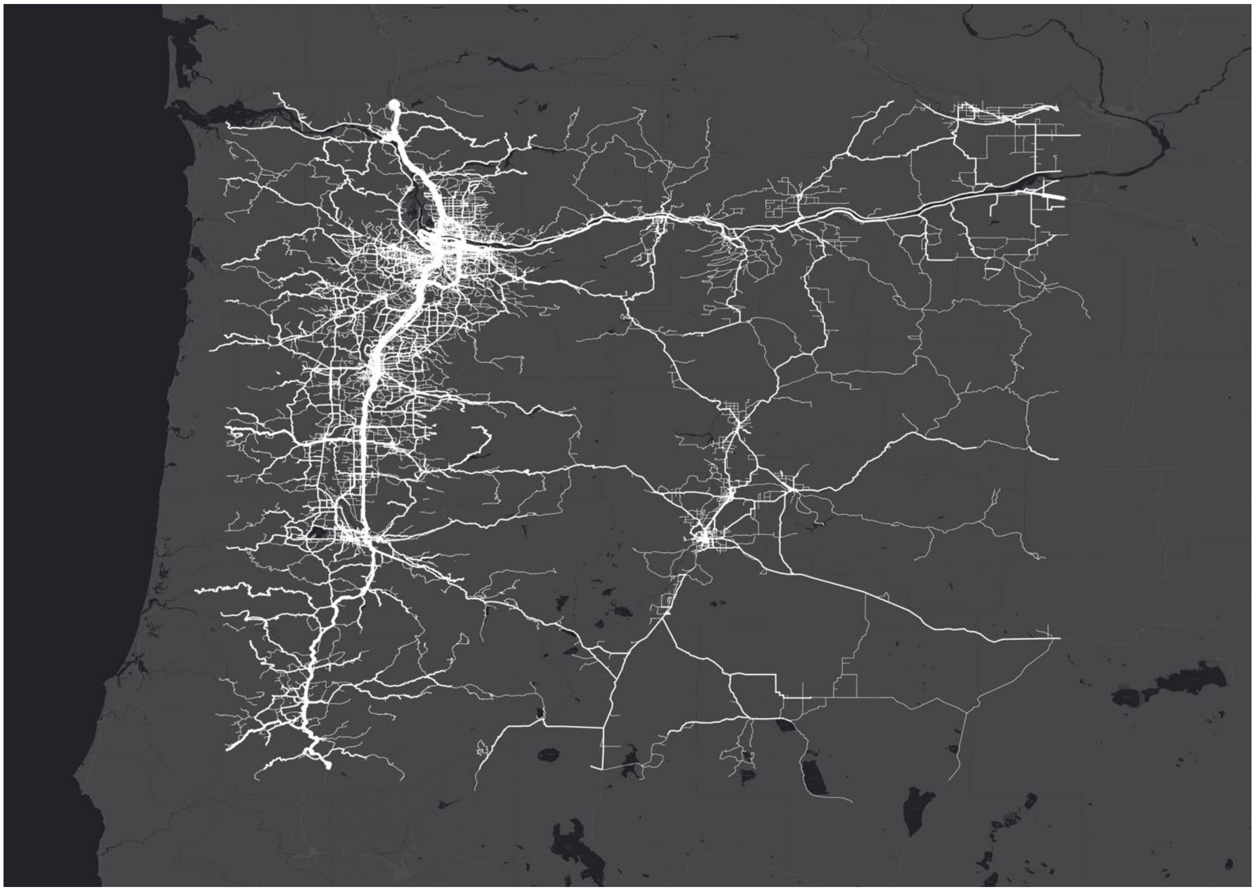

Figure 6: Freight Network Routes Before the Oregon Forest Fires of 2020

During the Fires

During the Oregon forest fires, significant portions of key highways were closed due to fire damage, high winds, and safety concerns. The EROAD data for this period shows dramatic changes in freight movement, with many routes either heavily reduced or entirely blocked. Freight traffic was rerouted to alternative highways, leading to congestion in certain areas. The "during" figure highlights these disruptions, showing reduced density along previously major freight routes and increased traffic in detour areas. This period underscores the immediate impact of natural disasters on freight networks, as trucks were forced to adapt to sudden route closures.

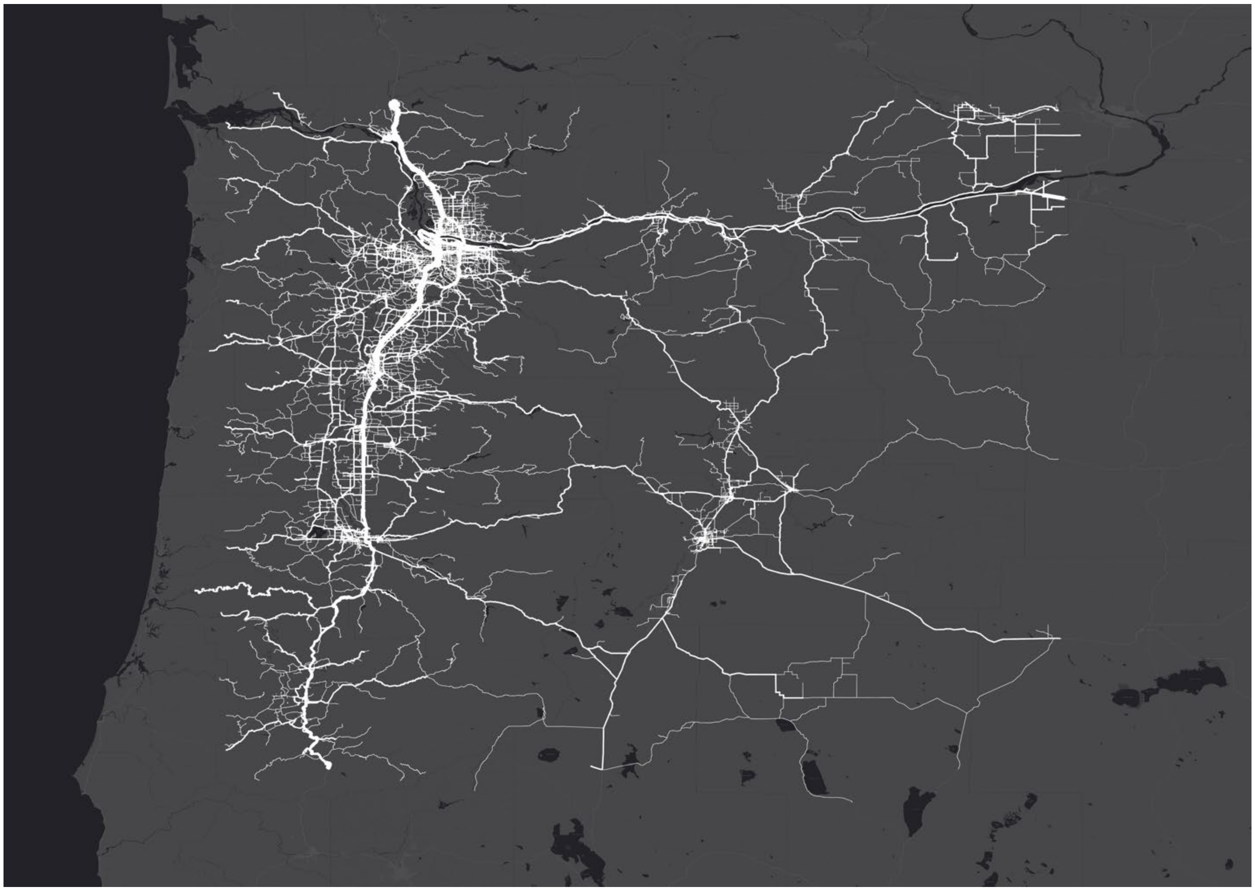

Figure 7: Freight Network Routes During the Oregon Forest Fires of 2020

Moreover, this figure highlights the disruption in key highways such as Highway 22 and Highway 126 experienced dramatic reductions in freight traffic, with alternate routes experiencing increased congestion.

After the Fires

Following the control of the fires, the data reflects a gradual recovery in freight traffic. Although some highways, such as Highway 22 and Highway 126, were reopened, the return to normal traffic levels was slow due to ongoing repair efforts and safety inspections. The "after" figure demonstrates a partial recovery in freight flow, with some routes returning to pre-disruption levels, while others remain underutilized due to lingering road damage or continued restrictions. Freight movement started to stabilize, but the network was not fully restored to its original state immediately after the fires were extinguished.

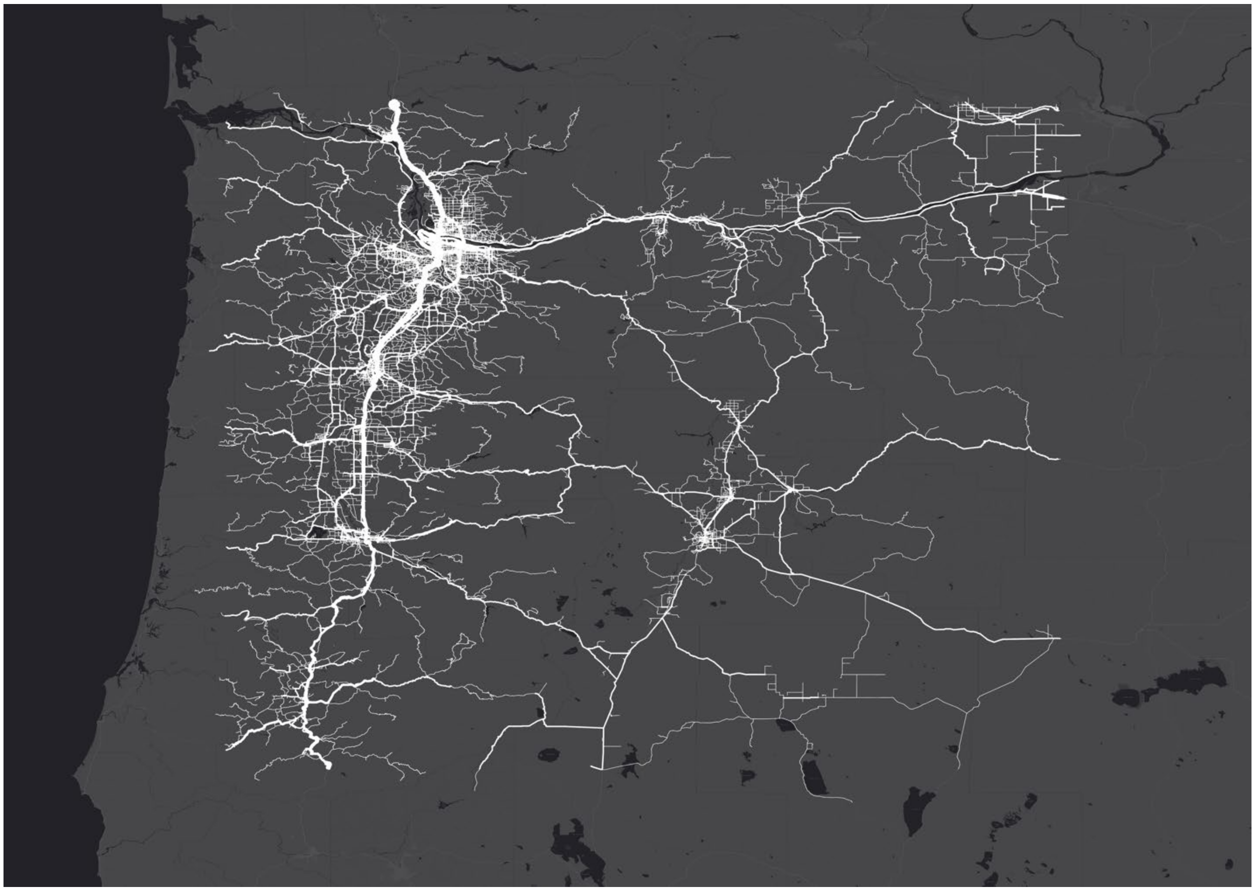

Figure 8: Freight Network Routes After the Oregon Forest Fires of 2020

Summary Comparison

Comparing the three periods of before, during, and after the Oregon forest fires reveals significant changes in the freight network. Before the fires, freight traffic moved smoothly, relying on the state's major highways. During the fires, closures of critical routes forced widespread rerouting, which led to congestion and reduced efficiency in freight movements. After the fires, although traffic began to recover, some routes remained disrupted, which affected the speed and volume of freight returning to normal levels. This analysis highlights the resilience of the freight network and the adaptability of freight companies in responding to disruptions. It also emphasizes the lasting effects that natural disasters can have on transportation infrastructure and supply chain reliability.

I-55 Mississippi River Bridge Closure—Tennessee

The I-55 Mississippi River Bridge, a vital transportation corridor connecting Tennessee and Arkansas, was closed from June 9 to June 23, 2024, for construction and maintenance work. This closure significantly disrupted freight traffic, requiring rerouting through alternative bridges and highways. Using the EROAD dataset, we analyzed freight movement patterns before, during, and after the closure to assess the impact on the network and the recovery process. By examining freight traffic flow across these three time periods, this analysis provides key insights into the resilience of the freight network and how it adapted to the temporary loss of a critical route for interstate commerce.

Before the Closure

Before the I-55 Mississippi River Bridge closure in June 2024, freight traffic flowed smoothly across the bridge, which serves as a critical interstate freight route connecting Tennessee and Arkansas. The "before" figure illustrates normal traffic patterns, showing consistent freight movements along I-55, with both northbound and southbound lanes handling substantial freight volumes. There were no significant disruptions, and the bridge played a key role in regional freight transportation, providing a direct connection over the Mississippi River for interstate commerce.

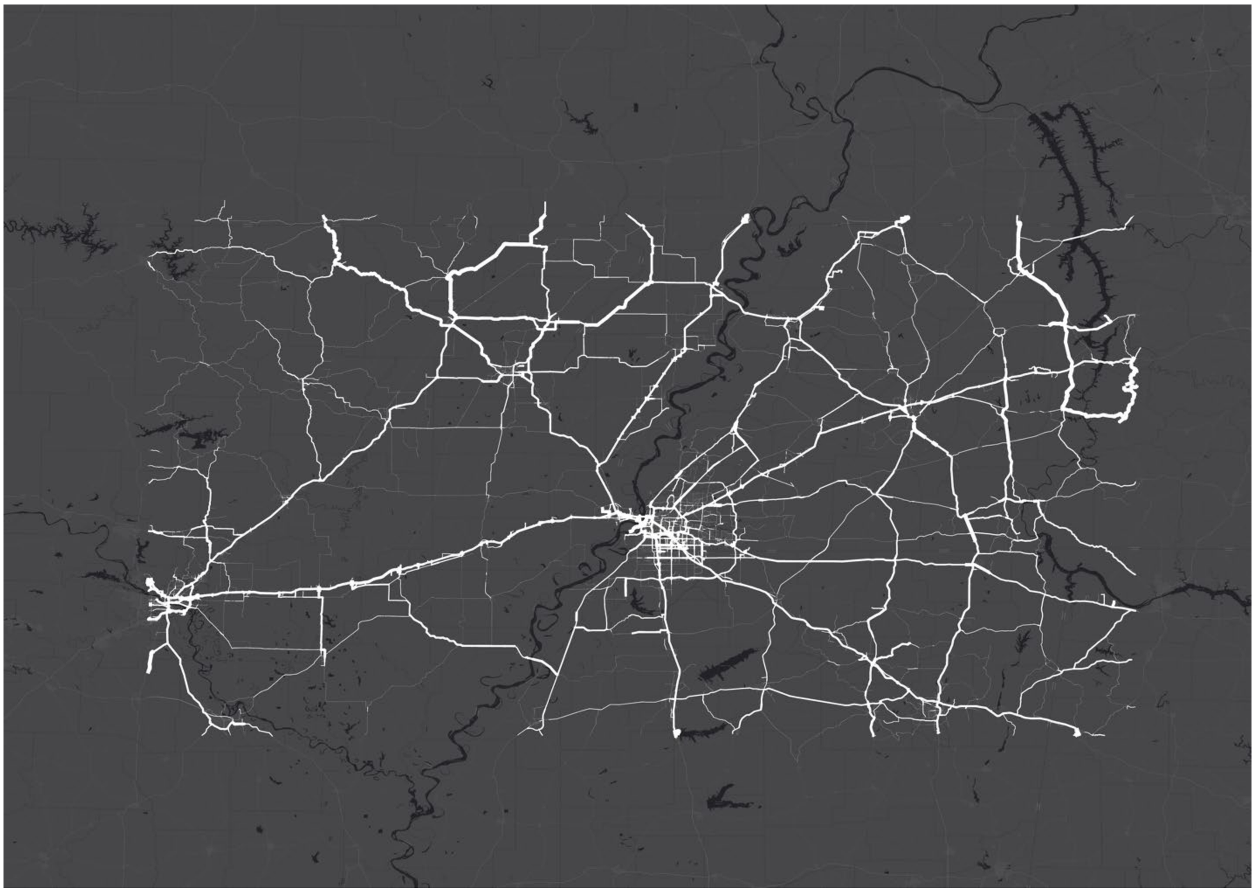

Figure 9: Freight Network Routes Before the I-55 Mississippi River Bridge Closure

Figure 10: Zoomed-In View of Freight Network Routes Before the I-55 Mississippi River Bridge Closure

During the Closure

During the closure from June 9 to June 23, 2024, significant disruptions occurred as both the northbound and southbound lanes of the I-55 bridge were closed to facilitate construction work. Freight traffic had to be rerouted to alternative bridges and highways, causing congestion on detour routes such as Bridgeport Road in Arkansas and South Parkway in Tennessee. The "during" figure highlights the reduction of traffic on the I-55 bridge and the increased density of freight traffic on nearby alternative routes, illustrating the immediate impact of the closure on freight movements. Detour routes became congested as rerouted traffic attempted to navigate around the closed bridge, leading to delays and longer travel times for freight carriers.

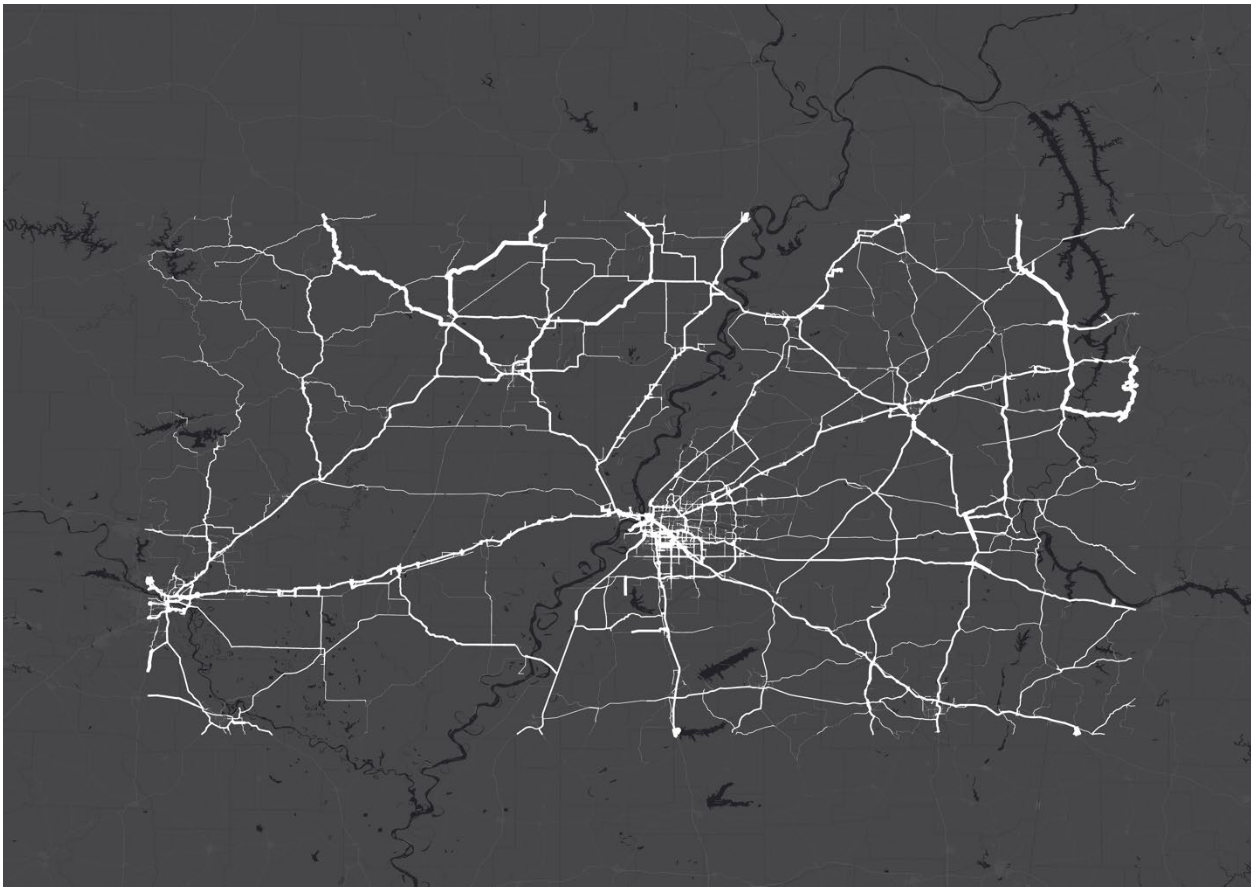

Figure 11: Freight Network Routes During the I-55 Mississippi River Bridge Closure

Figure 12: Zoomed-In View of Freight Network Routes During the I-55 Mississippi River Bridge Closure

After the Closure

Following the reopening of the I-55 bridge on June 23, 2024, freight traffic gradually returned to normal levels. The "after" figure shows the recovery of traffic flow across the bridge, with both northbound and southbound lanes restored to full capacity. However, the data also reveals that the return to pre-closure traffic levels was not immediate, as some freight traffic continued to utilize detour routes until the full recovery of normal traffic patterns. This reflects the time required for freight carriers to adjust back to their regular routes following the disruption.

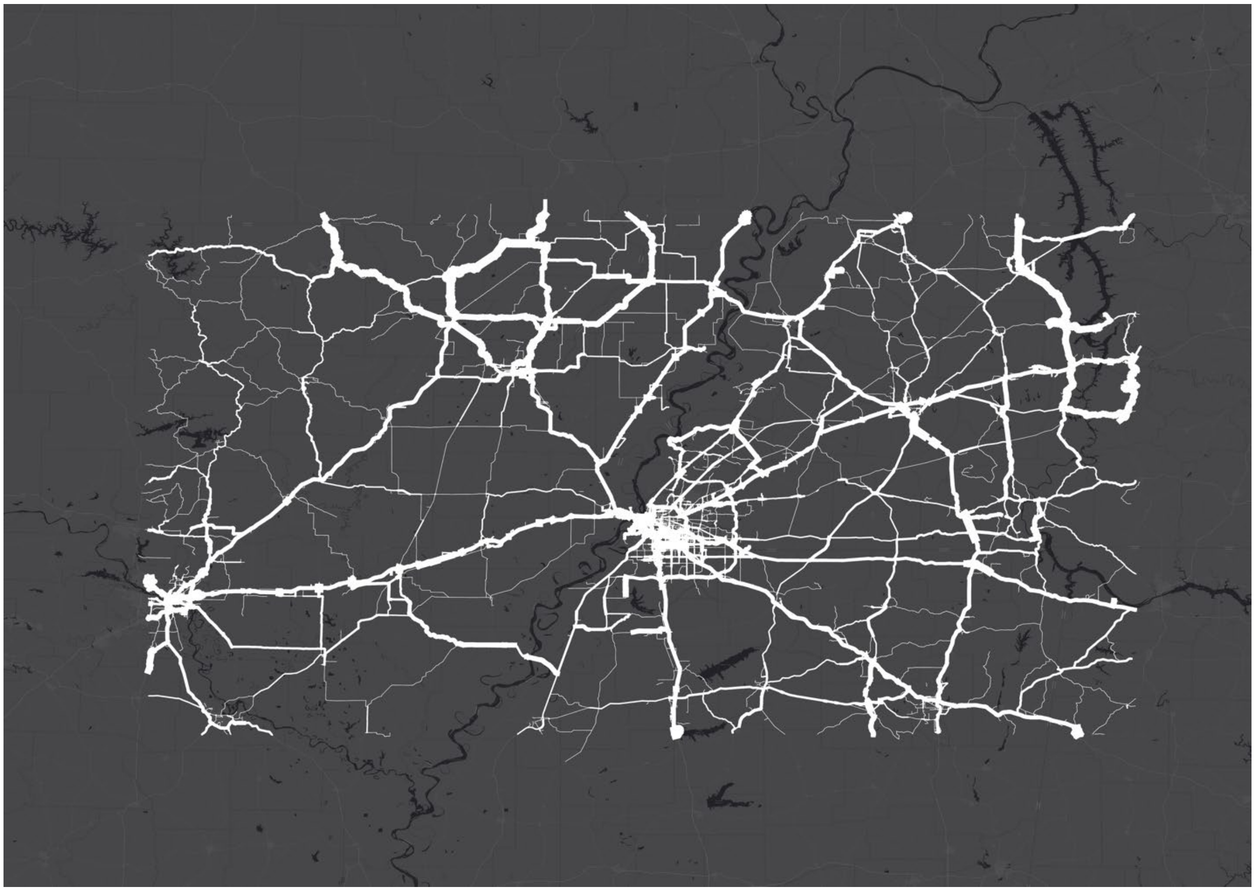

Figure 13: Freight Network Routes After the I-55 Mississippi River Bridge Closure

Figure 14: Zoomed-In View of Freight Network Routes After the I-55 Mississippi River Bridge Closure

Summary Comparison

Comparing the freight traffic patterns before, during, and after the I-55 Mississippi River Bridge closure reveals significant disruptions and adaptations within the freight network. Before the closure, the bridge facilitated a smooth flow of interstate freight traffic. During the closure, freight traffic was forced to reroute through alternate paths (see Figure 4), leading to congestion and delays on nearby highways. After the bridge reopened, freight traffic slowly returned to normal, though it took time for all routes to fully recover. This analysis emphasizes the importance of the I-55 bridge as a critical freight corridor and highlights the challenges faced by freight networks in adapting to infrastructure-related disruptions.

Hurricane Florence in North Carolina

Hurricane Florence, which made landfall in September 2018, caused widespread flooding and significant disruptions to North Carolina's transportation infrastructure, particularly affecting major freight routes such as Interstate 40, Interstate 95, and U.S. Highways 17 and 70. Using the EROAD dataset, this analysis examines how freight movements were impacted before, during, and after the storm. The study focuses on the adaptability of the freight network during the road closures and detours caused by flooding and highlights the gradual recovery of freight traffic in the aftermath. By analyzing freight patterns across these three stages, this report provides insights into the resilience of North Carolina's freight network and its response to extreme weather events.

Before the Storm

Prior to Hurricane Florence making landfall in September 2018, freight traffic in North Carolina flowed as expected, particularly along major freight routes such as Interstate 40 (I-40) and Interstate 95 (I-95). These highways are critical for moving goods across the state and the eastern seaboard. The "before" figure shows smooth freight movements along these key corridors, with no significant disruptions. Freight traffic density is evenly distributed across the state, illustrating the importance of these highways for interstate commerce.

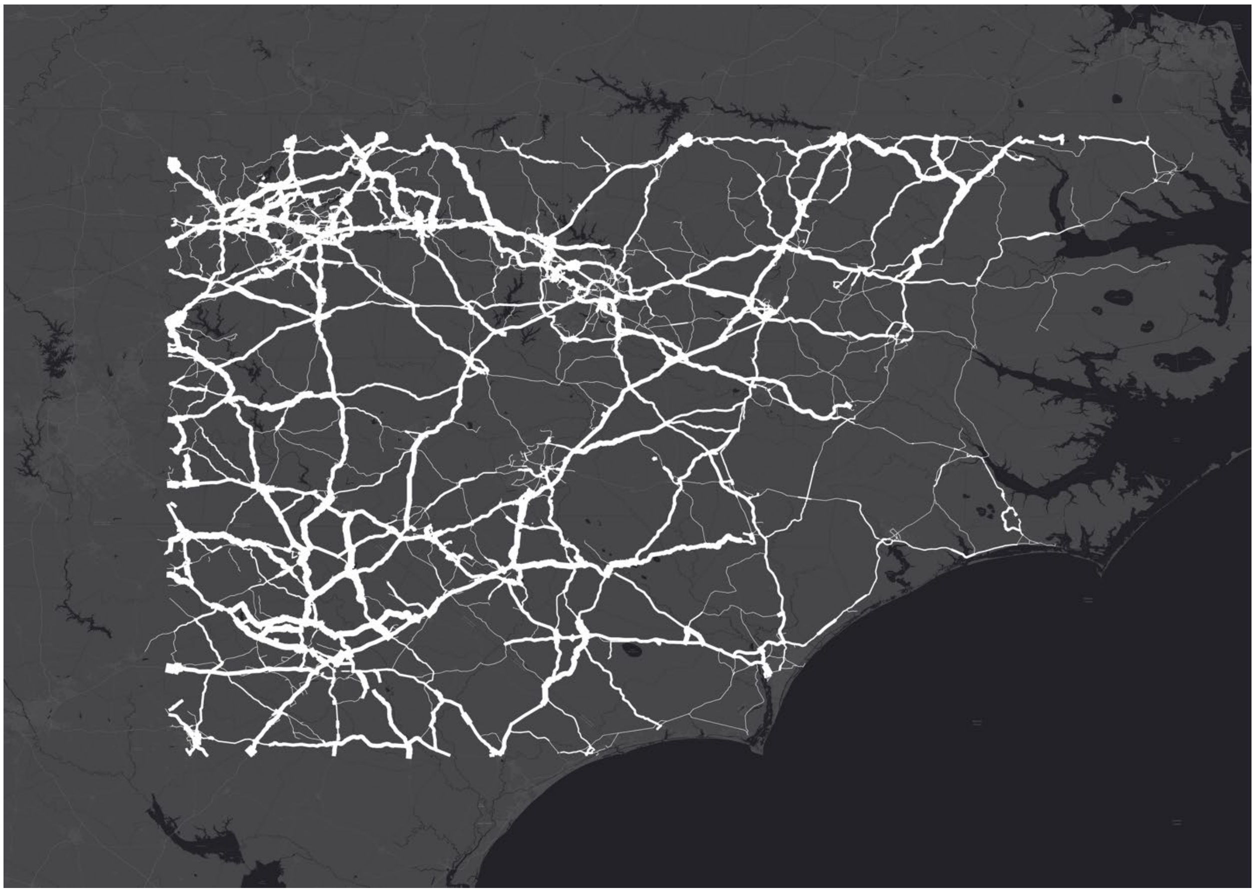

Figure 15: Freight Network Routes Before Hurricane Florence in North Carolina

During the Storm

As Hurricane Florence hit North Carolina in mid-September 2018, widespread flooding led to the closure of several major highways, including I-40, I-95, and U.S. Highways 17 and 70. The "during" figure highlights the severe impact of the storm on freight routes, showing significantly reduced traffic on the affected highways due to closures. Freight traffic was rerouted to higher ground and less flood-prone areas, resulting in congestion on alternative routes. This disruption illustrates the vulnerability of North Carolina's freight network to extreme weather events, as the storm temporarily crippled key transportation corridors.

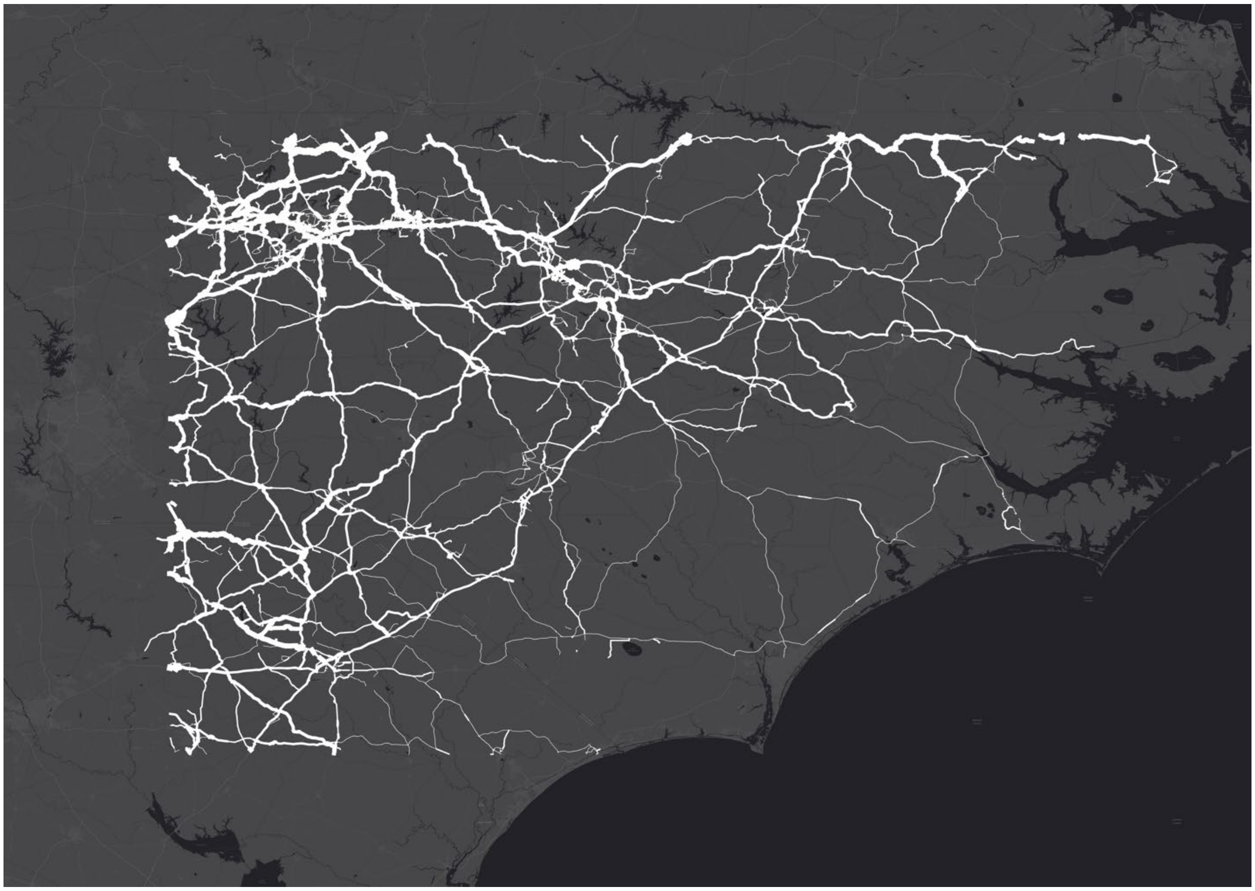

Figure 16: Freight Network Routes During Hurricane Florence in North Carolina

After the Storm

In the weeks following Hurricane Florence, as floodwaters receded and road repairs were completed, freight traffic began to return to normal. The "after" figure shows a gradual recovery in freight movement along I-40, I-95, and other impacted highways. While traffic levels were slowly restored, some areas continued to experience reduced freight flow due to lingering road closures and ongoing repairs. The post-storm recovery period underscores the resilience of the network, but it also highlights the long-term effects of natural disasters on freight transportation, as full recovery took time.

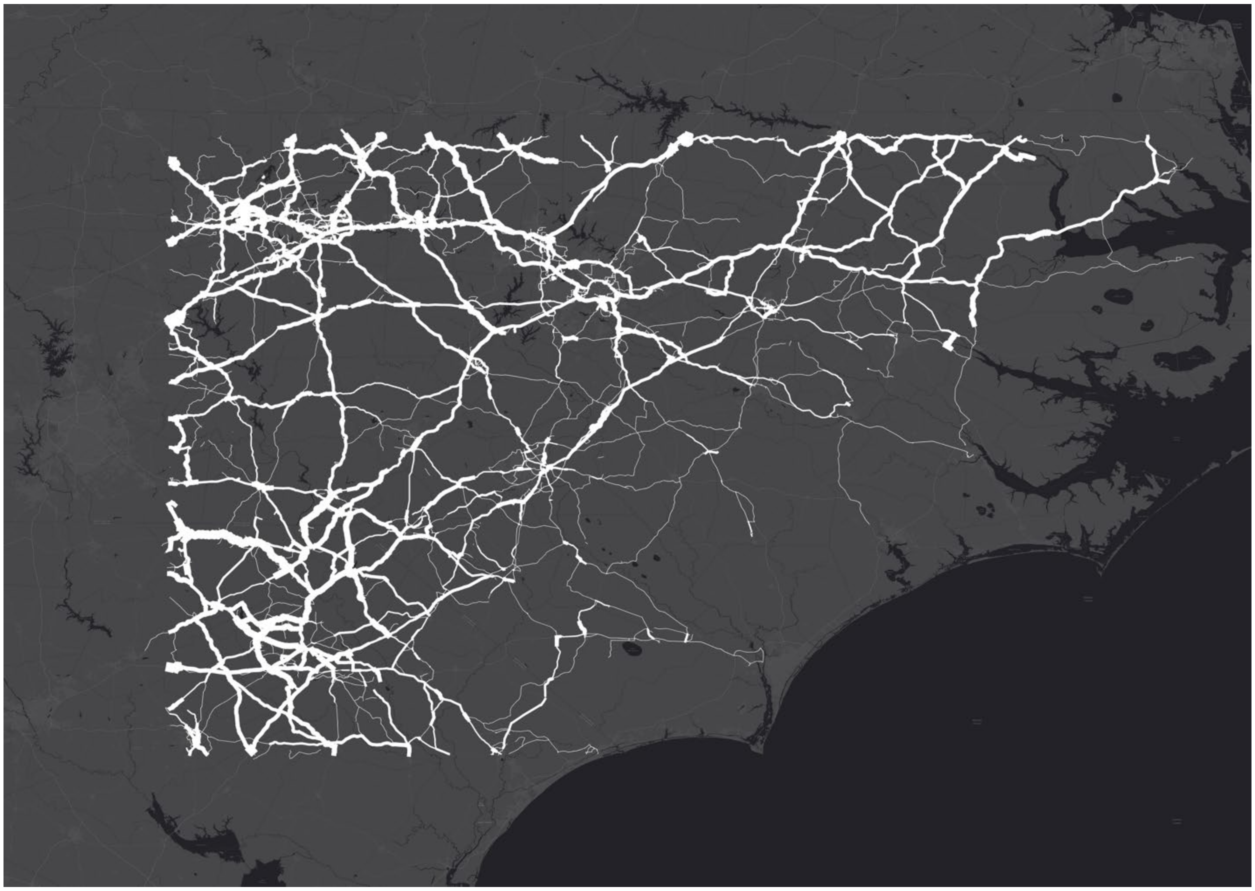

Figure 17: Freight Network Routes After Hurricane Florence in North Carolina

Summary Comparison

Comparing the freight network before, during, and after Hurricane Florence reveals significant disruptions to key freight corridors in North Carolina. Before the storm, major highways such as I-40 and I-95 supported consistent freight traffic. During the storm, widespread flooding forced road closures, which led to rerouting of freight traffic and congestion on alternative routes. After the storm, freight traffic gradually returned to normal, but the recovery process was slow, with some highways remaining partially closed for weeks. This analysis highlights the critical role of these highways in interstate commerce and the challenges posed by natural disasters to freight networks, emphasizing the need for resilient infrastructure capable of withstanding extreme weather events.

Section Summary

The analysis of the Oregon forest fires, the I-55 Mississippi River Bridge closure, and Hurricane Florence in North Carolina reveals key insights into how freight networks respond to significant disruptions. In Oregon, prior to the fires, freight traffic flowed normally, but during the wildfires, major highway closures led to widespread rerouting, causing congestion and delays on alternative routes. After the fires, although some routes reopened, the recovery of freight traffic was slow due to ongoing road repairs and lingering damage. The I-55 bridge closure showed similar patterns, with freight traffic operating smoothly before the closure, then rerouting during the construction period, leading to delays on detour routes. Once the bridge reopened, traffic gradually returned to normal, though it took time for freight carriers to fully revert to their regular routes.

Hurricane Florence in North Carolina caused widespread flooding, forcing the closure of key freight corridors like I-40 and I-95. During the storm, freight traffic was severely disrupted, with rerouting to less flood-prone areas, causing congestion on alternative routes. After the storm, the recovery of freight traffic was gradual, as some roads remained closed for weeks. These case studies collectively highlight the adaptability of freight networks in the face of natural disasters and infrastructure disruptions, but they also highlight the long-lasting impacts on transportation systems and supply chain reliability. The findings emphasize the importance of investing in resilient infrastructure to mitigate the effects of future disruptions and ensure smoother recovery processes.

Technical Transfer and Commercialization

Presentations & Publications

As far as presentation and publication, a portion of this work was presented at the FERSC Annual Research & Engagement Conference at Texas A&M University in April 2024. An abstract will be submitted to ASCE's International Conference on Transportation and Development to be held in Glendale, Arizona June 8th to the 11th of 2025. We will prepare a manuscript for submission for the ASCE conference Proceedings.

Community Engagement

No community engagement efforts until this point.

Other relevant efforts

In support of FERSC workforce development goals, a graduate student has been part of the research team performing tasks related to the objectives of the project.

Conclusions

This study has provided an investigation of freight network resilience using telematics data from the EROAD dataset provided to us by Robinsight. By focusing on three case studies—the Oregon Forest Fires of 2020, Hurricane Florence in North Carolina, and the I-55 Mississippi River Bridge closure in Tennessee—we were able to assess how freight networks behaved before, during, and after significant disruptions. Each case study revealed certain effects that natural disasters and infrastructure maintenance can have on freight routes, and how these networks adapt and recover over time. The use of telematics data was highly beneficial for identifying changes in freight movement patterns, rerouting, and network recovery across different geographic regions and events.

A major finding of this research is the value of real-time and historical telematics data in measuring freight network resilience. The EROAD data allowed for detailed segmentation of freight movements, offering a unique view into how crucial highways were affected during disruptive events and how freight carriers adapted to the temporary loss of major routes. In the Oregon and Hurricane Florence case studies, widespread road closures led to significant rerouting and congestion on alternative routes, while in the I-55 bridge closure case, freight traffic was forced to navigate around critical interstate connections, highlighting the dependence on a few key corridors for freight mobility. These disruptions not only affected local transportation but also had broader regional and interstate implications for the freight supply chain.

The ability to track and analyze freight movements during and after such events provides transportation agencies with essential insights into the resilience of their networks. By identifying bottlenecks and areas where recovery was slow, agencies can prioritize future infrastructure investments to improve network performance during similar events. Additionally, the use of telematics data provides a new way to develop more precise and actionable freight resilience metrics, such as travel time reliability, route efficiency, and cross-jurisdictional flow which is the focus of year 2 of this work (See Recommendations). These metrics can serve as tools for state planners to evaluate the vulnerability of critical freight corridors and plan for future disruptions, ensuring that goods continue to move efficiently even in the face of adversity.

In conclusion, this research demonstrates the potential of telematics data to better understand freight transportation resilience. By integrating advanced data processing and spatial analysis techniques, we were able to provide a clearer understanding of how freight networks respond to both natural and man-made disruptions. The insights gained from this study underscore the importance of building more resilient transportation systems, capable of withstanding the challenges posed by climate change, infrastructure aging, and evolving economic demands. Moving forward, the continued use of telematics data will be essential in supporting smarter, more data-driven decisions for transportation infrastructure planning, ensuring that freight networks remain robust and adaptable in an increasingly complex world.

Recommendations

In the upcoming phase of this project, we will expand upon the findings from the first year to better quantify the impact of freight disruptions across diverse case studies. The focus will be on further refining the methodologies developed in the first phase to assess network resilience with greater accuracy, building on the insights gained from the Oregon Forest Fires, the I-55 Mississippi River Bridge closure, and Hurricane Florence case studies. The use of telematics data has already demonstrated its potential in assessing disruption impacts, and further analysis will provide transportation agencies with more detailed and reliable tools for decision-making.

During the second year, one key objective will be the integration of additional datasets, such as crowdsourced and publicly available data, to supplement the telematics data obtained from EROAD. This will allow for a more comprehensive analysis of freight movements during disruptions. Specifically, we will focus on testing new disruption scenarios (we are currently working with Robinsight to collect data on Hurricanes Helene and Milton), developing enhanced freight performance measures, and simulating the impact of future closures or natural disasters on freight networks. By expanding the range of data sources and refining performance measures, we aim to develop a more flexible and scalable framework for analyzing freight network resilience under a variety of conditions.

The research will focus on developing and validating freight performance measures and testing them across different case studies and disruption types. This will help ensure their relevance and applicability in various contexts. Additionally, we will consider expanding the geographic scope of the study, applying the methodologies to other regions and states to assess the potential scalability of the tools developed.

To assist state transportation planners in their decision-making, we will provide recommendations based on the refined performance measures and scenario analyses. These recommendations will help guide infrastructure investments and identify key areas for improvement, particularly in enhancing network resilience to natural disasters and infrastructure disruptions.

Section Summary

In summary, Phase 2 of this project will build upon the foundational work from Phase 1 to further refine the methodologies used to assess freight network resilience. By integrating additional datasets and testing new scenarios, we aim to enhance the accuracy and applicability of the tools developed. The outcomes of this research will provide state transportation agencies with practical, data-driven tools for assessing and mitigating the impacts of freight disruptions, ultimately improving the resilience and efficiency of the nation’s freight networks.

Appendix

References

Akter, T., Hernandez, S., 2023. Representative truck activity patterns from anonymous mobile sensor data. International Journal of Transportation Science and Technology 12, 492–504.

Baroud, H., Barker, K., Ramirez-Marquez, J.E., Rocco S., C.M., 2014. Importance measures for inland waterway network resilience. Transp Res E Logist Transp Rev 62, 55–67.

Blake, D.M., Stevenson, J., Wotherspoon, L., Ivory, V., Trotter, M., 2019. The role of data and information exchanges in transport system disaster recovery: A New Zealand case study. International Journal of Disaster Risk Reduction 39, 101124.

Chen, C., He, F., Yu, R., Wang, S., Dai, Q., 2023. Resilience assessment model for urban public transportation systems based on structure and function. Journal of Safety Science and Resilience 4, 380–388.

Demissie, M.G., Kattan, L., 2022. Estimation of truck origin-destination flows using GPS data. Transp Res E Logist Transp Rev 159, 102621.

Foltin, P., Nagy, J., Ondryhal, V., 2023. Using Big Data Analysis in increasing transportation infrastructure resilience. Transportation Research Procedia 74, 1508–1515.

Gao, G., Meng, S., Wüthrich, M. V., 2022. What can we learn from telematics car driving data: A survey. Insur Math Econ 104, 185–199.

Ghaffarpasand, O., Pope, F.D., 2024. Telematics data for geospatial and temporal mapping of urban mobility: New insights into travel characteristics and vehicle specific power. J Transp Geogr 115, 103815.

Ghasemi, S.H., Lee, J.Y., 2021. Measuring instantaneous resilience of a highway bridge subjected to earthquake events. Transp Res Rec 2675, 1681–1692.

Hu, S., Shu, S., Bishop, J., Na, X., Stettler, M., 2022. Vehicle telematics data for urban freight environmental impact analysis. Transp Res D Transp Environ 102, 103121.

Kurth, M., Kozlowski, W., Ganin, A., Mersky, A., Leung, B., Dykes, J., Kitsak, M., Linkov, I., 2020. Lack of resilience in transportation networks: Economic implications. Transp Res D Transp Environ 86, 102419.

Liao, C.F., 2014. Generating reliable freight performance measures with truck GPS data. Transp Res Rec 2410, 21–30.

Morshed, S.A., Arafat, M., Mokhtarimousavi, S., Khan, S.S., Amine, K., 2021. 8R Resilience Model: A stakeholder-centered approach of disaster resilience for transportation infrastructure and network. Transportation Engineering 4, 100058.

Potter, A., Soroka, A., Naim, M., 2022. Regional resilience for rail freight transport. J Transp Geogr 104, 103448.

Serdar, M.Z., Koç, M., Al-Ghamdi, S.G., 2022. Urban Transportation Networks Resilience: Indicators, Disturbances, and Assessment Methods. Sustain Cities Soc 76, 103452.

Wang, N., Wu, M., Yuen, K.F., 2023. A novel method to assess urban multimodal transportation system resilience considering passenger demand and infrastructure supply. Reliab Eng Syst Saf 238, 109478.

Xu, P.C., Lu, Q.C., Xie, C., Cheong, T., 2024. Modeling the resilience of interdependent networks: The role of function dependency in metro and bus systems. Transp Res Part A Policy Pract 179, 103907.

Yanhong, F., Xiaofa, S., 2013. Research on Freight Truck Operation Characteristics Based on GPS Data. Procedia Soc Behav Sci 96, 2320–2331.

Zhang, W., Han, Q., Shang, W.L., Xu, C., 2024. Seismic resilience assessment of interdependent urban transportation-electric power system under uncertainty. Transp Res Part A Policy Pract 183, 104078.