RESEARCH REPORT

Institute of
Transportation
Studies

UNIVERSITY
OF
CALIFORNIA

Assessing the Functionality of Transit and Shared Mobility Systems after Earthquakes

Kenichi Soga, Ph.D., Professor, Department of Civil and Environmental Engineering. University of California, Berkeley
Louise Comfort, Ph.D., Professor Emerita, Graduate School of Public and International Affairs, University of Pittsburgh
Bingyu Zhao, Ph.D., Assistant Professor, Department of Civil and Environmental Engineering, Technische Universität Wien (Vienna University of Technology)
Yili (Kelly) Tang, Ph.D., Assistant Professor, Department of Civil and Environmental Engineering, University of Western Ontario
Tianyu Han, Ph.D student, Department of Civil and Environmental Engineering. University of California, Berkeley

June 2024

California
Resilient and Innovative
Mobility Initiative

Report No.: UC-ITS-RIMI-4K | DOI: 10.7922/G2NZ860C

Technical Report Documentation Page

1. Report No. UC-ITS-RIMI-4K	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Assessing the Functionality of Transit and Shared Mobility Systems after Earthquakes		**5. Report Date** June 2024
		6. Performing Organization Code ITS Berkeley
7. Author(s) Kenichi Soga, Ph.D. https://orcid.org/0000-0001-5418-7892; Louise Comfort, Ph.D. https://orcid.org/0000-0003-4411-1354; Bingyu Zhao, Ph.D. https://orcid.org/0000-0002-2369-7731; Yili (Kelly) Tang, Ph.D. https://orcid.org/0000-0002-5343-6823; Tianyu Han		**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Institute of Transportation Studies, Berkeley 109 McLaughlin Hall, MC1720 Berkeley, CA 94720-1720		**10. Work Unit No.** N/A
		11. Contract or Grant No. UC-ITS-RIMI-4K
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org		**13. Type of Report and Period Covered** Final Report (October 2022– October 2023)
		14. Sponsoring Agency Code UC ITS

15. Supplementary Notes
DOI:10.7922/G2NZ860C

16. Abstract

Located within the seismically active Pacific Ring of Fire, California's transportation infrastructure, especially in the Bay Area, is susceptible to earthquakes. A review of current research and stakeholder interviews revealed a growing awareness of emergency preparedness among local jurisdictions and transit agencies in recent years. However, many have yet to formalize and publish their recovery plans. This study introduces an agent-based multimodal transportation simulation tool to enhance post-earthquake transportation resilience. Integrating a road network simulator with a metro system simulator, the tool employs an optimized Dijkstra-based algorithm to calculate optimal routes, travel times, and fares. A case study is conducted for the East Bay, using the simulator to gauge the impact of a compromised Bay Area Rapid Transit (BART) system. The results suggested that original BART passengers could face either longer commute times or higher costs during the recovery phase of a major earthquake without appropriate policies. Such outcomes could disproportionately burden low-income riders, affecting their mobility and overall travel time.

17. Key Words Public transit, multimodal transportation, disaster resilience, earthquakes, evacuation, computer simulation	**18. Distribution Statement** No restrictions.

19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 36	**22. Price** N/A

Form Dot F 1700.7 (8-72) Reproduction of completed page authorized

Assessing the Functionality of Transit and Shared Mobility Systems after Earthquakes

Kenichi Soga, Ph.D., Professor, Department of Civil and Environmental Engineering. University of California, Berkeley
Louise Comfort, Ph.D., Professor Emerita, Graduate School of Public and International Affairs, University of Pittsburgh
Bingyu Zhao, Ph.D., Assistant Professor, Department of Civil and Environmental Engineering, Technische Universität Wien (Vienna University of Technology)
Yili (Kelly) Tang, Ph.D., Assistant Professor, Department of Civil and Environmental Engineering, University of Western Ontario
Tianyu Han, Ph.D student, Department of Civil and Environmental Engineering. University of California, Berkeley

June 2024

California
Resilient and Innovative
Mobility Initiative

Report No.: UC-ITS-RIMI-4K | DOI: 10.7922/G2NZ860C

Table of Contents

About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

The California Resilient and Innovative Mobility Initiative

The California Resilient and Innovative Mobility Initiative (RIMI) serves as a living laboratory—bringing together university experts from across the four UC ITS campuses, policymakers, public agencies, industry stakeholders, and community leaders—to inform the state transportation system's immediate COVID-19 response and recovery needs, while establishing a long-term vision and pathway for directing innovative mobility to develop sustainable and resilient transportation in California. RIMI is organized around three core research pillars: Carbon Neutral Transportation, Emerging Transportation Technology, and Public Transit and Shared Mobility. Equity and high-road jobs serve as cross-cutting themes that are integrated across the three pillars.

Acknowledgments

This study was made possible with funding received by the University of California Institute of Transportation Studies from the State of California through a one-time General Fund allocation in the 2021 State Budget Act for the Resilient and Innovative Mobility Initiative. The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project. The authors would also like to thank Alameda County Transportation Commission, Association of Bay Area Governments (ABAG), Bay Area Rapid Transit (BART), California Resilience Alliance, Metropolitan Transportation Commission (MTC), San Francisco Bay Area Planning and Urban Research Association (SPUR), and TransSIGHT for their valuable inputs.

Disclaimer

Table of Contents

List of Tables

List of Figures

Executive Summary

Executive Summary

California, situated atop the Pacific Ring of Fire, is recurrently exposed to seismic events. With a network of fault lines, notably the San Andreas, the state's infrastructure, especially its transportation system, is vulnerable to seismic disruptions (USGS 2023). The San Francisco Bay Area (the Bay Area), with its complex topography and reliance on key transportation channels, exemplifies this vulnerability. The 1989 Loma Prieta earthquake, which damaged the San Francisco-Oakland Bay Bridge, underscores the critical need for the enhanced preparedness of this kind of disruptive events (Daekin 1991).

Local governments, transit agencies, non-governmental organizations (NGOs), and researchers have contributed to enhancing transportation system resilience against earthquakes. However, research suggests that many local governments and transportation agencies have not made their post-disaster strategies public despite encouragement from the federal government in recent years. In addition, there have been few multimodal traffic simulations tailored for the recovery stage of an earthquake. This study bridges this gap by introducing a multimodal transportation simulation tool specifically designed for post-earthquake scenarios. The proposed tool can assist stakeholders in assessing the impact of potential earthquakes on public mobility, enabling more strategic recovery planning.

To gain more comprehensive insights into the resilience of the Bay Area's transportation systems, our team identified and conducted structured interviews with key stakeholders from local governments, transit agencies, NGOs, and private entities. From these consultations, we underscore the following findings:

- Many jurisdictions, including transit agencies and local governments, are demonstrating increased awareness of emergency and disruptive event preparedness. Despite a push from the federal government, however, only a few have formalized and published their recovery plans.
- There is a gap in available post-earthquake transportation simulation tools. These tools are vital for proactive planning, efficient response, and recovery during seismic events.
- Lessons from the COVID pandemic underscore the importance of adaptability in transportation planning. Modelling should include the impact of COVID and can help the agencies to update their strategies and tools.

To address the need for post-earthquake planning and policymaking, we developed an agent-based multimodal transportation simulation tool in this study. Combining a road network simulator with a metro system simulator, the tool utilizes a Dijkstra-based algorithm to determine optimal routes, travel times, and fares. The proposed multimodal simulation tool can be useful in scenario planning and policymaking. It can guide funding allocation decisions, ensuring both equity and efficiency, and serve as a critical aid in decision-making during emergencies.

After calibrating this simulation tool with trip data from the Metropolitan Transportation Commission (MTC), we then used the simulator to evaluate the implications of a hypothetical service suspension for the Bay Area Rapid Transit (BART) system in the East Bay.

The East Bay, notorious for its traffic congestion, relies heavily on BART to connect major cities. Factoring in the area's seismic vulnerability, we used our tool to simulate the consequences of a hypothetical earthquake-induced shutdown of the MacArthur BART station. We assumed that trains could not pass through the station due to damage, and free shuttles would serve as a bridge between the Ashby Station and the 19th Oakland Street Station, ensuring continuity in the route for those who take BART. The simulation results indicated that compared to normal conditions, shutting down the MacArthur station would increase the average travel time for a typical BART passenger from 39.2 minutes to 46.2 minutes. This increase can be attributed to the need to take emergency shuttles and await subsequent BART trains due to the closure of the MacArthur Station. If impacted passengers opt for driving or using ride-hailing services, they would benefit from reduced travel time, but their travel fares would escalate by 130 percent. Furthermore, this shift would contribute to a 1.1 percent increase in the region's overall travel time due to further congestion. Since nearly 30 percent of BART passengers are low-income, if the BART system were to be compromised due to an earthquake and lacked adequate response, it could severely impact the travel time and overall mobility of the low-income community (BART 2023).

Contents

Introduction

Earthquakes in California

In the diverse landscape of global natural disasters, the seismic activities in California hold a distinct position. The state's geographical location places it atop the Pacific Ring of Fire, a major area in the Pacific Ocean basin known for its frequent earthquakes and volcanic activity. Within this seismically active environment, California is crisscrossed by numerous fault lines, such as the well-known San Andreas Fault (USGS 2023). These fault lines represent boundaries between tectonic plates. When the stress from these plates' movements surpasses the friction holding them together, it manifests as an earthquake (USGS 2023). Consequently, regions with multiple fault lines, like California, tend to experience earthquakes more frequently. These seismic activities range from minor tremors to catastrophic events, such as the 1906 San Francisco earthquake, each potentially impacting the state's infrastructure.

Earthquakes can have profound impacts on the transportation systems of a region. When seismic events occur, they can damage or destroy roads, bridges, tunnels, railway tracks, and airport facilities, rendering them impassable or unsafe for use. Cracked pavements, collapsed overpasses, and misaligned rail tracks can disrupt daily commutes, impede emergency response, and stall the movement of goods and services (McCullough 1994). Moreover, the immediate aftermath of an earthquake is often massive traffic congestion and gridlock due to damaged infrastructure and rerouted vehicular movement. Repairing damaged infrastructure can be time-consuming and expensive, leading to long-term transportation challenges for the affected region.

The San Francisco Bay Area

In light of California's seismically active environment, regions like the San Francisco Bay Area (the Bay Area), with its intricate topography and urban complexities, need to pay particular attention to earthquake preparedness. Situated in Northern California, this region’s major fault lines, the San Andreas, Hayward, and Calaveras (Figure 1) make this area particularly vulnerable to seismic disruptions (USGS 2023). The United States Geological Survey (USGS) has estimated a 72 percent probability of an earthquake with a magnitude of 6.7 or greater striking the region within the upcoming 30 years (Figure 1). The region’s varied geography, from the estuary of the San Francisco Bay to the Santa Cruz and Diablo Ranges, further complicate the challenges posed by earthquakes.

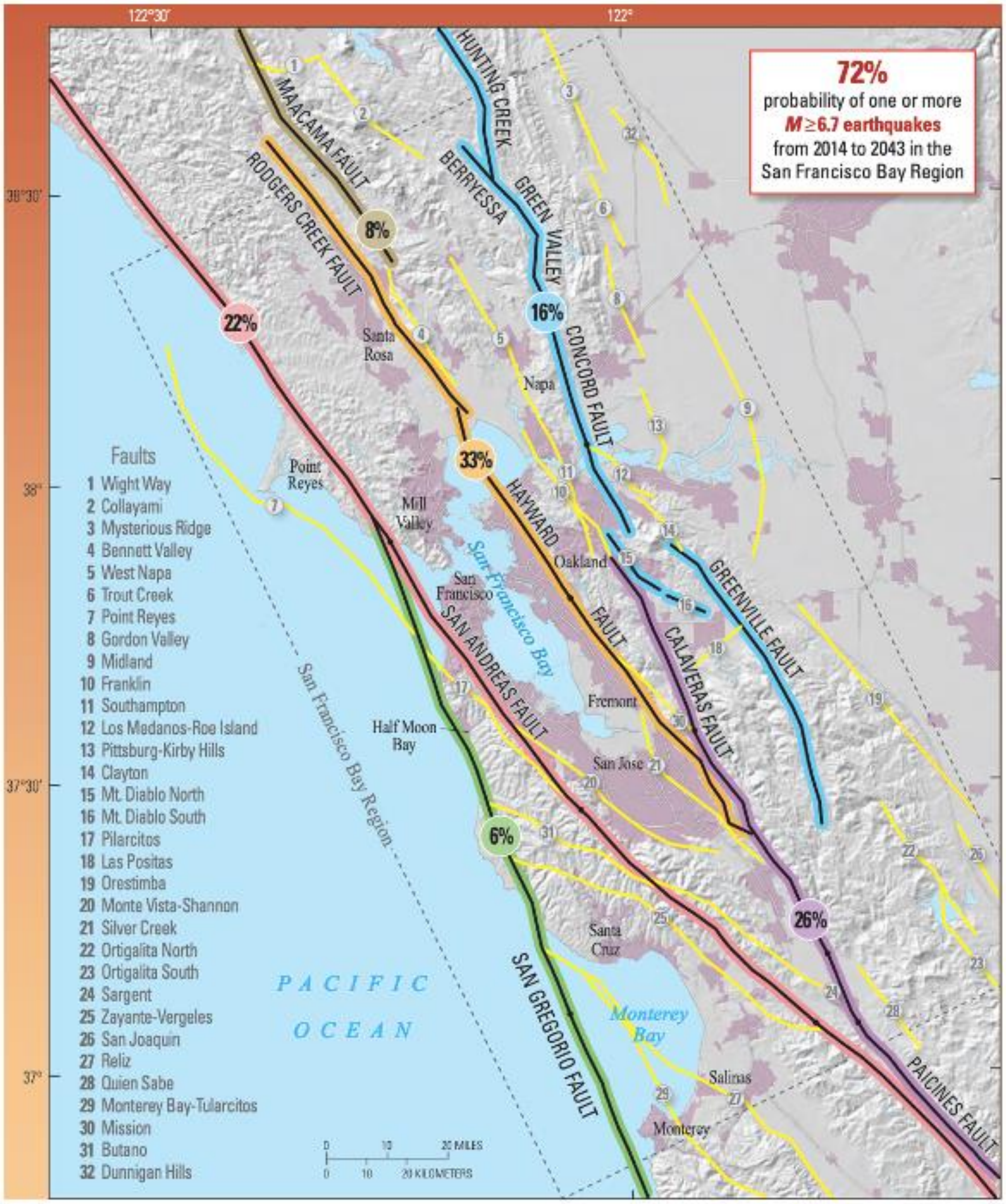


Figure 1. Map of known active faults and earthquake probabilities in the San Francisco Bay Area (USGS 2016).

Due to the unique topography of the Bay Area, the City of San Francisco relies on several vital bridges, such as the Golden Gate Bridge and the San Francisco-Oakland Bay Bridge (the Bay Bridge), for inter-city connectivity. Any compromise in their integrity can substantially disrupt the region's transportation system. The 1989 Loma Prieta earthquake, for instance, caused a section of the Bay Bridge's upper deck to collapse, which severely impeded daily travel to and from the city (Daekin 1991).

The 1989 Loma Prieta Earthquake

The Loma Prieta earthquake in October 1989 led to significant damage to roadways across the Bay Area. While many of the impacted roads had nearby alternatives or short detours that drivers could use, there was an inevitable rise in traffic congestion and longer travel times. Yet, most journeys were still manageable with minor interruptions. However, for the roughly one month it was closed for repairs by the California Department of Transportation, the Bay Bridge did not offer a convenient alternative for vehicle travel. Given that nearly 245,000 vehicles and almost 400,000 people used the bridge daily, its shutdown posed a major disruption. Although the Bay Area Rapid Transit Authority (BART) (which connects San Francisco and Oakland by tunnel under the Bay) and local ferries added capacity to cope with the situation, overall traffic in the region still became more congested, leading to more delays (Daekin 1991).

In the aftermath of the earthquake, BART proved a resilient and effective alternative for commuters when the Bay Bridge was compromised. However, given the Bay Area's vulnerability to seismic activity, there is no guarantee that BART or other transportation systems will fare as well in the future. Given the high probability of another major earthquake striking the region in the coming years, it is crucial for municipal authorities, transportation agencies, and the community to bolster their preparedness. Efficient post-disaster recovery hinges on well-coordinated planning and established protocols. A comprehensive long-term recovery strategy is essential to provide critical guidance to local government and agencies, expedite the restoration process, and mitigate disruptions to the region's mobility.

Purpose of this Report

In recent years, the federal government has strongly urged local governments and agencies to devise hazard recovery plans. Yet, few entities in the Bay Area have published their post-disaster recovery plans. Concurrently, there is a notable gap in post-earthquake traffic simulation models, particularly for the recovery phase. To address this, we developed a multimodal transportation simulation tool for predicting traffic conditions in the aftermath of earthquakes. This tool can help with not only general planning and policymaking during the recovery stage but also in formulating equitable transportation solutions for all residents. We based our model on a hypothetical earthquake scenario in the East Bay. By calibrating it with Metropolitan Transportation Commission (MTC) travel data, we gauged the potential repercussions of a suspended BART system on the average travel time and associated costs in the region.

Structure of the Report

The report is organized as follows. The Background section includes reviews of existing plans and reports released by the government agencies and relevant studies published by other researchers. To better understand the current status of and potential gaps in transit system resilience in the Bay Area, the research team conducted interviews with relevant stakeholders, which are documented in the Interview section.

Building on the knowledge gained from these interviews and our review of existing research, we developed a multimodal transportation simulation prototype based on two in-house transportation simulators. After calibrating this model with public data, we then used the model to access the potential impact of a suspended BART system in the East Bay as a case study. The report concludes with a Discussion section where we address the impact of the COVID-19 pandemic and equity issues.

Background: Response and Recovery Planning

This section reviews (1) publicly available plans and reports on the resilience of transportation systems published by governments, agencies, and NGOs; and (2) relevant studies of traffic simulations of emergency or hazard response and recovery.

Publicly Available Plans and Reports

Faced with aging infrastructure and the threat of seismic events, numerous local agencies and governments in the Bay Area have addressed the region's transportation resiliency. BART's Local Hazard Mitigation Plan (2022), mandated by the Federal Emergency Management Agency (FEMA), took the lead in identifying hazards local communities and the region could encounter. This report highlighted the structural vulnerability of BART facilities. A similar endeavor, preparation of the Multijurisdictional Hazard Mitigation Plan was undertaken by MTC in 2021. Collaborating with eight other transit agencies, the MTC plan evaluated the risks posed by hazards to transit facilities in the Bay Area, with an emphasis on structural vulnerabilities. Earlier, in 2008, the California Governor's Office of Emergency Services (Cal OES) formulated the Regional Emergency Coordination Plan (RECP) Transportation Subsidiary Plan, which laid out the coordination mechanism among the OES Regional Emergency Operations Center (REOC), the sixteen Operational Areas in the OES Coastal Region, and the State Operations Center (SOC) during regional emergencies. It further delineated the roles of transportation agencies and provided guidelines for the REOC in emergency situations.

Building on the RECP's foundation, MTC in 2018 produced the San Francisco Bay Area Regional Transportation Emergency Management Plan, offering specialized guidance for Bay Area transportation agencies during regional emergencies, emphasizing information sharing, inter-agency coordination, and mutual aid. Recognizing future possible environmental hazards, MTC and the Association of Bay Area Governments (ABAG) in 2021 published Plan Bay Area 2050, which addressed potential impacts of climate change and sea-level rise. It proposed "bus bridges" as a potential solution to connect transit stations during inundation, though BART was not included in this framework. In addition to Plan Bay Area 2050, MTC and ABAG embarked on another cycle of long-range planning, releasing their Futures report in 2020. This report delved into the potential impact of a 7.0 magnitude Hayward earthquake on the region's transportation systems, specifically examining disruptions in travel routes and network junctions. While these efforts had different approaches or areas of concentration, the objective remained consistent, which was to identify vulnerabilities and strategies to ensure the resilience and safety of the Bay Area's transit infrastructure in the face of potential threats.

In recent years, there has been a discernible shift in focus at both the federal and state levels towards the recovery aspect of potential hazards. FEMA published the National Disaster Recovery Framework (NDRF) in 2016, which integrates the activities of various stakeholders, from emergency managers to NGOs, to maximize resource utilization and bolster community resilience post-incident. Mirroring this federal initiative, California introduced its own California Disaster Recovery Framework (CDRF) in 2019. The CDRF uses the state's past experiences, aligns with the federal recovery structure, and ensures seamless delivery of assistance to affected communities. With these frameworks in place, local, state, tribal, and federal entities, along with private and non-governmental organizations, are expected to have cohesive and efficient strategies for both hazard preparedness and post-incident recovery. However, it is important to recognize that these frameworks only provide general guidance on actions that could be taken in the recovery stage, and many local jurisdictions and transit agencies in California have not yet published their formal recovery plans.

Relevant Studies

Beyond the government agency reports, researchers have conducted many studies on the resilience of transportation systems during seismic events. A significant body of research has been devoted to hazard prevention, particularly examining the seismic vulnerability of transportation infrastructure systems themselves and its impact on services. For example, using the San Francisco Bay area as a representative case, Kiremidjian (2007) investigated the earthquake risks posed to bridges within transportation systems. The study revealed that damage from liquefaction was the primary threat, and increasing the resilience of transportation infrastructure against liquefaction can reduce the post-event travel delays assuming fixed travel demand. An (1997) studied the collapse mechanism of the Daikai subway station in Kobe, Japan during the Great Hanshin earthquake in 1995. The study examined the structural failure of an intermediate column due to its inadequate shear capacity and suboptimal ductility and proposed methods to augment the seismic resistance of subway systems in order to keep the transportation accessibility after a large earthquake. These insights offer guidance on strengthening certain transportation facilities to keep the transportation accessibility during the post-earthquake stage.

Parallel to this, there is a growing interest in the public response during the recovery stage following seismic disturbances. Feng (2020) formulated a model to gauge the efficacy of road networks in the immediate aftermath of an earthquake, incorporating aspects such as unpredictable driver behavior and road blockages. Chang (2001) presented post-disaster performance metrics for transportation systems, drawing from observations of the 1995 Kobe earthquake. The study documented pronounced performance declines in Kobe's rail and highway networks, however, rail systems recovered more quickly. Chang (2011) studied the vulnerabilities of transportation networks to earthquakes and the complexities of post-earthquake travel demand.

In summary, while significant efforts have been made by government agencies and researchers in understanding the resilience of transportation systems during earthquakes, there is a gap in understanding the behavior of multimodal traffic in the recovery stage of an earthquake. This study bridges this gap by introducing a multimodal transportation simulation tool specifically designed for post-earthquake scenarios. The proposed tool can assist stakeholders in assessing the impact of potential earthquakes on public mobility, enabling more strategic recovery planning.

Interviews: Stakeholders Discuss Transportation Resilience and Preparedness

After reviewing pertinent plans and reports, we identified a list of relevant stakeholders who might be able to offer multifaceted insights into the resilience of the Bay Area's transportation systems. These stakeholders include representatives from local governments, transit agencies, NGOs, and private firms. The team conducted structured interviews with these individuals. Table 1 provides detailed information on their positions, affiliations, and corresponding sectors.

Table 1. List of interviewed stakeholders.

Stakeholder	Position	Affiliation	Sector
1	Director of Planning	Alameda County Transportation Commission	Government
2	Resilience Planner	Association of Bay Area Governments (ABAG)	NGO
3	Principal Engineer	Bay Area Rapid Transit District (BART)	Transit Agency
4	Executive Director and Board President	California Resilience Alliance	NGO
5	Emergency Coordinator	Metropolitan Transportation Commission (MTC)	NGO
6	Transportation Policy Manager	San Francisco Bay Area Planning and Urban Research Association (SPUR)	NGO
7	Data Analyst	TransSIGHT	Private Company

The interviews began with an overview of the proposed study and were followed by questions tailored to the respective stakeholder. These stakeholders provided a comprehensive view of the current state of and aspirations for transportation resilience and preparedness in the Bay Area. For clarity and systematic presentation, the insights gleaned from these interviews have been categorized into the following topics.

1. Strategic Planning & Current Initiatives

- **Futures**: MTC used their travel models for scenario planning, studying a number of factors, including the 7.0 magnitude Hayward scenario, but the incorporation of earthquake impacts was fairly rudimentary (broken links and nodes in the travel network).
- **Plan Bay Area 2050**: The 2021 report acknowledges the implications of sea level rise on transportation, but it does not assess earthquake impacts.
- **Regional Network Management**: Initiatives are underway to enhance transit navigation in terms of ease, convenience, and equity. The vision is to manage transit services as a cohesive and efficient network.

2. Awareness & Preparedness

- **Post-COVID Landscape**: The COVID pandemic has heightened awareness among transit agencies about the need for preparedness against unprecedented disruptive events.
- **Performance Metrics**: The system prioritizes on-time performance for individual modes of transit and the broader transportation framework. Additionally, there is an increasing emphasis on optimizing customer experience and timely notifications.
- **Recovery Protocols**: Despite encouragement at the federal and state level, many jurisdictions and agencies have not published formal recovery plans.
- **Mutual Aid**: This kind of coordination framework is an effective method in emergency response and recovery.

3. Transportation Trends & Patterns

- **BART Parking**: The pandemic-induced decline in parking at BART stations was observed.
- **Alternative Transit Modes**: It is necessary to include ferries as one of the transportation modes in the Bay Area.
- **COVID's Lasting Influence**: The pandemic has largely changed people’s travel patterns, which should be included in the study.

4. Modeling & Forecasting Challenges

- **Key Variables**: Models should incorporate factors such as power, fuel, and electricity, especially given disparate recovery timelines and diverse fuel systems.
- **Behavioral Predictions**: Predicting travel behavior in post-earthquake scenarios remains a challenge.
- **Utility of Models**: Stakeholders believe that models can be instrumental in guiding decisions related to funding allocation.

5. Community & Organizational Interactions

- **Equity**: All communities are considered equally during the emergency response.

- **Diverse Agencies**: There are 27 to 30 transit agencies in the Bay Area, which can make coordination more challenging during the recovery stage of an earthquake.
- **Guaranteed RIDE HOME**: Each county has measures in place with funding support to assure commuters of a guaranteed ride back home.

Following a thorough examination of these insights, the research team underscored the following pivotal findings.

- Many jurisdictions, including transit agencies and local governments, are demonstrating increased awareness of emergency and disruptive event preparedness. Despite a push from the federal government, only a few have formalized and published their recovery plans.
- There is a gap in available post-earthquake transportation simulation tools. Such tools are vital for proactive planning, efficient response, and recovery during seismic events.
- The proposed multimodal simulation tool can be useful in scenario planning and policymaking. It can guide funding allocation decisions, ensuring both equity and efficiency, and serve as a critical aid in decision-making during emergencies.
- Lessons from the COVID pandemic underscore the importance of adaptability in transportation planning. The model should include the impacts of COVID and could help agencies to update their strategies and tools.

Post-Disaster Traffic Simulation Tools

Through the stakeholder interviews and analysis of government reports and relevant studies described above, we identified a potential gap in traffic simulations of the recovery phase following seismic events. To aid in post-earthquake planning and policymaking, we developed a multimodal transportation simulation tool in this study. This tool combines (i) a road network simulator and (ii) a metro system simulator. In this section, we present these simulators and describe the integrated multimodal simulation methodology. A case study focusing on the East Bay is discussed in the following section.

Road Network Simulator

The Semi-dynamic Traffic Assignment with Residual Demand is an agent-based road network simulator (Zhao 2019) which offers good computational performance as well as the ability to produce sensible traffic simulation results. It operates on a quasi-equilibrium principle, ensuring a balance between computation speed and realistic traffic behavior. By incorporating the contraction hierarchy and a priority-queue based Dijkstra's algorithm, the model can efficiently route a vast number of trips, making it suitable for both small towns and large cities.

The model can compute and visualize intricate traffic flows, enabling detailed congestion analyses in time increments less than one hour. It also provides a framework for assessing regional mobility under disruptions like road closures or infrastructural damage.

Metro System Simulator

The Integrated Data-driven Agent-based Simulator (Zhao and Tang 2022) is an agent-based tool designed for predicting city-scale transit usage. Optimized for integration with Global Transit Feed Specification (GTFS) datasets, the simulator can easily work with global transit operators. Its design enables the modification of network inputs to account for unforeseen infrastructure challenges, such as station outages due to natural disasters.

The model can capture the detailed behavior of different entities, from individual travelers to trains and platform operations. down to the second. It allows for thorough analyses of platform congestion during peak times. By aligning traveler data with smartcard transactions, the tool can provide insights into train loading patterns and capacities. The simulator also features a simple Origin-Destination (OD) structure, supporting empirical investigations into demand-responsive strategies. If demand parameters are not provided, the model can also generate a random OD dataset. Moreover, it has a high computational efficiency, which allows for quick analyses and offers potential for optimization in transportation planning.

Multimodal Traffic Simulation

Integrating the above road network simulator and the metro system simulator, the proposed multimodal transportation simulation tool is adept at capturing the behavioral dynamics of individual travelers across diverse transportation modes, with evaluations conducted at sub-hourly intervals.

As the tool is designed to be compatible with both OpenStreetMap (OSM) and GTFS datasets, it can help to integrate road networks and metro systems into one multimodal network. For each agent within this simulation, an advanced Dijkstra-based algorithm is employed to plan routes from the origin to the destination. This planning is predicated upon estimated travel times, operating under the assumption that every agent invariably selects the route with the minimal travel time. In addition, this tool is adapted for post-disaster scenarios, offering flexibility to accommodate change in network inputs, such as road obstructions or station closures resulting from seismic events.

The tool can compute and record both travel fare and travel time for each agent. In addition, the efficient computational design of the model ensures that it can derive optimal transportation strategies and policy recommendations for various scenarios, negating the necessity for supercomputing resources.

Case Study: The East Bay, CA

The East Bay, encompassing key regions of the eastern San Francisco Bay Area, often struggles with significant traffic congestion, especially on primary arteries like I-80 and I-880 during peak hours. While BART provides a viable travel alternative, connecting Oakland and other cities to the broader Bay Area, for drivers bridges such as the Bay Bridge between Oakland and San Francisco can become notable chokepoints, frequently slowing down commuting in the region. Local traffic in urban centers like downtown Oakland with dense road networks and high pedestrian activity presents its own challenges.

Given the intricate traffic conditions and high travel demands in the East Bay, the transportation system is particularly susceptible to seismic events. In this case study, we utilized the proposed multimodal transportation simulation tool to assess the potential impact on regional travel time and cost resulting from a BART station closure due to earthquake damage.

Network Input

Road Network

This case study focuses on the highway network in the San Francisco Bay Area. Highway data, which includes details like length and capacity, was sourced from OpenStreetMap using the OSMnx package (Boeing 2017). The road network for the Bay Area contains 11,616 nodes and 16,427 edges (Figure 2).

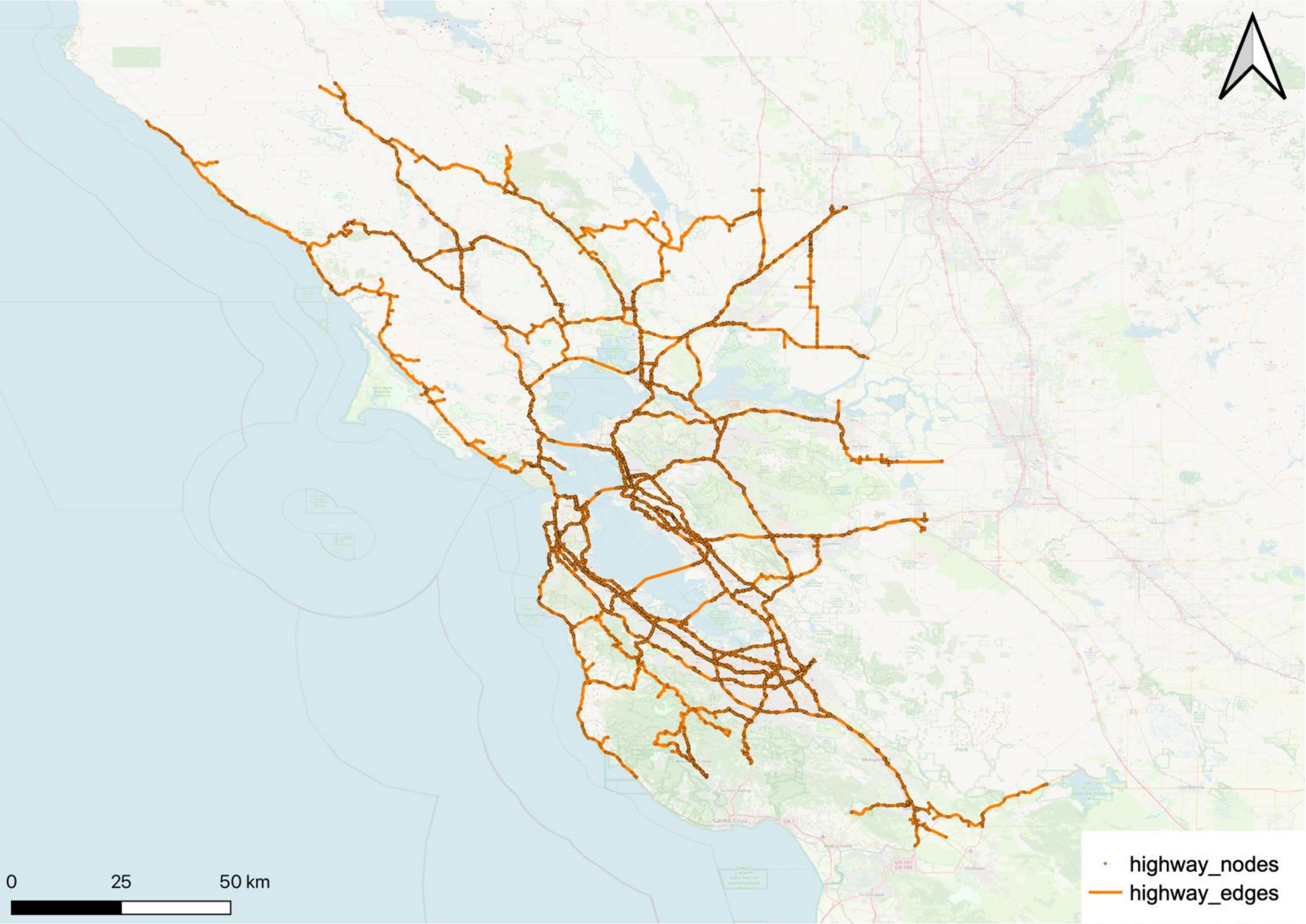


Figure 2. Highway network of the Bay Area.

Metro Network

The metro network data was derived from BART's GTFS data. Given the study's focus on the East Bay, only the Orange Line of the BART system was examined. This line extends from the Berryessa/North San José station to the Richmond station, encompassing 21 stations across the cities of San Jose, Milpitas, Fremont, Union City, Hayward, San Leandro, Oakland, Berkeley, El Cerrito, and Richmond. In all, the metro network for the East Bay (Orange Line) includes 21 nodes and 40 edges (Figure 3).

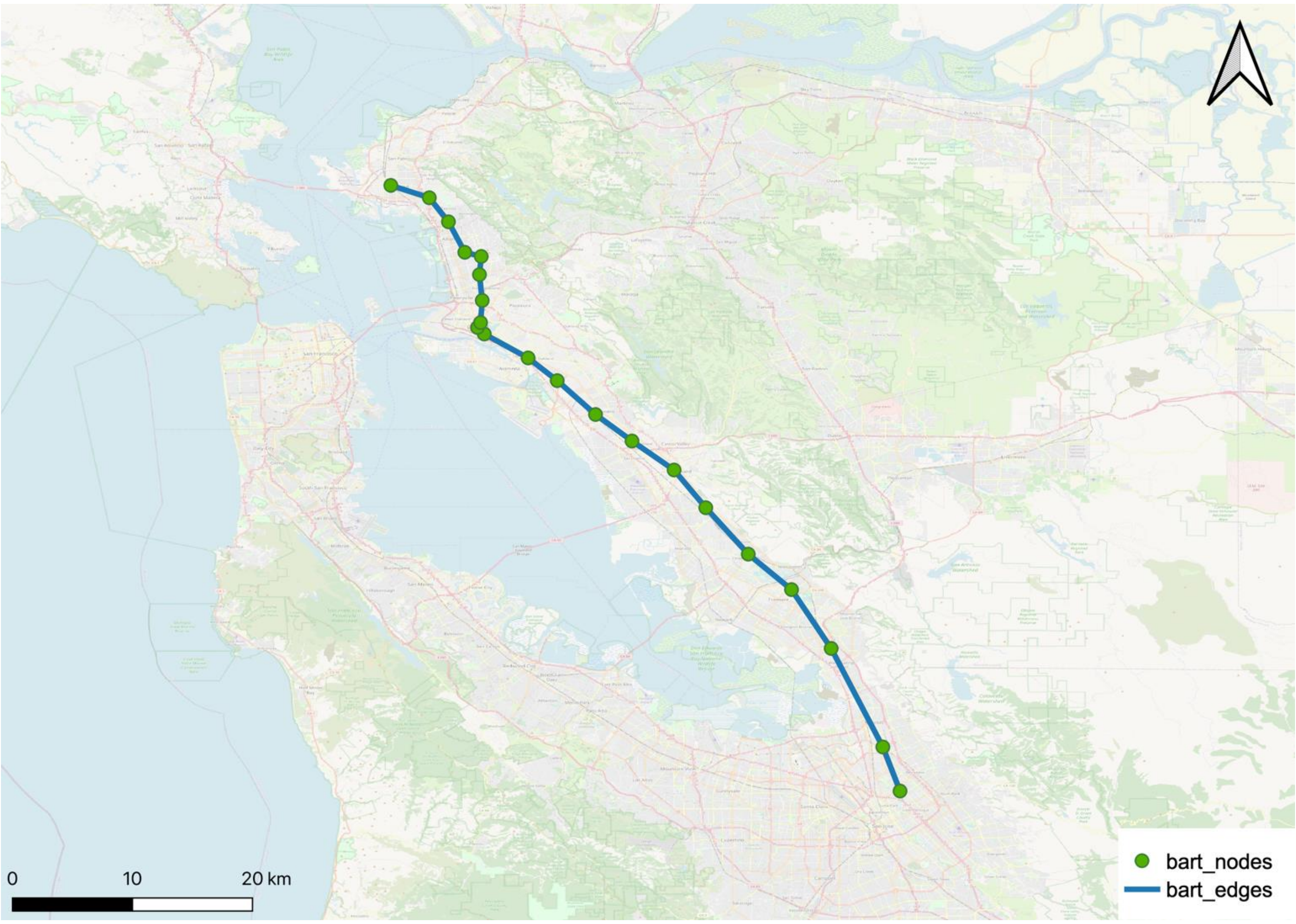


Figure 3. Metro network of the East Bay (Orange Line).

Virtual Link

As the local network is not included in this case study, metro stations are linked to the nearest highway ramp through virtual links. These virtual links are conceptualized as having zero length and infinite capacity, resulting in no travel time for travelers (Figure 4). While they aid in computational modeling, it is important to note that these links are not actual roads.

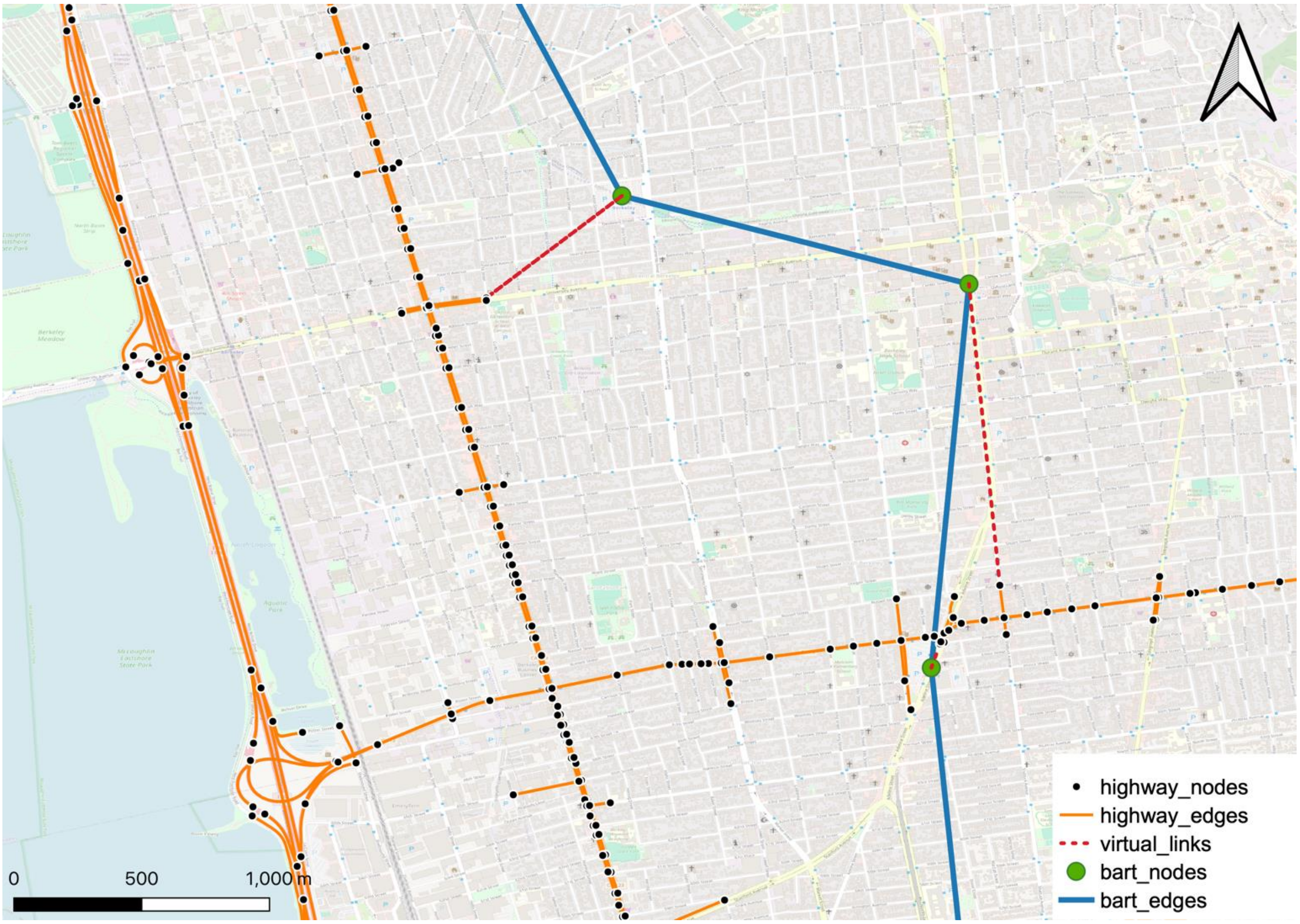


Figure 4. Virtual links (red dash lines).

Demand Input

Background Traffic

Background traffic data was sourced from the MTC travel model (MTC 2022). This data comprises individual trip details, including the origin traffic analysis zone (TAZ), destination TAZ, departure hour, travel purpose, and tour mode. For this study, only travel data for individuals who drive were extracted to represent the background traffic. Additionally, the origin and destination for each agent were randomly assigned to a node on either the highway or metro network within the respective TAZs.

Between 6 AM and 9 AM, which is considered the peak period, 2,117,058 trips are undertaken by individuals in the Bay Area according to the MTC travel model. It is presumed that highways are the preferred routes for these trips when feasible. Utilizing the multimodal transportation tool, the highway network congestion level for background traffic at 7:30 AM is depicted in Figure 5. The congestion level of traffic is quantified using the

Volume-to-Capacity (V/C) ratio. A V/C ratio less than 1.0 suggests that the facility operates below its capacity, indicating availability for additional vehicles. Conversely, a V/C ratio greater than 1.0 signifies that the facility is operating above its capacity, leading to congestion, heightened delays, and a potential need for enhancements or alternate routes.

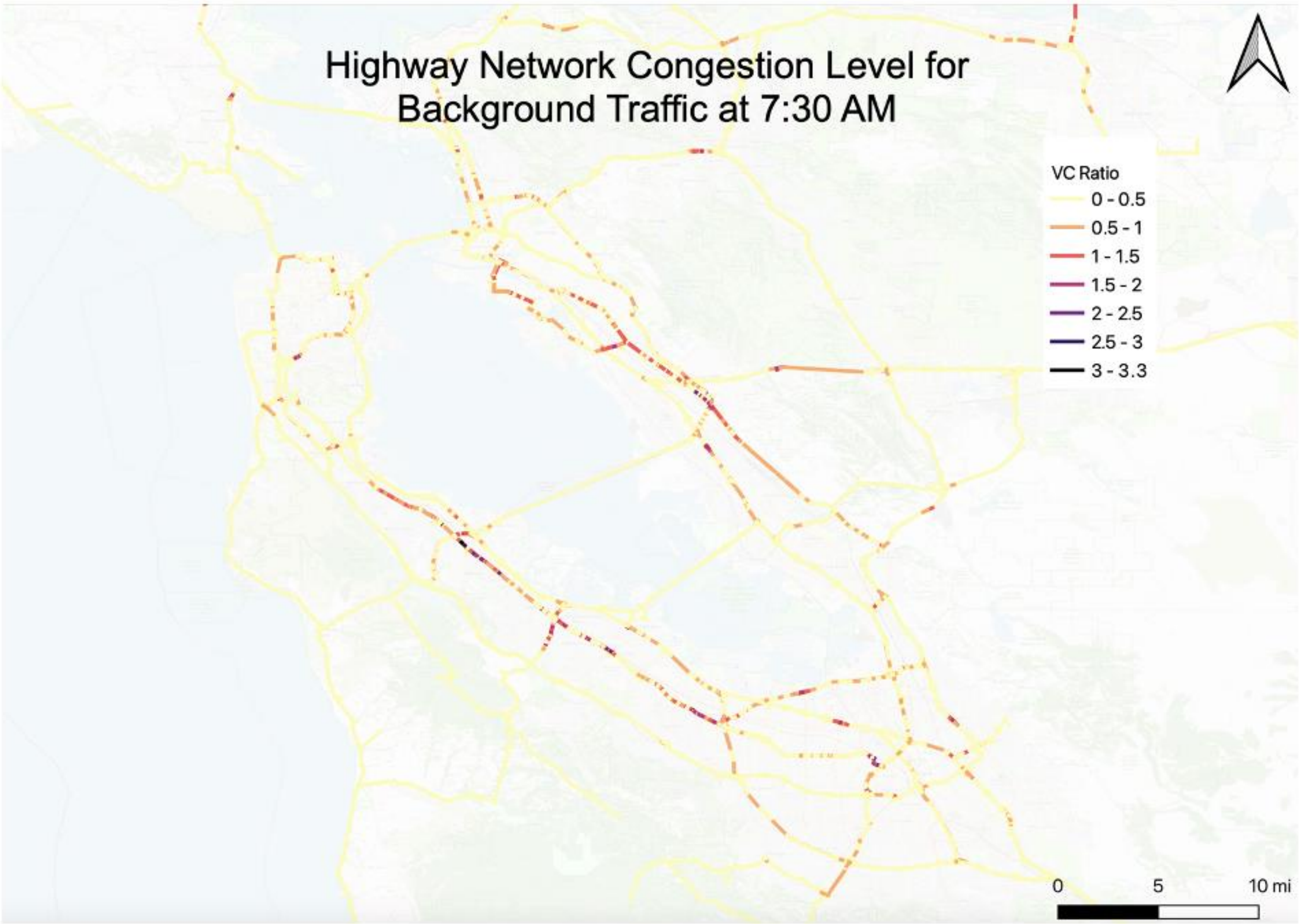


Figure 5. Highway network congestion level for background traffic at 7:30 AM.

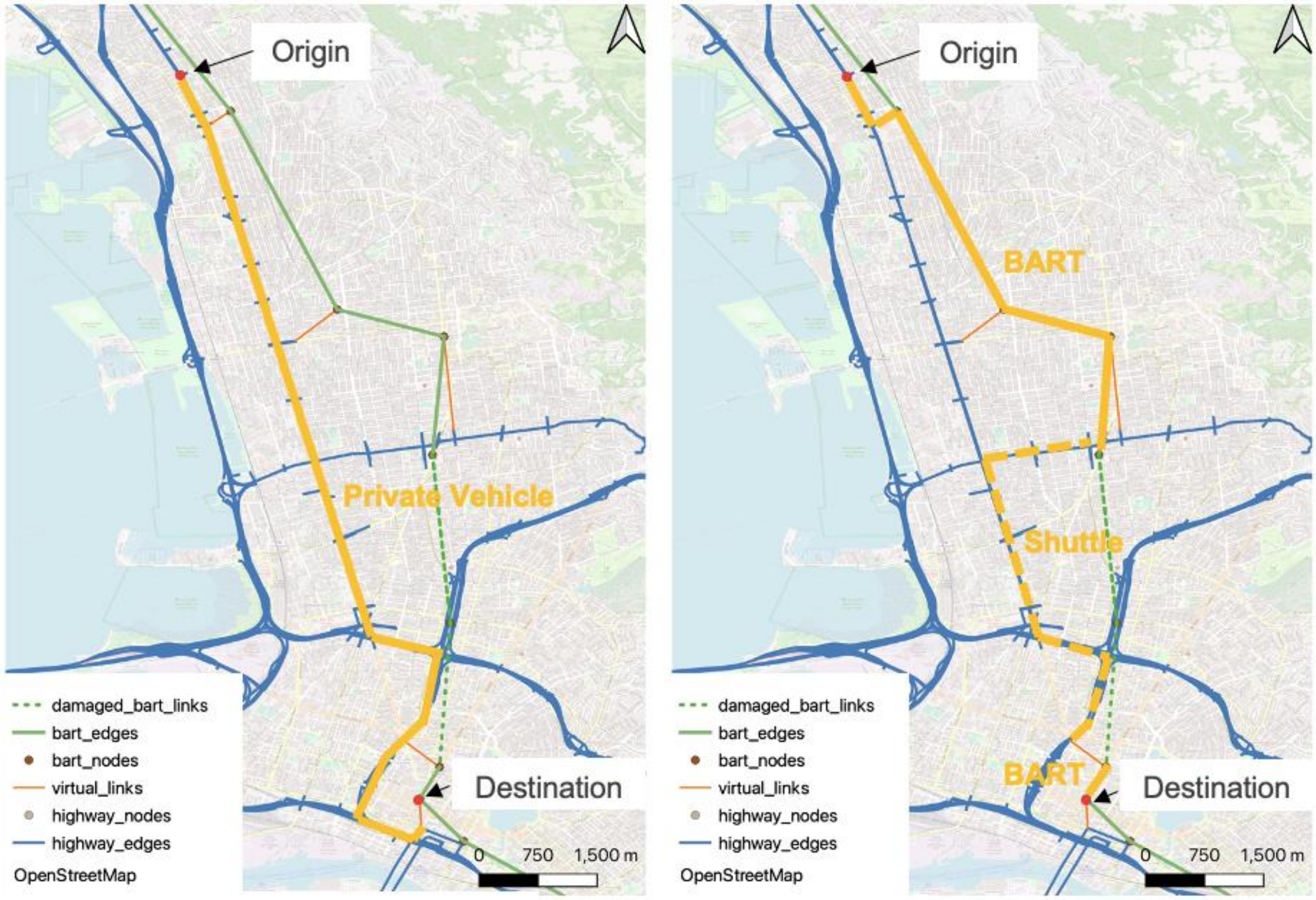
Random Origin-Destination (OD)

Based on BART ridership data, an estimated 5,000 passengers will take the BART Orange Line during the peak hours (6 AM to 9 AM) (BART 2023). We assumed that individuals utilizing BART will either start or conclude their journey near a BART station. As a result, we randomly allocated either the starting point or endpoint of these passengers to a BART station on the Orange Line, with the other end to a highway node in the East Bay.

Findings

Since this study does not incorporate a travel behavior model, it is simplistically assumed that all 5,000 passengers commuting via BART after the hypothesized earthquake will either (1) utilize BART in conjunction with emergency shuttles or (2) drive or opt for ride-hailing services like Uber and Lyft.

In the scenario where the MacArthur Station must be closed due to earthquake damage, any individual who previously relied on passing through MacArthur Station and still wishes to use BART would need to board an emergency shuttle. This shuttle would serve as a bridge between the Ashby Station and the 19th Oakland Street Station, ensuring continuity in the route. A detailed trajectory of an individual navigating this altered route is depicted in Figure 6.



Drive/Ride-hailing Service (Orange Line)

BART (Orange Line) + Emergency Shuttle (Dashed Orange Line)

Figure 6. Rerouted BART Trips by car and bus shuttle following earthquake.

Given the following assumptions, the simulation estimates for average travel time and average travel cost for the 5,000 original BART passengers are detailed in Table 2.

- The road network remains intact.
- BART riders will have access to complimentary emergency shuttles provided by transit agencies. These shuttles will operate between Ashby Station and 19th Street Oakland Station, with frequencies coordinated to match BART train schedules. Sufficient shuttle capacity will be available to ensure that passengers experience minimal to no waiting times.
- Travel costs for driving or ride-hailing options are set at $0.9 per mile.
- There is no waiting time for the ride-hailing service, as the BART station is assumed to be a hub for the drivers.

Table 2. Simulation results for the 5,000 original BART passengers.

Scenario		Average Travel Time (minute)	Average Waiting Time (minute)	Average Travel Cost ($)
Normal	BART	39.25	4.86	9.65
	Drive/Ride-hailing	25.14	0	20.55
MacArthur Shutdown	BART+ Emergency Shuttle	46.21	6.09	9.65
	Drive/Ride-hailing	25.14	0	20.55

Table 2 shows that compared to the normal situation, shutting down MacArthur Station will increase the average travel time for a typical BART passenger from 39 minutes to 46 minutes if they decide to take BART. This increase can be attributed to the need to take an emergency shuttle and to await a subsequent BART train. However, this option would not increase their average travel fare. If the impacted 5,000 passengers opt for driving or using ride-hailing services, while they would benefit from reduced travel time, their costs would more than double. Furthermore, this shift would contribute to a 1.1 percent increase in the region's overall travel time (for both the 5,000 original BART passengers and the background traffic travelers) due to further congestion.

Discussion

Impact of COVID-19

During our stakeholder interviews, many highlighted the impact of COVID-19 on transportation patterns. Due to safety and other concerns, BART ridership dropped to approximately 40 percent of its pre-COVID levels (BART 2023). Concurrently, the pandemic had a huge impact on working habits, as remote work became far more prevalent than before. Consequently, should another earthquake occur in the Bay Area, stakeholders noted that fewer people might need to commute, potentially alleviating some traffic concerns. However, it is essential to recognize that many frontline and fieldwork individuals would still require transportation, especially those who are low-income. The importance of providing affordable transportation options for these individuals will be further explored in the following subsection.

Equity

In 2022, both BART and LA Metro (the main transit provider in Southern California) carried out customer experience/satisfaction surveys. The findings revealed that nearly 29 percent of BART riders were low-income, with household incomes below $60,000 for a family of four (BART 2023). In contrast, LA Metro reported that about 83 percent of its riders across Metro buses, trains, and Metro Micro vehicles have household incomes of less than $50,000 annually (LA Metro 2022). Given that low-income populations tend to rely more heavily on public transit, BART plays a crucial role in facilitating travel for these individuals in the Bay Area. Our simulation results indicate that opting for driving or using ride-hailing services significantly increases travel expenses compared to using BART, as shown in Table 2. Consequently, low-income passengers would be more inclined to choose BART or other public transit options like buses. However, if the BART system were to be compromised due to an earthquake and lacked adequate response, it could severely impact the travel time and overall mobility of the low-income community.

Limitations of Current Studies and Future Works

Road Network

In this study, we focused exclusively on the highway network due to the constraints of our model. To compensate for the lack of a modelled local road network, we introduced a virtual link to bridge BART stations with the highway system. This, however, introduced some inaccuracies in estimating travel times and costs, especially since many BART stations are not close to the highway network. This limitation also prevented us from incorporating the bus system, another vital mode of transit, into our model. In Phase 2 of the RIMI project, we aim to enhance the traffic simulation component of our model to integrate the local road network.

This will not only enable more precise estimates of individual travel times and costs but also allow us to include buses as an additional transportation option.

Ride-hailing Service

In our case study, we integrated the option of ride-hailing services for the affected BART passengers. Yet, we made several assumptions regarding these services. Notably, we overlooked factors like the availability of ride-hailing vehicles in the region and the associated wait times for passengers. In Phase 2 of the project, we plan to refine our model to account for these elements and to adopt a more realistic pricing mechanism for ride-hailing services. Furthermore, we will explore potential policies, such as carpooling options within ride-hailing services, in our future work.

Travel Behavior

Another primary limitation of this study is the absence of behavioral data and modeling. In our case study, we made a rudimentary assumption that BART passengers would either continue using BART or switch to cars, presenting two extreme scenarios. Nonetheless, travel mode choices are influenced by many factors including travel time, fare, and waiting periods. In Phase 2, we aim to integrate a logit model to better simulate individuals' travel behavior under various scenarios. Predicting travel patterns post-seismic events, particularly in the aftermath of COVID, remains a challenge. We plan to consult relevant studies and work under the assumption that travel behavior will revert to normal patterns during the recovery phase.

Earthquake Simulation and Infrastructure Recovery

In this study, we proposed a hypothetical situation in which the MacArthur Station was completely closed off, preventing trains from passing through, yet we did not include the precise impact of earthquakes on the BART system. In the upcoming phase of our project, we aim to partner with a team from the University of California, Los Angeles (UCLA) who will undertake the task of assessing seismic risks by analyzing hazards, such as shaking demands, understanding structural responses, estimating potential damages, and projecting restoration timelines. Utilizing the multimodal simulator developed in the current RIMI project, we will gauge the impact of an earthquake on regional mobility and identify the optimal transportation strategies or policies during the recovery phase across various scenarios.

References

An, Xuehui, Ashraf A. Shawky, and Koichi Maekawa. 1997. "The Collapse Mechanism of a Subway Station During the Great Hanshin Earthquake," *Cement and Concrete Composites*, Volume 19, Issue 3, 1997, Pages 241-257. ISSN 0958-9465, https://doi.org/10.1016/S0958-9465(97)00014-0

Association of Bay Area Governments (ABAG) and Metropolitan Transportation Commission (MTC). 2020. "Futures." https://mtc.ca.gov/sites/default/files/Horz_Futures_Report.web_.pdf

Association of Bay Area Governments (ABAG) and Metropolitan Transportation Commission (MTC). 2021. "Plan Bay Area 2050." https://www.planbayarea.org/sites/default/files/documents/Plan_Bay_Area_2050_October_2021.pdf

Bay Area Rapid Transit (BART). 2022. "Local Hazard Mitigation Plan." https://www.bart.gov/sites/default/files/docs/Local%20Hazard%20Mitigation%20Plan__V1.1_0.pdf

Bay Area Rapid Transit (BART). 2023. "2022 BART Customer Satisfaction Survey." https://www.bart.gov/sites/default/files/docs/CS2022_Report_040423.pdf

Bay Area Rapid Transit (BART). 2023. "Monthly Ridership Report September and Trailing 12-months." https://www.bart.gov/sites/default/files/2023-10/202309%20MRR.pdf

Boeing, Geoff. 2017. "OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks," *Computers, Environment and Urban Systems*, Volume 65, 2017, Pages 126-139, ISSN 0198-9715, https://doi.org/10.1016/j.compenvurbsys.2017.05.004.

California Governor's Office of Emergency Services (Cal OES). 2008. "San Francisco Bay Area Regional Emergency Coordination Plan - RECP Transportation Subsidiary Plan." http://bayareauasi.org/sites/default/files/resources/RECP%2520Transportation%2520Subsidiary%2520Plan.pdf

California Governor's Office of Emergency Services (Cal OES). 2019. "California Disaster Recovery Framework." https://www.caloes.ca.gov/wp-content/uploads/Recovery/Documents/2019-California-Disaster-Recovery-Framework.pdf

Chang, Liang, Amr S. Elnashai, and Billie F. Spencer Jr. 2012. "Post-earthquake Modelling of Transportation Networks," *Structure and Infrastructure Engineering*, Volume 8, Issue 10, Pages 893-911. DOI: 10.1080/15732479.2011.574810

Chang, Stephanie E., and Nobuoto Nojima. 2001. "Measuring Post-Disaster Transportation System Performance: The 1995 Kobe Earthquake in Comparative Perspective," *Transportation Research Part A: Policy* *and Practice*, Volume 35, Issue 6, 2001, Pages 475-494. ISSN 0965-8564, https://doi.org/10.1016/S0965-8564(00)00003-3.

Deakin, Elizabeth. 1991. "Transportation Impacts of the 1989 Loma Prieta Earthquake: The Bay Bridge Closure," UC Berkeley: University of California Transportation Center. https://escholarship.org/uc/item/6rb2j9pf

Federal Emergency Management Agency (FEMA). 2016. "National Disaster Recovery Framework." https://www.fema.gov/sites/default/files/2020-06/national_disaster_recovery_framework_2nd.pdf

Feng, Kairui, Quanwang Li, and Bruce R. Ellingwood. 2020. "Post-earthquake Modelling of Transportation Networks Using an Agent-based Model," *Structure and Infrastructure Engineering*, 16:11, 1578-1592. DOI: 10.1080/15732479.2020.1713170

Kiremidjian, Anne, James Moore, Yue Yue Fan, Ozgur Yazlali, Nesrin Basoz, and Meredith Williams. 2007. "Seismic Risk Assessment of Transportation Network Systems," *Journal of Earthquake Engineering*, 11:3, 371-382. DOI: 10.1080/13632460701285277

Los Angeles County Metropolitan Transportation Authority (LA Metro). 2022. "Results of our 2022 Customer Experience Survey." https://thesource.metro.net/2022/10/27/results-of-our-2022-customer-experience-survey/

Metropolitan Transportation Commission (MTC). 2018. "San Francisco Bay Area Regional Transportation Emergency Management Plan." https://mtc.ca.gov/sites/default/files/MTC%20Bay%20Area%20RTEMP%202018%20Update.pdf

Metropolitan Transportation Commission (MTC). 2021. "Multijurisdictional Hazard Mitigation Plan." https://mtc.ca.gov/sites/default/files/documents/2021-05/2021%20MTC%20HMP_Public%20Draft_March%204.pdf

Metropolitan Transportation Commission (MTC). 2022. "MTC/ABAG Forecasting, Modeling & Surveys." http://data.mtc.ca.gov/data-repository/

United States Geological Survey (USGS). 2016. "Earthquake Outlook for the San Francisco Bay Region 2014–2043." https://pubs.usgs.gov/fs/2016/3020/fs20163020.pdf

United States Geological Survey (USGS). 2023. "Quaternary Fault and Fold Database of the United States." https://www.usgs.gov/programs/earthquake-hazards/faults

United States Geological Survey (USGS). 2023. "What Is a Fault and What Are the Different Types?" https://www.usgs.gov/faqs/what-a-fault-and-what-are-different-types

Zhao, Bingyu, Krishna Kumar, Gerry Casey, and Kenichi Soga. 2019. "Agent-Based Model (ABM) for City-Scale Traffic Simulation: A Case Study on San Francisco," International Conference on Smart Infrastructure and Construction 2019 (ICSIC). January 2019, 203-212, https://doi.org/10.1680/icsic.64669.203

Zhao, Bingyu, Yili Tang, Chaofeng Wang, Shuyang Zhang, and Kenichi Soga. 2022. "Evaluating the flooding level impacts on urban metro networks and travel demand: behavioral analyses, agent-based simulation, and large-scale case study", *Resilient Cities and Structures*, Volume 1, Issue 3, 2022, Pages 12-23, ISSN 2772-7416, https://doi.org/10.1016/j.rcns.2022.10.004.