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16. ABSTRACT

This study focuses on Caltrans District 4 in the San Francisco Bay Area (Alameda, Contra Costa, Marin, Napa, San Francisco, Santa Clara, San Mateo, Solano, and Sonoma). It proposes a framework to identify and prioritize critical bridge corridors that enable access to emergency facilities, including hospitals, fire stations, police stations, Caltrans maintenance facilities, airports, seaports, and ferry terminals. Bridges are first grouped into corridors using an interchange-based approach. Next, a shortest-path algorithm is applied to find routes from each zip-based zone to its nearest facility of each type. Corridor "usage" is computed from how frequently corridors appear on these access routes, and total usage is used to rank corridor criticality. Bridges within top corridors are then evaluated and ranked using damage probabilities. The proposed method is validated against Google Maps, showing 5.6% route dissimilarity, indicating that access to critical facilities strongly depends on Caltrans routes. Corridor importance varies by facility type because facility distributions differ. For example, District 4 contains 563 fire stations across 298 zones, so most zones access a fire station locally and only 31 zones require Caltrans bridges, whereas 159 zones require Caltrans bridges to reach hospitals. The study also compares corridor rankings with and without population weighting. Without population, top corridors often occur in rural areas that serve as sole connectors for multiple zones; adding population shifts priorities toward densely populated areas, highlighting the need to define planning objectives. An updated methodology is proposed to remove selected corridors and recomputes rankings to test impacts, showing rural corridors are often irreplaceable while urban networks are highly redundant. Finally, another optimization method is introduced to minimize the number of Caltrans bridges used, trading off travel time to reduce recovery designations and costs. A web-based platform implements and visualizes these methods.

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Determination of Recovery Bridge Corridors by Comparing Post EQ Network

Final Report

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Dec 2, 2025

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Executive summary

This study is completed for District 4 San Francisco Bay Area composing counties: Alameda, Contra Costa, Marin, Napa, San Francisco, Santa Clara, San Mateo, Solano, Sonoma; This study proposes a framework for identifying critical bridge corridors that provide access to emergency facilities, including hospitals, fire stations, police stations, Caltrans maintenance facilities, airports, seaport, and ferry terminals, based on the usage of each corridor. First, an interchange-based method is introduced to group bridges into multiple corridors. Then, a shortest-path method, **Method A**, is used to determine routes from each zone to its nearest emergency facility. The usage of each corridor for facility access is calculated, and total usage is used as the ranking criterion. Finally, bridges within the most critical corridors are analyzed and ranked based on their damage probabilities.

Method A is validated against Google Maps, showing only a 5.6% dissimilarity, which confirms that access to critical facilities heavily relies on Caltrans routes. Additionally, it is observed that the must-have bridges and corridors vary with facility types. There are 563 fire stations in the 298 zip-based zones in the District 4, resulting in fire stations close to zones and only 31 zones need Caltrans bridges to access a fire station. In contrast, 159 zones need Caltrans bridges to access hospitals. Further, The top-ranked corridors also vary by facility type due to differences in spatial distribution.

Moreover, a comparative analysis was conducted to assess the impact of including versus excluding population data in the corridor ranking process. The results indicate that when population is not considered, the highest-ranked corridors tend to be located in rural areas, as these roads often serve as the sole connections for multiple zones. Some top-ranked corridors are also found in urban regions with high facility density, where access routes are shared by many zones. On the other hand, incorporating population data shifts the top rankings toward corridors in densely populated areas. This suggests that different prioritization criteria can lead to significantly different corridor rankings. Therefore, it is important to clarify the intended planning objective—whether to prioritize coverage across all zones or focus on areas with higher population density—before selecting a ranking approach.

In addition, the possibility that some corridors cannot be improved due to various issues is also considered. This approach is referred to as **Method A-alternative**. In this method, selected corridors can be removed from the network, and a new corridor ranking is generated by reapplying Method A. This alternative method can be used for testing the impact of each corridor on travel time by removing them individually. It is found that removing corridors in rural areas results in many inaccessible zones, as these corridors often serve as the only access routes. In contrast, removing corridors in urban areas does not typically lead to inaccessible zones or significant increases in travel time, demonstrating the strong redundancy of urban road network.

Furthermore, an alternative method–**Method B**–is proposed. Method B employs an optimization model aimed at minimizing the number of Caltrans bridges used. It provides Caltrans with an additional tool, especially if the goal is to reduce costs by designating fewer bridges as recovery bridges, assuming that some relaxation in travel time is acceptable.

A web-based decision support platform is developed to implement the above methods for identifying and visualizing critical Caltrans bridge corridors used to access key facilities.

Acknowledge

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The authors would like to acknowledge the valuable guidance and support provided by the Caltrans colleagues, listed in alphabetical order by last name: Sam Ataya, Shawn Hart, Mark Mahan, Cameron Oakes, Tom Shantz, Chris Traina, Christian Unanwa, John Xu, Sharon Yen, Tony Yoon, and Toorak Zokaie. We greatly appreciate the many progress meetings they held with us and the constructive feedback they provided throughout the development of this project. We are especially thankful to our project manager, Sharon Yen, for her consistent coordination, clear communication of project requirements, and dedicated support, which ensured that we were able to deliver all reports and tools on schedule.

1 Introduction

Recently adopted Seismic Design Criteria (SDC) 2.0 create an optional seismic performance target that exceeds what is applied to Ordinary Standard Bridges (OSB), deemed a "Recovery Bridge (RB)". Bridges designed to the more stringent criteria can be expected to remain undamaged in a modest earthquake (i.e., functional evaluation earthquake) and incur only moderate damage in a severe design level event (i.e., safety evaluation earthquake). From the perspective of Caltrans' Division of Engineering Services (DES), the choice of post-earthquake performance level is made at the District level since the benefits and costs of the project level design alternatives are evaluated at the District level.

It is generally agreed that Recovery Bridges should be implemented when the consequences of being down for an extended period are severe. According to the SDC, recovery bridges shall serve as vital links for rebuilding damaged areas and providing public access shortly after an earthquake. Although guidelines and experience exist on how to construct Recovery Bridges, a knowledge gap remains in identifying the critical bridge corridors. In particular, these Recovery Bridges should play a key role in supporting post-earthquake access to emergency facilities such as hospitals, fire stations, police stations, airports, seaports, and ferry terminals.

There are some existing studies on the identification of critical bridges. Generally, they can be categorized into two groups: (a) optimization-based and (b) metric ranking-based. For optimization-based methods, researchers typically define an objective function, such as minimizing costs, and apply relevant constraints to identify a set of bridges that minimize retrofitting and expected repair costs (Dong et al., 2014; Jafari et al., 2024). These models can be applied in both pre- and post-earthquake contexts: prior to an earthquake, they are used to identify critical bridges for strengthening; after an earthquake, they help determine the optimal sequence for bridge repairs. For pre-earthquake critical bridge identification, Silva-Lopez and Baker (2022) built an optimization model with an objective function to minimize upfront and post-earthquake repair costs while ensuring the travel time between origins and destinations is within the maximum acceptable time. Further, Wu and Chen (2023) built an optimization model to maximize the resilience of the road network while limiting the upfront budge. Similar. For post-earthquake bridge repair sequence, Zhao et al (2020) proposed a multi-objective recovery optimization model for the road-bridge network to obtain the optimal recovery scheme of damaged bridges by taking into consideration the restoration ability and economic loss. This model was then solved by non-dominated sorting genetic algorithm II (NSGA-II). Zhang et al. (2025) built an optimization model with the aim of maximizing network resilience to determine the bridge repair schedule and a modified genetic algorithm was developed to obtain the near-optimal solution. Moreover, some studies have integrated pre-earthquake critical bridge identification and post-earthquake bridge repair into a bi-objective optimization model, aiming to maximize network resilience while minimizing the costs associated with both pre-earthquake retrofitting and post-earthquake repair activities. (Zhang et al., 2020; Jafari et al., 2024; Gomez and Baker, 2019). Although these studies consider optimal methods selecting critical bridges in road networks, differing objectives and constraints result in different optimization models, limiting the versatility of these models.

Due to this issue, the engineering field has increasingly turned to metric-based methods. The most classical metrics are centrality measures, including degree centrality, closeness centrality, eigenvector centrality, and betweenness centrality (Li et al., 2020; Alzoor et al., 2021). These metrics measure the importance of a node in the graph and only focus on the topological characteristic of the network (Lentil et al., 2020). In addition, some studies have used fragility curves as criteria for determining retrofit prioritization (Nielson et al., 2003). However, these metrics are sensitive to the road network structure or bridge structure and do not consider the vehicle movement. Therefore, they are unable to capture the importance of the bridges to people's travel. Recently, some researchers took into consideration traffic flow when ranking the retrofitting sequence of bridges. Zhang et al (2017) considered the network topology, redundancy, traffic flow, and ranked bridges based on them. Li et al (2025) proposed a metric based on the visit probability of bridges, which evaluates the likelihood of a bridge being used during commute travel. This metric reflects the functional significance of bridges for everyday mobility. However, there are not existing studies on the identification of critical bridges for emergency travel.

Additionally, these existing studies focus solely on identifying individual critical bridges. However, they overlook an important fact: a bridge identified as critical may not function effectively if its surrounding bridges are not also critical, as they cannot work together to provide a coherent transportation service.

To address these issues, this study proposes a framework for identifying critical bridge corridors that provide access to emergency facilities, based on the usage of each corridor. First, an interchange-based method is introduced to group bridges into multiple corridors. Then, shortest-path and optimization-based methods (referred to as

Methods A and B in the following sections) are used to determine routes from each zone to its nearest emergency facility. The usage of each corridor for facility access is calculated, and total usage is used as the ranking criterion. Finally, bridges within the most critical corridors are analyzed and ranked based on their damage probabilities. The main contributions of this study are as follows:

(1) An interchange-based bridge division method is proposed to cluster bridges into corridors, enabling corridor-level ranking of bridges.

(2) Shortest-path and optimization-based methods are proposed to determine the corridor usage.

(3) Multiple types of emergency facilities, including hospitals, fire stations, police stations, Caltrans maintenance facilities, airports, seaports, and ferry terminals, are considered in identifying critical bridge corridors that support post-earthquake emergency access.

The remainder of the paper is organized as follows. **Section 2** introduces the framework for identifying critical bridge corridors. **Section 3** describes the study area and presents an analysis of the top-ranked corridors and bridges. **Section 4** describes the online application tool. **Section 5** discusses potential future research. **Section 6** summarizes the key findings and provides recommendations based on the analysis.

2 Methodology

2.1 Overview

Figure 1 presents the framework of this study, which consists of three parts: preliminaries, route planning, and corridor ranking. In the preliminaries section, the definitions of origins, destinations, corridors, and path sections are introduced. In the route planning section, two methods, Methods A and B, are proposed. Method A is based on the shortest path, while Method B is based on optimization. By applying either of these two methods, the bridge usage and corridor usage for each type of facility access can be determined. Following this, corridor ranking is performed. If the ranking targets access to a single facility type, corridors are ranked based on their usage for accessing that facility type. If the ranking targets access to multiple facility types, corridors are ranked based on their aggregated score across those types. Finally, after identifying the critical corridors, the bridges within them are ranked according to their importance, defined as the product of their usage and damage probability.

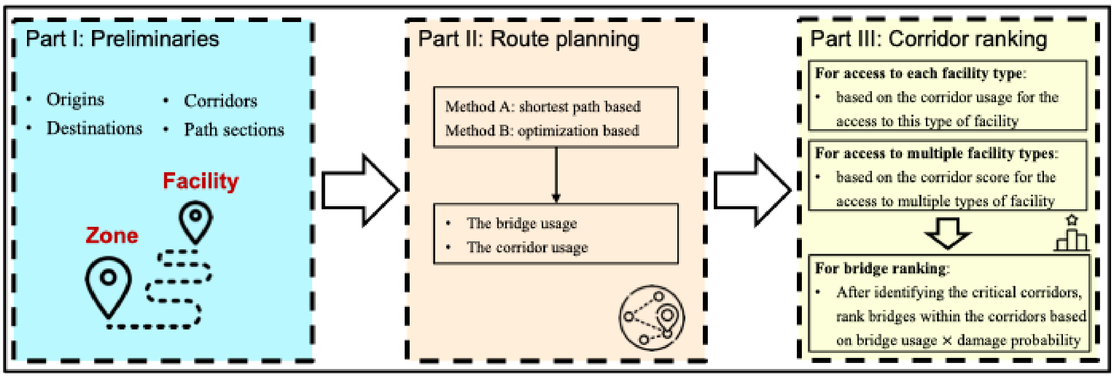


Figure 1 Framework of the study

2.2 Origins and destinations

The origins/destinations in this study are the centroids of zip-based zones and locations of critical facilities, including hospitals, fire stations, police stations, Caltrans maintenance facilities, airports, seaports, and ferry terminals. For simplicity, it is assumed that each zone has one travel demand to/from each type of facility. For example, each zone only has one travel demand to a hospital and this person travels from the centroid of this zone to the hospital. **Figure 2** gives an example. In this example, the orange dot is the centroid of a zone which people travel from or to. It is noted that we consider round trips, not just one-way trips. This is because people need to travel from their zones to critical facilities and be able to return to their zones. Therefore, for each zone-facility pair, both the zone and the facility serve as origins and destinations. In the following sections, the origin-destination (O-D) pairs are referred to as zone-facility pairs unless otherwise specified.

Figure 2 An example showing the origin and destination.

2.3 Corridors and path sections

Corridors are defined as the routes between two interchanges. **Figure 3** gives an example of a corridor. The orange nodes are interchanges. Therefore, the route between these two interchanges is a corridor.

A path section refers to the portion of a path between an O-D pair that lies entirely on Caltrans routes. **Figure 3** gives an example. The red and blue lines are the path sections, each starting from one on-ramp and ending at one off-ramp.

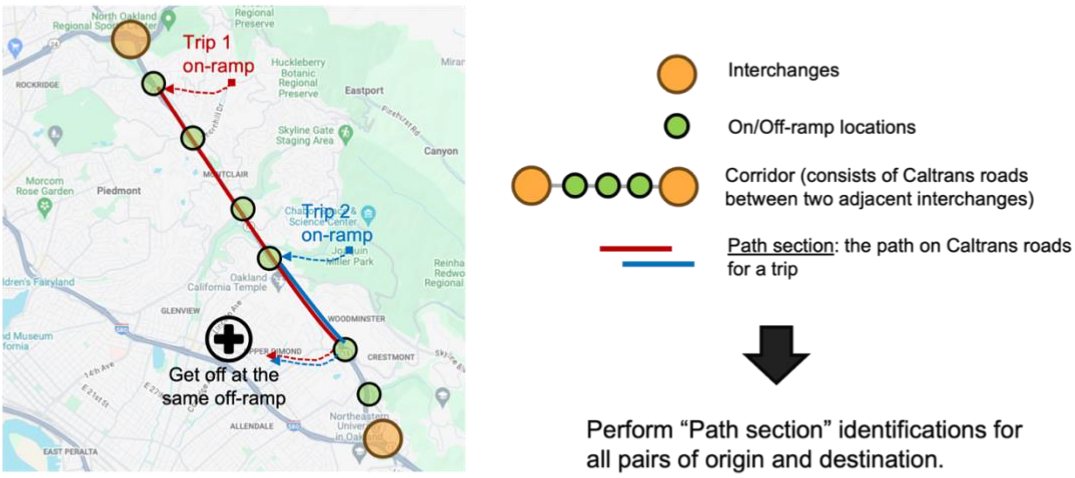


Figure 3 An illustration of corridors and path sections.

2.4 Methods A – shortest path based.

In this method, each zone chooses its closest critical facility using the shortest path. The shortest paths of all O-D pairs are added to identify the Caltrans routes for this method. It contains three steps.

- **Step 1**, For each zone, identify the shortest travel path to and from the nearest facility using Caltrans routes. Travel time is calculated based on the speed limits of both Caltrans routes and local roads. Note that if the shortest travel path does not involve any Caltrans routes, the zone is excluded from further consideration.
- **Step 2**: Find the path section for every O-D pair.
- **Step 3**: Identify the corridors and bridges that belong to the path sections in Step 2. Then, determine whether each zone utilizes a given corridor. The indicator $\mathbb{1}_{z,i,facility} = 1$ denotes that Zone z uses Corridor i to access a facility of type $facility$.

For the assistance of understanding of this section, examples and instructions are provided in **Appendix 8.1**.

2.4.1 Method A-Alternative: shortest paths with user given constraints.

In this method, each zone still chooses its closest critical facility using the shortest path, but under the sub-network where some corridors need to be remained untouched. It also contains three steps.

- **Step 1**: Identify the untouched corridors and remove them from the network.
- **Step 2**: Use Method A to find the closest facility for each zone and identify the path section for each O-D pair in the updated network. Then, determine whether each zone utilizes a given corridor.
- **Step 3**: Identify the corridors and bridges that belong to the path sections in Step 2.

For the assistance of understanding of this section, examples and instructions are provided in **Appendix 8.1**.

2.5 Methods B – optimization based.

In this method, the objective is to minimize the number of bridges/corridors that are needed for access by all zip-based zones. Therefore, the goal is to find the minimum number of bridges while ensuring that the travel time for each person is less than N times the original shortest path travel time, where N refers to time allowance factor, which is a user-defined parameter. The output of this method is the required bridges for each O-D pair. The corridors where these essential bridges are located are the essential corridors. The usage of these corridors can then be calculated. In this section, the mathematical model for Method B is given. For the assistance of understanding this section, examples and instructions are provided in **Appendix 8.3**.

2.5.1 Path candidates under the time allowance factor N

The path set $\mathbf{P}^{(o,d)}$ for an OD pair (o, d), which includes paths with travel times less than N times the original shortest path travel time, needs to be precomputed, and the bridges on each path must also be identified. For different Ns, the path set $\mathbf{P}^{(o,d)}$ for an OD pair (o, d) is generally different. If N is larger, indicating more travel time is allowed, there are more paths in the path set $\mathbf{P}^{(o,d)}$. Examples are given in **Appendix 8.3.1**.

2.5.2 Objective function

The objective is to minimize the number of bridges that are used, given as follows:

$$minimize \sum_{k \in \mathbf{K}} x_k \tag{1}$$

where $\mathbf{K}$ represents the bridge set and x_k is a binary variable, indicating whether Bridge k is selected or not.

2.5.3 Constraints

If an O-D pair chooses a path, the bridges along that path need to be selected. Furthermore, since round trips are considered, if a D is selected for an O, there should also be a path going from this D back to this O. These constraints are expressed using the following mathematical formulations.

$$\left(\sum_{k \in \mathbf{K}} a_{odjk} - \sum_{k \in \mathbf{K}} a_{odjk} \cdot x_k\right) - M(1 - y_{odj}) \leq 0, \forall o \in \mathbf{O}, d \in \mathbf{D}, j \in \mathbf{P}^{(o,d)} \tag{2}$$

$$\left(\sum_{k \in \mathbf{K}} a_{dojk} - \sum_{k \in \mathbf{K}} a_{dojk} \cdot x_k\right) - M(1 - y_{doj}) \leq 0, \forall o \in \mathbf{O}, d \in \mathbf{D}, j \in \mathbf{P}^{(d,o)} \tag{3}$$

$$\sum_{j \in \mathbf{P}^{(o,d)}} y_{odj} \geq z_{od}, \forall o \in \mathbf{O}, d \in \mathbf{D} \tag{4}$$

$$\sum_{j \in \mathbf{P}^{(d,o)}} y_{doj} \geq z_{od}, \forall o \in \mathbf{O}, d \in \mathbf{D} \tag{5}$$

$$\sum_{d \in \mathbf{D}} z_{od} \geq 1, \forall o \in \mathbf{O} \tag{6}$$

$$x_k \in \{0,1\} \tag{7}$$

$$y_{odj} \in \{0,1\} \tag{8}$$

$$z_{od} \in \{0,1\} \tag{9}$$

where $\mathbf{O}$ represents the zone set, $\mathbf{D}$ represents the facility set, and $\mathbf{P}^{(o,d)}$ denotes the path set for an O-D pair (o, d). The parameter a_{odjk} equals 1 if Bridge k is on Path

j for the O-D pair (o, d), and 0 otherwise. The binary variable y_{odj} indicates whether Path j for the O-D pair (o, d) is selected, and z_{od} is a binary variable indicating whether the O-D pair (o, d) is selected.

2.6 Corridor ranking

2.6.1 Corridor ranking for access to each facility type.

In the scenario of each facility access, corridors are ranked based on their corridor usage for the access to each type of facility. The corridor usage is defined as the zone count, indicating the number of zones that use a corridor to access a type of facility. The formula is given as follows:

$$zc_{i,facility} = \sum_{z \in \boldsymbol{Z}} \mathbb{1}_{z,i,facility} \quad (10)$$

Where $\mathbb{1}_{z,i,facility} = 1$ denotes that Zone z uses Corridor i to access a facility of type $facility$ and $zc_{i,facility}$ denotes the corridor usage of Corridor i that is used by zones for the access to facilities of type $facility$.

2.6.2 Corridor ranking for access to multiple facility types.

In the scenario of multiple facility access, corridors are ranked based on their score. The corridor score is calculated as follows:

$$score_i = \sum_{facility} \widetilde{zc}_{i,facility} \times w_{facility} \quad (11)$$

$$\widetilde{zc}_{i,facility} = \frac{zc_{i,facility}}{zc_{max,facility}} \quad (12)$$

$$\sum_{facility} w_{facility} = 1 \quad (13)$$

where $zc_{i,facility}$ represents the zone count of Corridor i for a certain facility access, $zc_{max,facility}$ represents the maximum zone count for a certain facility access, and $\widetilde{zc}_{i,facility}$ represents the normalized zone count of Corridor i. Additionally, $w_{facility}$ represents the weight for a certain facility access (a user-defined parameter), and $score_i$ denotes the corridor score of Corridor i.

2.6.3 Bridge ranking.

After identifying top-ranked corridors, next step is to identify the critical bridges on these corridors. It is noted that not all the bridges on the top-ranked corridors are needed for emergency travel. As for how to rank bridges, we provide a formula to calculate the importance of each bridge, but this formula is only a reference. Caltrans can decide whether to use it or not. The formula is as follows:

$$importance_b = usage_b \times p_b^{dam} \quad (14)$$

where $usage_b$ represents the times that Bridge b is used, while p_b^{dam} represents the damage probability that Bridge b cannot function any more after an earthquake, which should be given by Caltrans.

3 The Bay Area Case

3.1 Zip-based zones and critical facilities.

Zip Codes are a system of postal codes used by the United States Postal Service (USPS) to identify specific geographic regions for the purpose of efficiently delivering mail. Currently, Zip codes are widely recognized and used by the public and in various fields, including emergency response. Zip codes are simpler to communicate and understand for laypersons, making them ideal for public-facing applications, as each person knows the zip code of the area in which they live or work. Therefore, in this study, zip-based zones are used for origins/destinations. There are 298 zip-based zones, as shown in **Figure 4**.

Critical facilities in this project include hospitals, fire stations, police stations, Caltrans maintenance facilities, airports, seaports, and ferry terminals. Their spatial distributions and counts vary, as shown in **Figure 5–Figure 8**. There are 78 hospitals, 563 fire stations, 205 police stations, 59 maintenance facilities, 25 airports, 5 seaports, and 14 ferry terminals in District 4. Many facilities are concentrated around the San Francisco Bay, which is reasonable, as this area is more developed and more densely populated than the other suburban area.

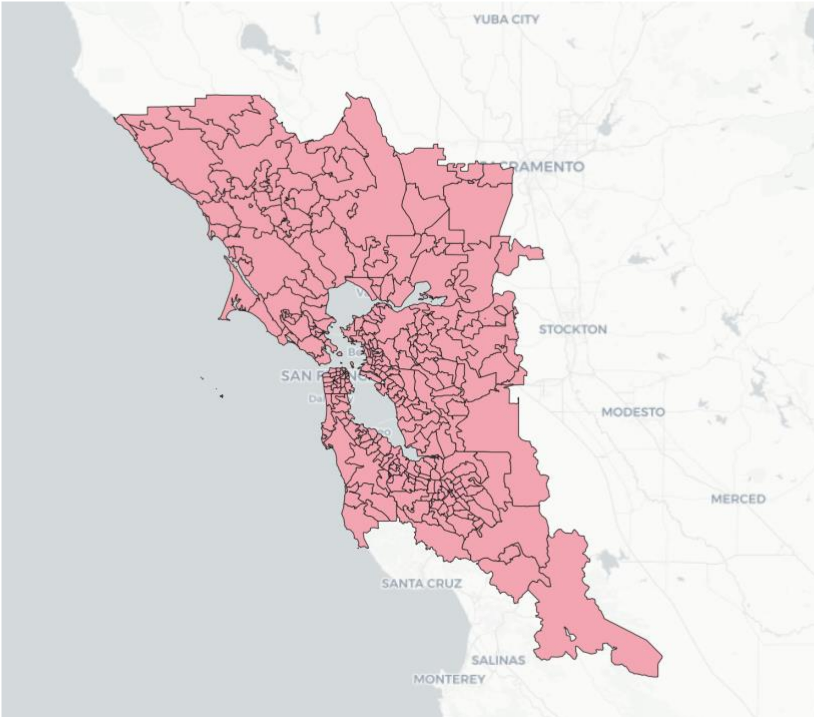
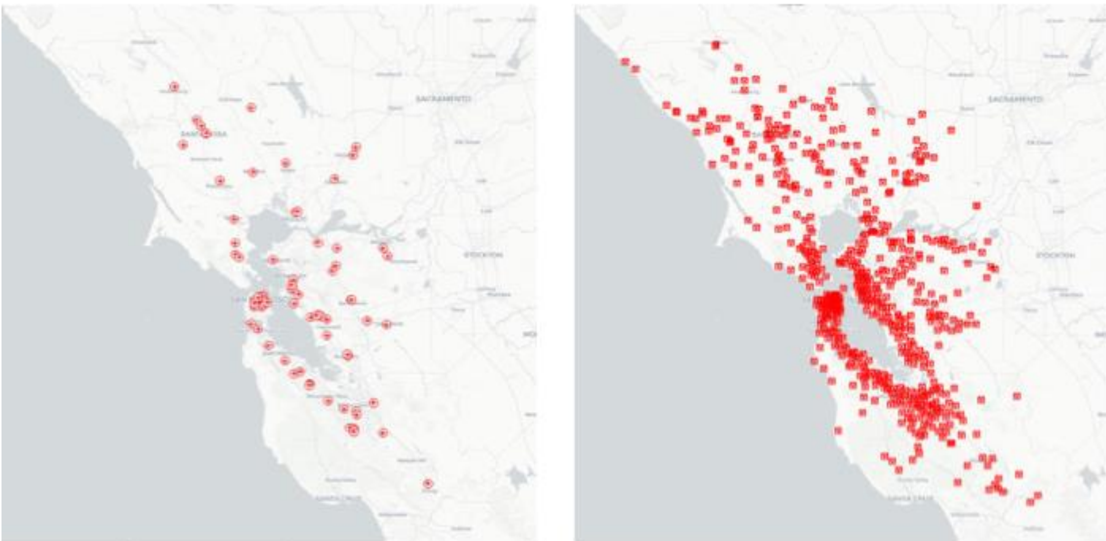


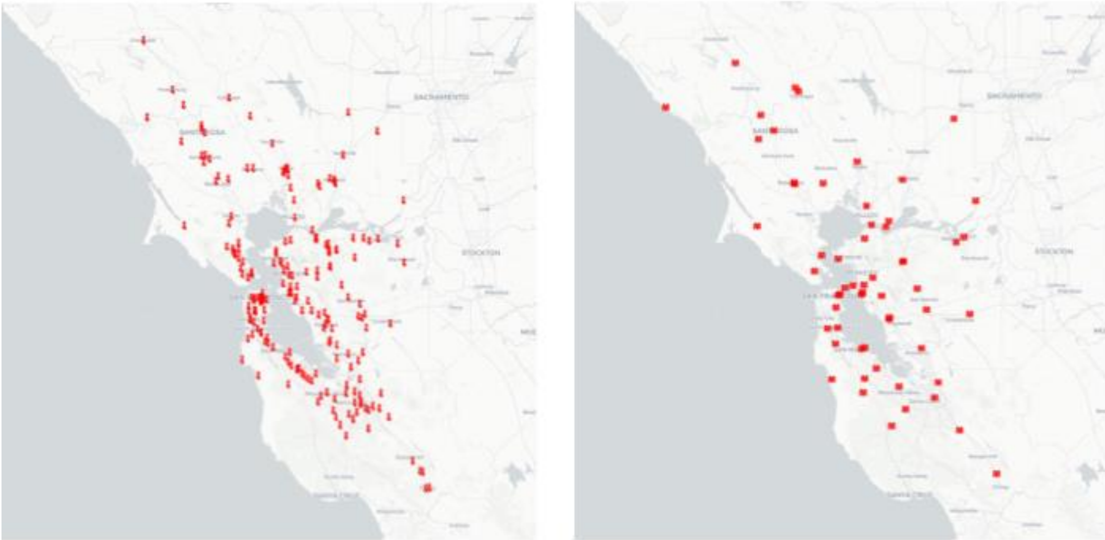
Figure 4 The locations of 298 zip-based zones.



(a) Hospitals (78 in total)

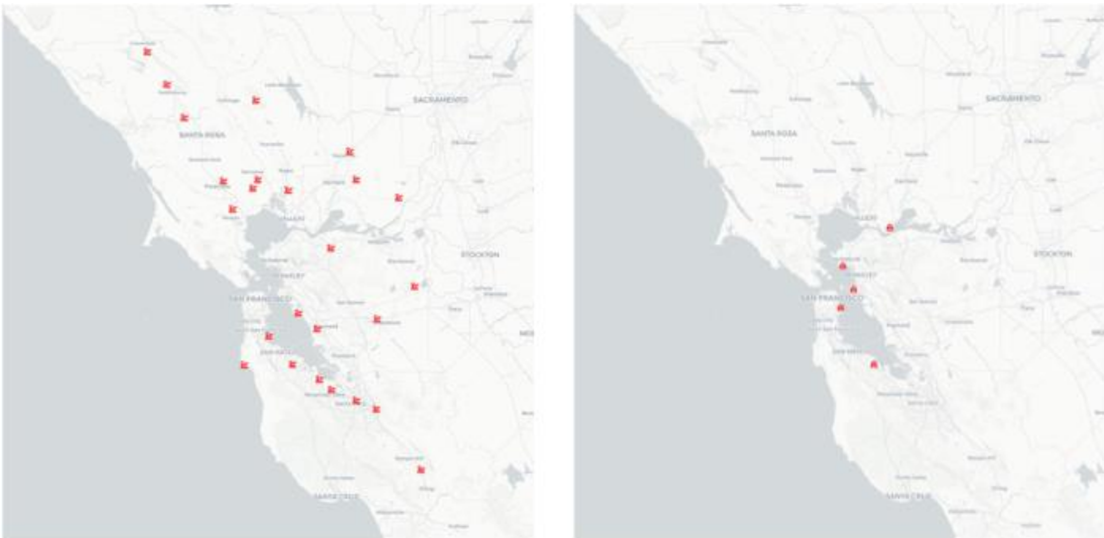
(b) Fire stations (563 in total)

Figure 5 The locations and number of each type of critical facility.



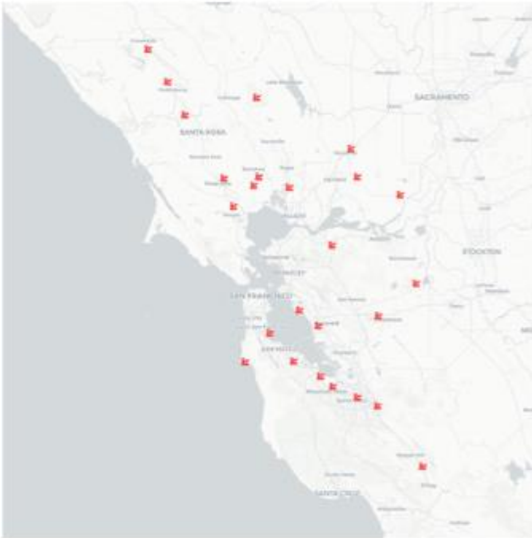
(c) Police stations (205 in total) (d) Maintenance facilities (59 in total)

Figure 6 The locations and number of each type of critical facility (continued).



(e) Airport (25 in total) (f) Seaport (5 in total)

Figure 7 The locations and number of each type of critical facility (continued).



(g) Ferry terminals (14 in total)

Figure 8 The locations and number of each type of critical facility (continued).

3.2 Bridge traffic network

As shown in **Figure 9**, the bridge traffic network consists of two types of elements: nodes and links. A node represents one road intersection or zone centroid. There are several types of nodes: highway junctions, on/off ramp nodes, bridge nodes, and zone centroids. A link represents the stretch of road between two adjacent nodes. There are several types of links, including highway segments, on/off ramps, and virtual links. The following subsections explain each element.

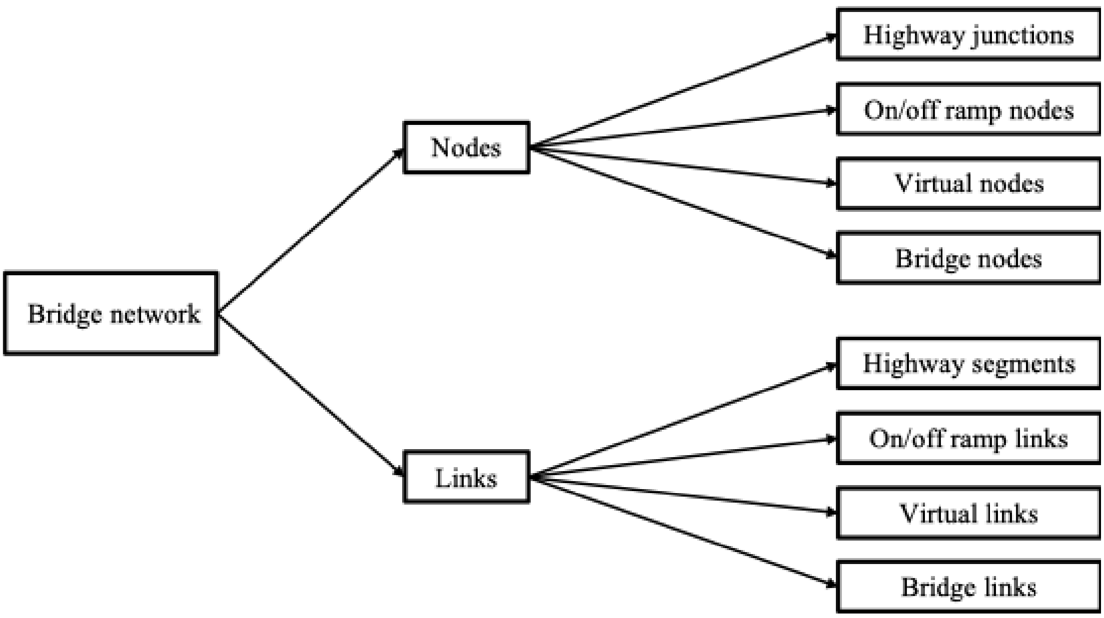
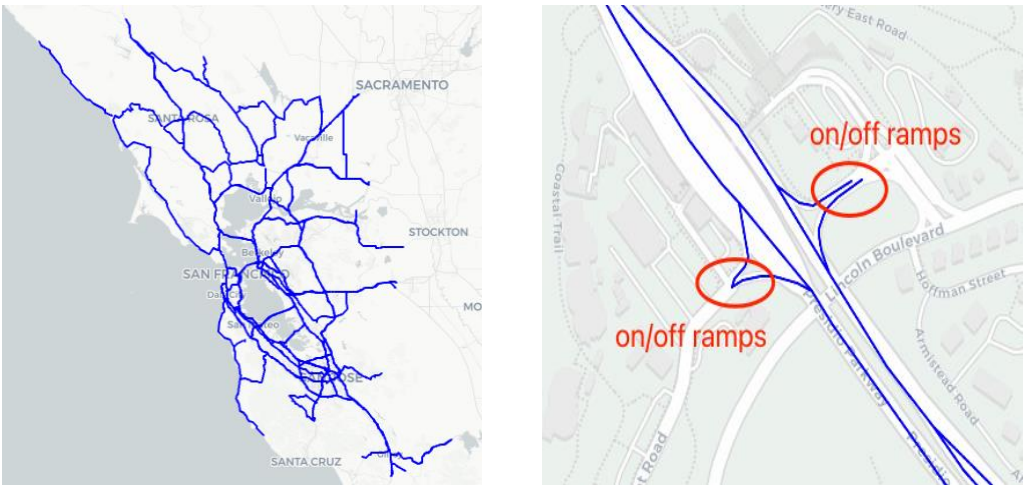


Figure 9 Components of a bridge network.

3.2.1 Highway junctions, segments, on/off ramp nodes, and links.

The Caltrans highway routes in District 4 are provided by Caltrans and then mapped to an open-source road network (https://www.openstreetmap.org/) to identify the corresponding Caltrans highway junctions, segments, on/off ramp nodes, and links. **Figure 10(a)** shows the extracted highway network while **Figure 10(b)** displays the on/off ramps.

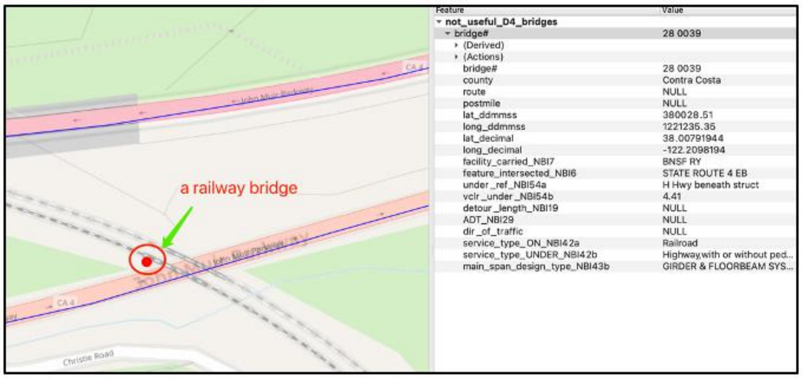


(a) The highway network (b) Example of on/off ramp nodes

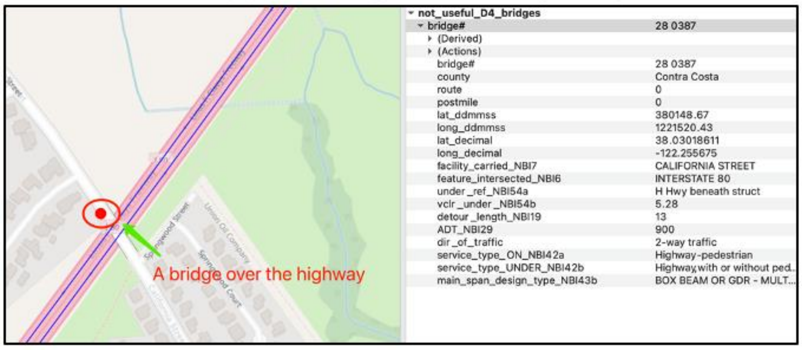
Figure 10 The highway network and on/off ramp nodes.

3.2.2 Bridge nodes and links.

The extracted highway network does not cover the information about which links are bridges. However, the identification of bridge links is necessary as it serves the construction of bridge traffic network for the determination of critical corridors. Data about the locations of bridges on highways are given by Caltrans. There are 1,997 Caltrans bridges in total in District 4. However, some bridges are not on the highway, but over the railways and some bridges cross the highway, beneath which is the highway. **Figure 11** shows two examples of these bridges. After manually checking each bridge, 196 bridges are removed, and 1,801 bridges are kept. **Figure 12** presents these 1801 bridges. A challenge with this bridge dataset is that the bridges are not mapped or linked to the road network data. Therefore, a matching process is designed to connect the bridge dataset to the highway network. **Figure 13** shows an example of mapping a bridge to the highway network. This bridge carries two-way traffic and is therefore mapped to two links of different directions. Further, in the following analysis, it is better to use nodes to represent bridges, rather than links. Therefore, we further process the mapped links and split each of them into several bridge links and bridge nodes. **Figure 14** gives an example about how to split the mapped links. It is noted that some bridges only carry one-way traffic, so that they only have one bridge node. After processing, there are 2,900 bridge nodes.



(a) An example of a railway bridge



(b) An example of a bridge over the highway

Figure 11 Examples of Caltrans bridges that are not connected to the highway.

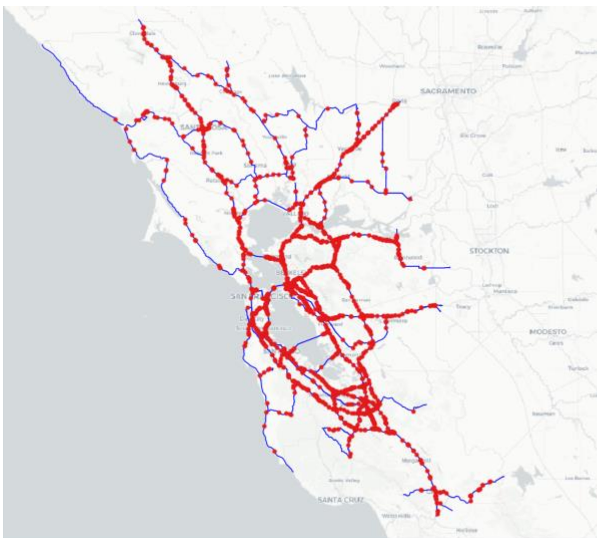


Figure 12 Locations of the 1,801 bridges.

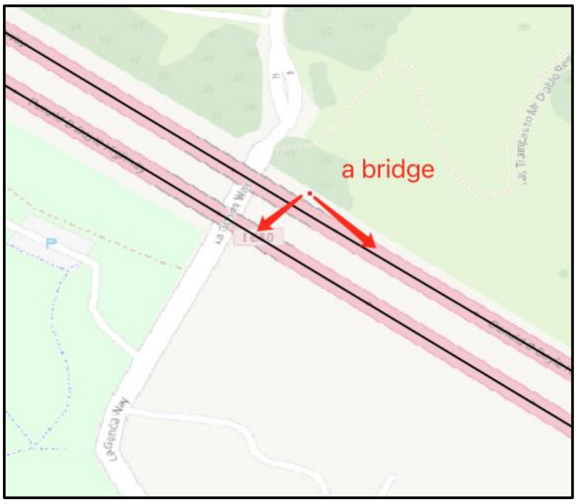


Figure 13 An example of mapping a bridge to the road network.

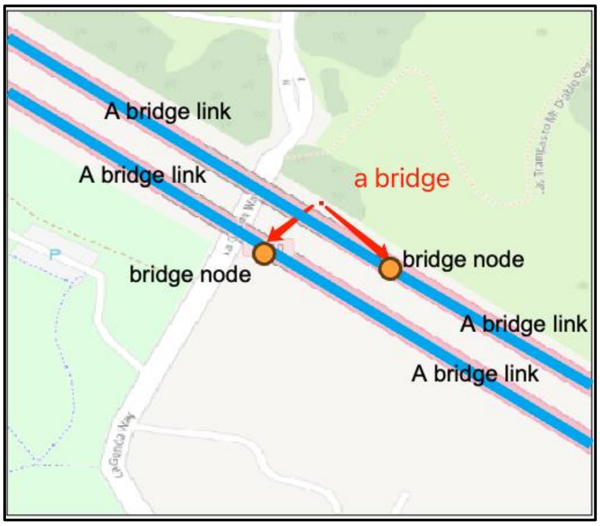


Figure 14 An example of splitting the mapped links.

3.2.3 Virtual nodes and links.

Centroids of the zones and the locations of facilities are treated as "virtual nodes", which are the origins/destinations of trips. Virtual links are then used to connect the virtual nodes to the on/off ramp nodes from the highway road network. Virtual links are used as an abstract way to represent the "first" or "last" segment of the trip on the local roads, e.g., from a highway off-ramp to home. The free flow travel time of each virtual link is the sum of free flow travel times of local links of the shortest path between the virtual node and the on/off ramp node.

The virtual nodes and links form pathways that connect highway on/off ramps to local origins or destinations. This arises a new question: how many on/off ramp nodes should be connected to each virtual node?

We establish the following rule: each virtual node is connected to all on/off ramp nodes within a half-hour drive under free-flow traffic conditions. If the number of on/off ramp nodes that connect to a virtual node is less than ten or the closest on/off ramp node is more than a half-hour drive away, at most ten shortest virtual links connecting on/off ramp nodes to the virtual node are retained. Using a "half-hour" or other distance limitation does not affect Methods A and B. For Method A, the shortest path to the closest facility is always used. Since Caltrans routes have significantly higher speed limits than local roads, travel on local roads lasts only a few minutes. For Method B, the following rule (also mentioned in **Section 2.5**) applies: "When it is stated that the travel time is relaxed to N times the original shortest path travel time, it implies that only the highway travel time is relaxed, while the local road travel time remains unchanged". Thus, in Method B, only virtual links with a travel time equal to or less than the local road travel time on the shortest path are selected.

However, different distance limitations may affect Method A–alternative. In this method, the shortest path must be recalculated after selected bridges in certain corridors are removed. This may force some zones to take slightly longer detours on local roads. The distance limitations are user-defined parameters—for example, users may choose 30 minutes, 60 minutes, and so on. If 30 minutes is set as the distance limitation, a zone is considered to have lost access to a facility when its shortest local-road travel time exceeds 30 minutes in the modified network. Therefore, different distance limitations represent varying tolerances for local-road travel time in Method A–alternative.

3.2.4 Corridors

Under this study, there are 161 predefined corridors in District 4, based on the definition in **Section 2.3**. The corridors are numbered according to a specific prioritization rule. The first priority in naming is given to the type of route, in the order: Major Highway Routes, Auxiliary Highway Routes, and then others. The second priority is based on geographic orientation from south to north, and the third priority follow from west to east.

Additionally, each corridor is identified using a naming convention that follows this structure: District No. – Residing county abbreviations – Highway No. – Sub-identifier (if the first three elements are not sufficient to uniquely distinguish corridors).

These corridors are shown in **Figure 15(a)**. Additionally, **Figure 15(b)** provides examples of some corridor names, while **Figure 15(c)** displays their corresponding IDs. The detailed information of the 161 corridors is provided in **Appendix 8.7**.

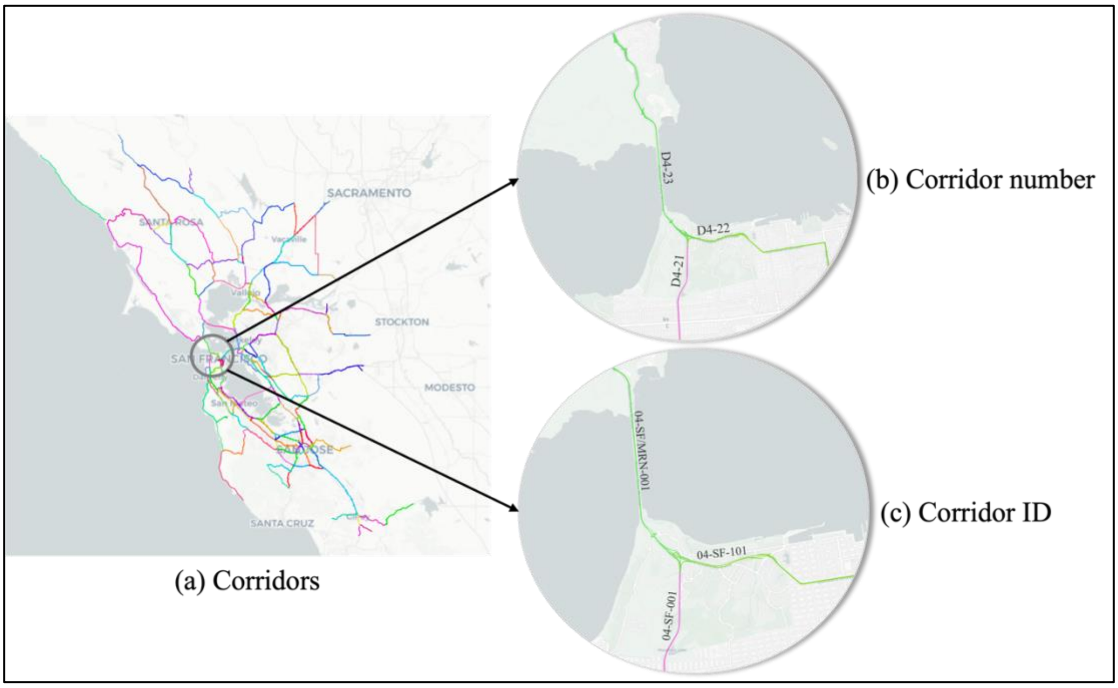


Figure 15 Corridors in District 4.

3.3 Cases of applying Method A

3.3.1 Method verification.

Firstly, we need to validate that the shortest paths obtained in Method A are truly the shortest paths in reality. Therefore, the shortest path derived from our network for each O-D pair is compared to that obtained from Google Maps. The Google Maps routes were collected at 3:00 a.m. on December 30, 2024, when real-time traffic conditions can be reasonably assumed to represent free-flow traffic. **Figure 16** presents two examples. The paths in **Figure 16(a)** align well, whereas the paths in **Figure 16(b)** do not match. The reason for this discrepancy is that, for the origin-destination pair in **Figure 16(b)**, the actual shortest path relies on a local road, highlighted in green. This path initially follows the Caltrans route, then exits midway, take the local road, and later re-enters the Caltrans route. However, this project aims to assess the importance of each bridge corridor without relying on local roads. Therefore, once a vehicle enters the Caltrans route, it cannot exit the Caltrans route midway. Under this constraint, the path shown in blue is obtained. It is noted that this constraint is incorporated into the built network, where a vehicle enters the Caltrans route through a virtual link (i.e., a local road) and exits to reach its destination through another virtual link. This setup ensures that the vehicle cannot exit midway and re-enter the Caltrans highway in order to eliminate the uncertainty due to driver behavior.

Table 1 shows the path dissimilarity rate for all zone-closest facility pairs for each type of facility access. It is seen that the dissimilarity rate for fire station access is the lowest, with a value of 0.5%. This is because there are many fire stations around each zone. The paths for a closer zone-facility pair are more similar, leading to a lower dissimilarity rate. For the other types of facility access, their dissimilarity rates are around 6%. This, to some extent, indicates that driving from these critical facilities to zones heavily relies on Caltrans routes if people want to have the shortest travel time.

Figure 16 Examples of shortest path comparisons between Google Maps and the network used in this study.

Table 1 Path dissimilarity rate for all zone-closest facility pairs for each type of facility access.

Facility type	Dissimilarity rate
Hospital	6%
Fire station	0.5%
Police station	7%
Maintenance facility	7%
Airport	7%
Seaport	7%
Ferry terminal	5%

3.3.2 Results analysis

Figure 17–Figure 23 and **Table 2** present the results applying Method A to different types of facility access. It is noted that if bridges on a corridor are not used by any path section, this corridor is not "must-have" corridor. This is because this project only targets bridge corridors in Caltrans network. If zones do not use Caltrans bridges to access facilities, these zones are assumed to be still able to access facilities after earthquakes without using Caltrans network, so that when calculating the zone count for each corridor, these zones are not included.

It is seen that the number of "must-have" corridors for fire station access is the smallest, at only 32, with an average round-trip travel time of just 9.15 minutes. This is because only 31 out of 298 zones rely on Caltrans routes to reach fire stations, and District 4 has 563 fire stations–more than twice the number of zones–resulting in very short paths to the nearest fire stations. Additionally, the maximum zone count for corridors is 2, indicating that these 31 zones using Caltrans bridges are spatially dispersed. In contrast, accessing other types of facilities requires significantly more corridors and much longer average round-trip travel times. For example, all zones need 115 corridors to access the closest hospitals, with an average travel time of 26.23 mins, 70 corridors to access police stations, with an average travel time of 21.28 mins, 116 corridors to access Caltrans maintenance facilities, with an average travel time of 21.70 mins, 129 corridors to access airports, with an average travel time of 36.25 mins. Additionally, seaports and ferry terminals require the most corridors (134 each) and the longest travel times (58.67 and 64.12 minutes, respectively). This is because District 4 has only 5 seaports and 14 ferry terminals, meaning zones in remote areas must traverse many corridors and spend significantly more time to reach these facilities.

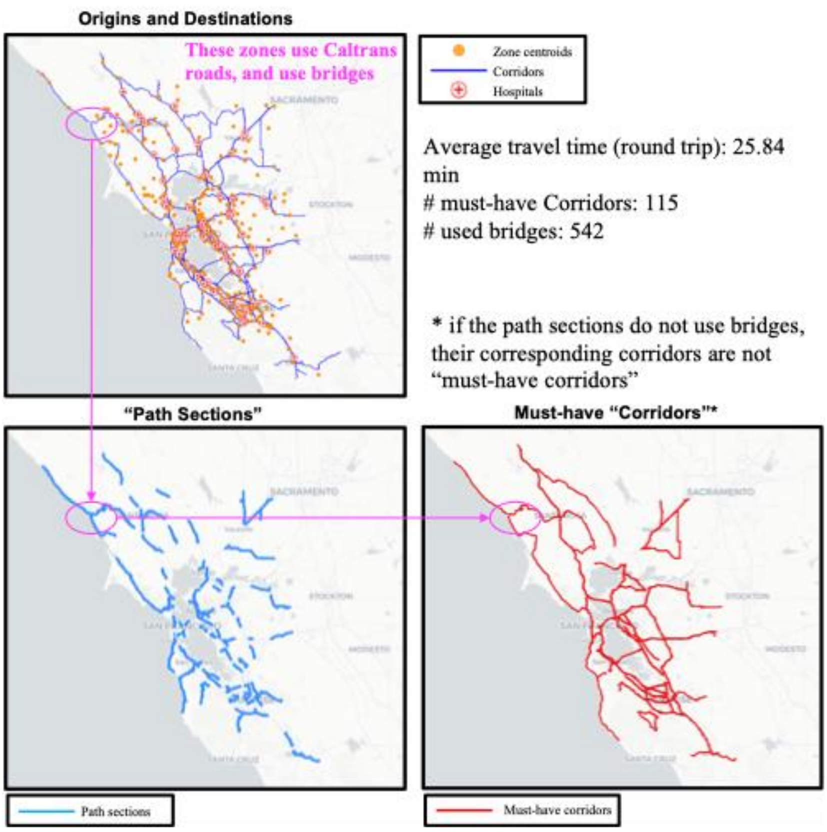


Figure 17 Results applying Method A for hospital access.

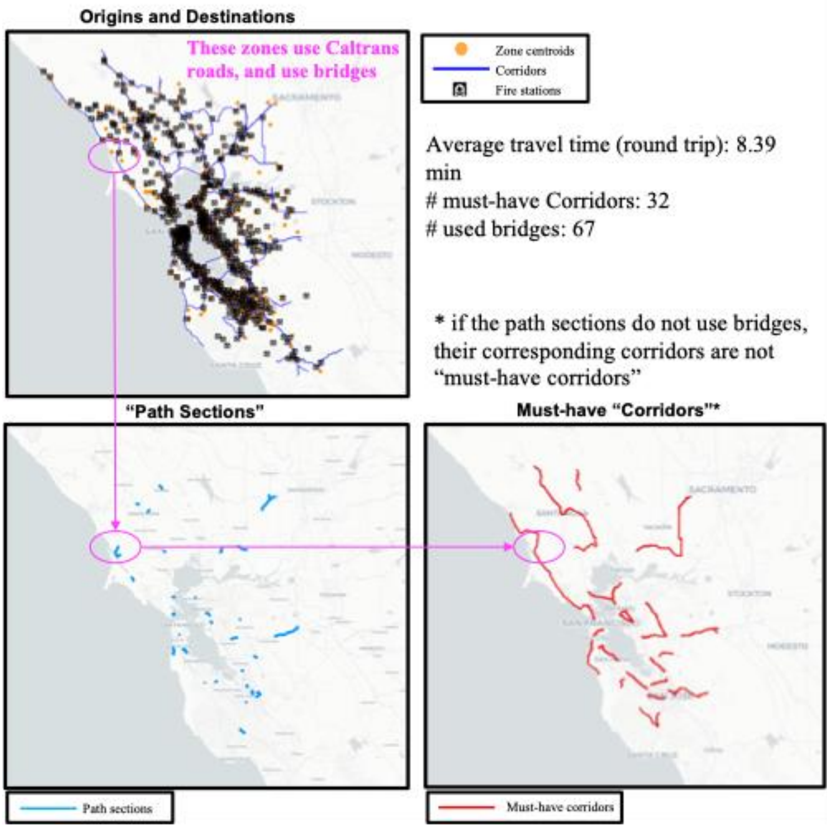


Figure 18 Results applying Method A for fire station access.

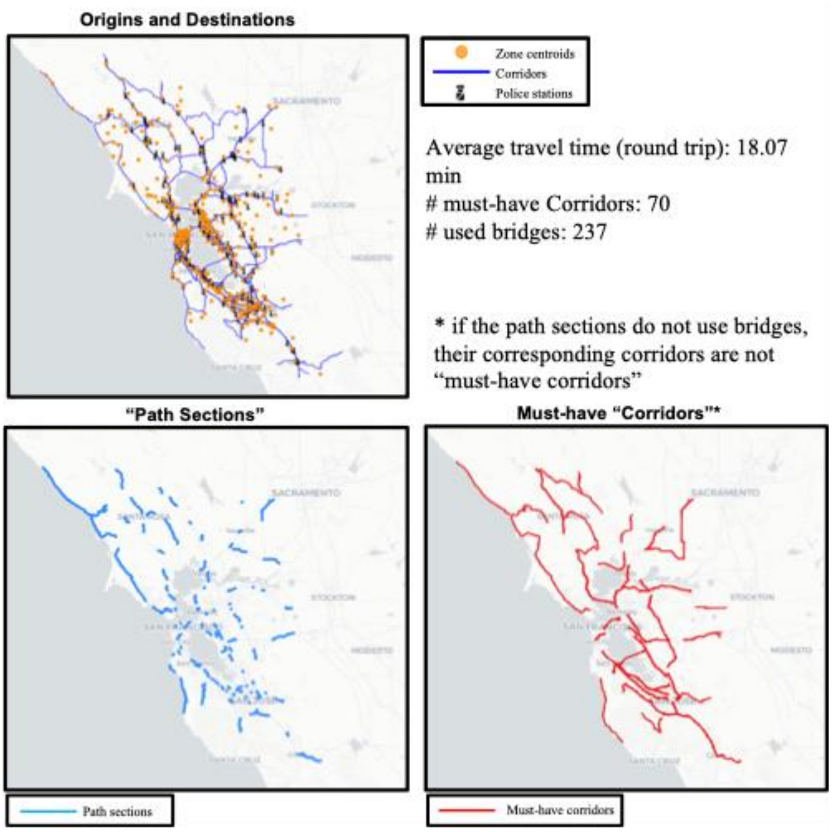


Figure 19 Results applying Method A for police station access.

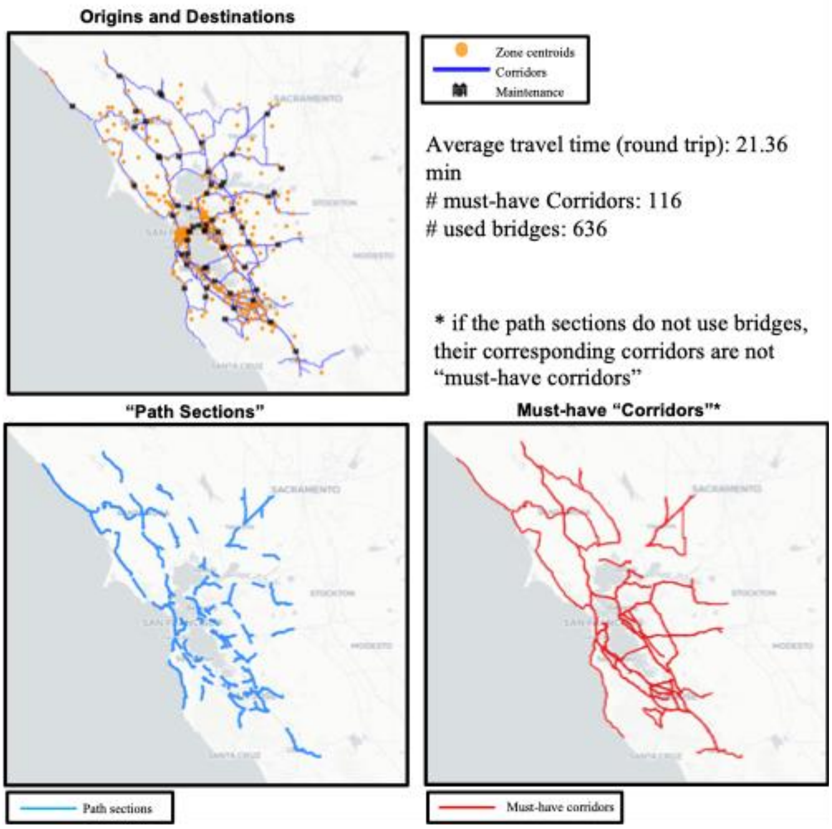


Figure 20 Results applying Method A for Caltrans maintenance facility access.

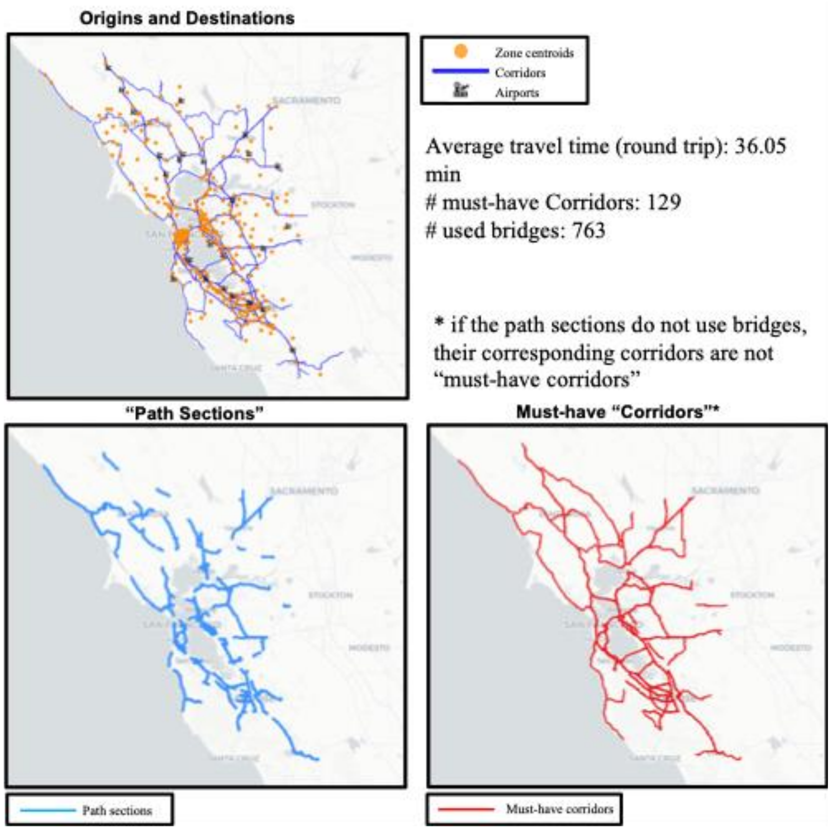


Figure 21 Results applying Method A for airport access.

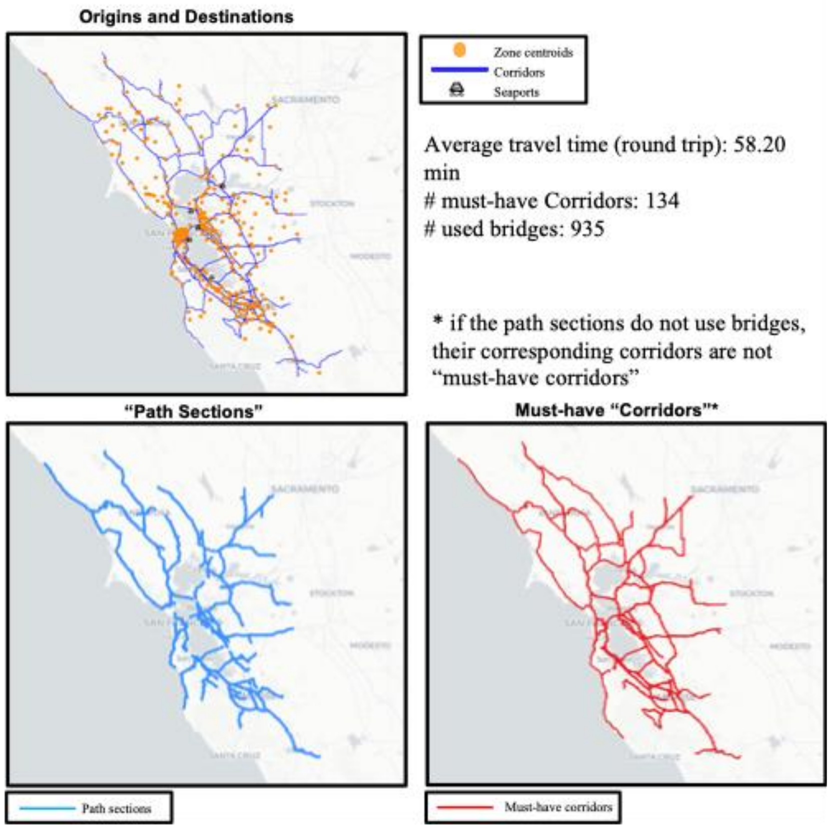


Figure 22 Results applying Method A for seaport access.

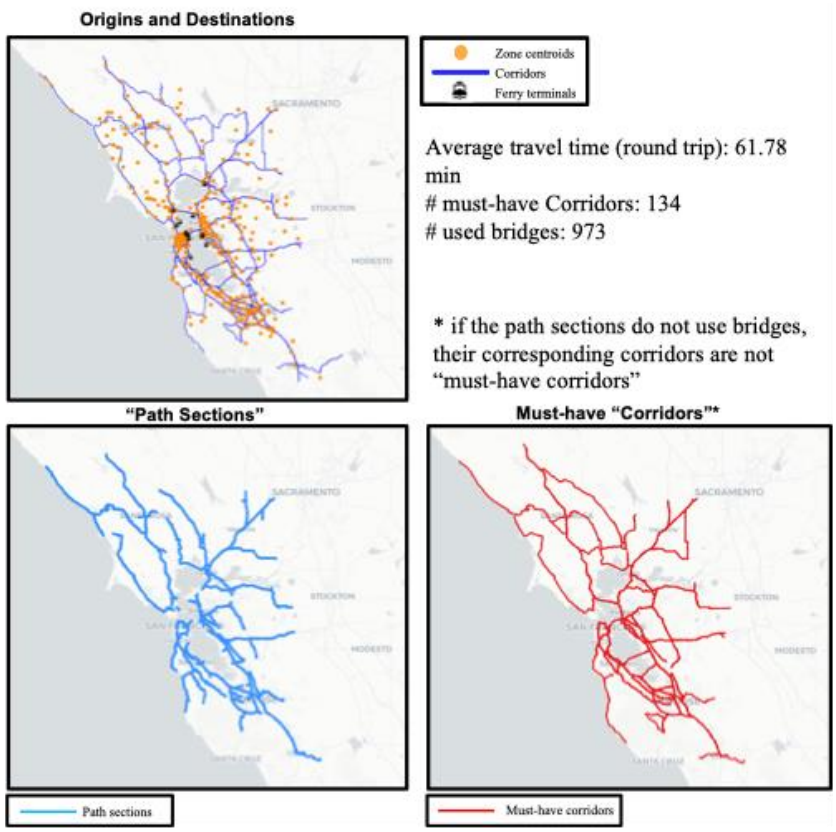


Figure 23 Results applying Method A for ferry terminal access.

Table 2 Results for all zone-closest facility pairs for each type of facility access.

Facility type	Facility count	#zones needing Caltrans routes (298 in total)	#zones needing Caltrans bridges (298 in total)	#corridors (161 corridors in total)	Maximum zone count for corridors
Hospital	78	190	159	115	13
Fire station	563	68	31	32	2
Police station	205	156	109	70	10
Maintenance	59	247	215	116	11
Airport	25	259	249	129	31
Seaport	5	289	286	134	61
Ferry terminal	14	281	268	134	60

Figure 24 presents the top-ranked corridor for each type of facility access and for all facility types with equal weights. The ranking is based on zone count of each corridor, as explained in **Section 2.6.1**. It is found that the top-ranked corridor for each type of facility varies. This is reasonable as the spatial distributions of these facilities vary, as shown in **Figure 5–Figure 8**. For example, Corridor 25 (04-MRN/CC-580) ranks the top for seaport access. This is because for the zones in the Marin County and Sonoma County, the closest seaport is the Richmond port. They all need to cross the Richmond-San Rafael Bridge to reach this port, resulting in the high demand for this corridor. Corridor 36 (04-SON-116-3) ranks the top for not only hospital and police station access, but for all facility types under equal weights, which means that this corridor is relatively more important than others since more zones require to use this corridor.

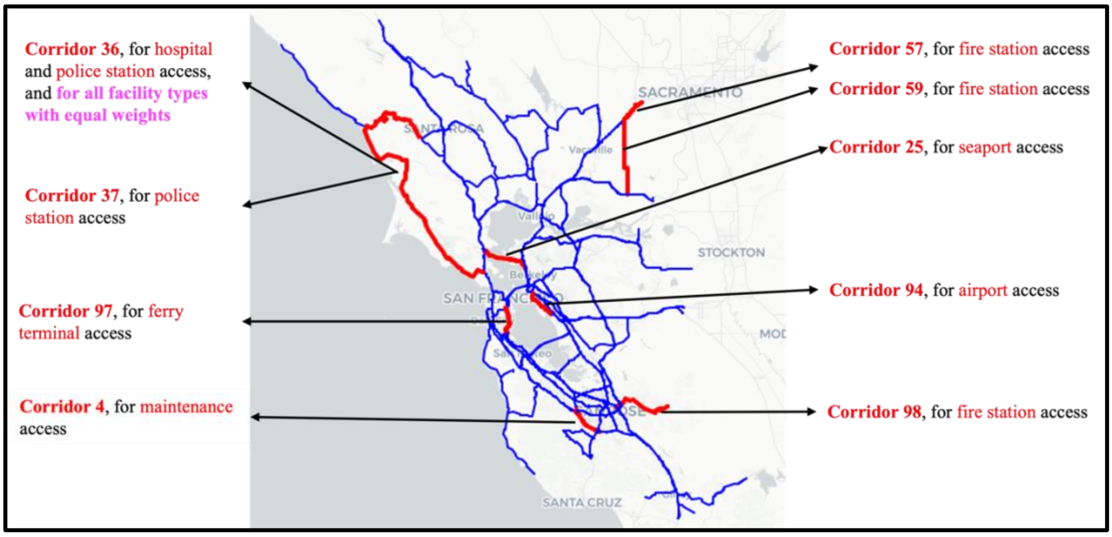


Figure 24 The top-ranked corridor for each type of facility access and for all facility types with equal weights.

3.3.3 Comparative analysis

In the previous analysis, each zone is treated equally, with a single unit of travel demand per zone. In this case, if a zone uses a corridor, the corridor is counted once. This section presents an alternative ranking where corridor importance is weighted by zone population. Under this approach, if a zone uses a corridor, the corridor is counted proportionally to the zone's population. The corridor score is calculated using the following formulas:

$$score_i = \sum_{facility} \widetilde{wzc}_{i,facility} \times w_{facility} \tag{15}$$

$$\widetilde{wzc}_{i,facility} = \frac{wzc_{i,facility}}{wzc_{max,facility}} \tag{16}$$

$$wzc_{i,facility} = \sum_{z \in \boldsymbol{Z}} \mathbb{1}_{z,i,facility}\, pop_z \tag{17}$$

$$\sum_{facility} w_{facility} = 1 \tag{18}$$

where $wzc_{i,facility}$ represents the weighted zone count, $\widetilde{wzc}_{i,facility}$ represents the normalized weighted zone count, and pop_z represents the population of zone z. If $pop_z = 1$ for all zones, $wzc_{i,facility} = zc_{i,facility}$.

The population of zip-based zones in District 4 is obtained from the United States Census Bureau (https://www.census.gov). **Figure 25–Figure 26** show corridors that rank within the top N% for more than half of facility types under both equal-weight and population-weight approaches. It is seen that the top ranked corridors when zones are equally treated are primarily in rural areas, as they are often the only roads providing access for many zones. Some are also in well-developed areas where facilities are concentrated, requiring zones to use these corridors to reach the facilities. In contrast, the top ranked corridors based on zone population are all in densely populated areas, with none of the rural corridors ranking among the top. This is expected, as corridors in such areas are used more frequently, resulting in a higher $wzc_{i,facility}$. Therefore, it is necessary to discuss whether to use equal-weighted approach or population-weighted approach to rank corridors.

(a) Corridors that rank within the top 30% for more than half of facility types

(b) Corridors that rank within the top 40% for more than half of facility types

(c) Corridors that rank within the top 50% for more than half of facility types

Figure 25 Corridors that rank within the top N% in over half the number of facility types when each zone is given equal weight.

(a) Corridors that rank within the top 30% for more than half of facility types

(b) Corridors that rank within the top 40% for more than half of facility types

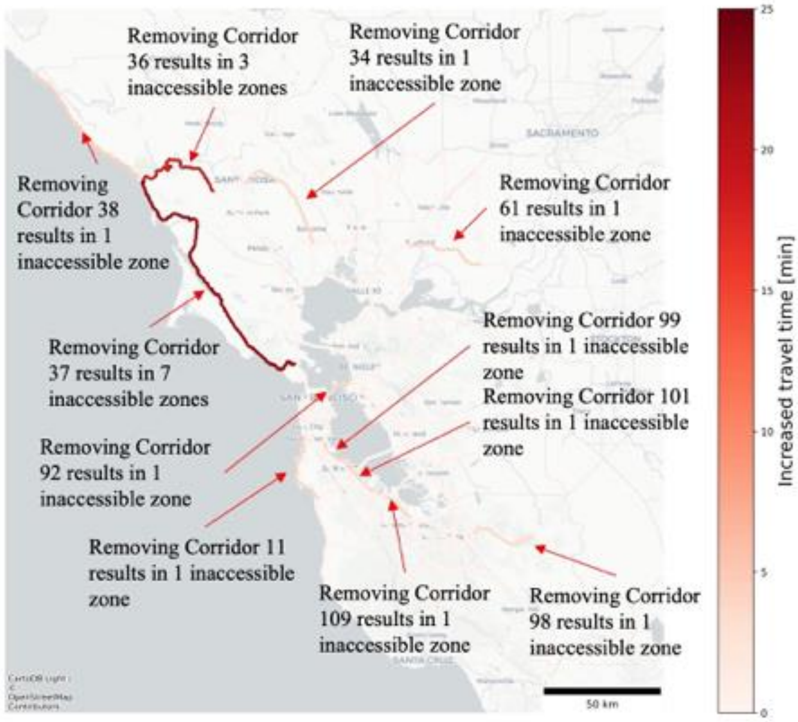
(c) Corridors that rank within the top 50% for more than half of facility types

Figure 26 Corridors that rank within the top N% in over half the number of facility types when weighted by zone population.

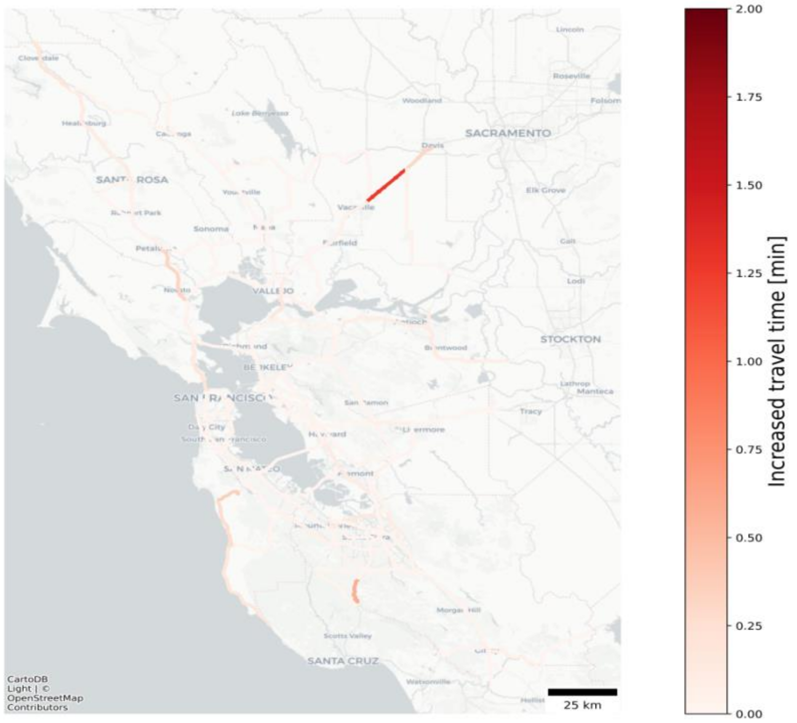
3.4 Cases of applying Method A-alternative

3.4.1 Results analysis

Each corridor is removed individually to analyze its separate impact on access to critical facilities. If a zone cannot be accessed, a penalty travel time of infinite hours is assumed. **Figure 27** shows the increase in average travel time for zones to access hospitals due to the individual removal of corridors. It is seen that removing most of the corridors does not increase travel time much and all zones still access hospitals. However, removing some corridors, especially those that are the only roads out for zones in the suburban area, result in these zones inaccessible. For instance, if Corridor 37 (04-MRN/SON-001) cannot be used, 7 zones cannot access hospitals, leading to an increase in the average round-trip travel time of 22.39 mins. Removing Corridors 36 (04-SON-116-3) results in 3 zones having no way to reach hospitals, while removing Corridors 38, 11, 61, 109, 101, 99, 92, 34, and 98 leads to 1 inaccessible zone. It is suggested that more attention should be given to corridors in remote areas, as they are the only roads available to people living in the surrounding zones.



(a) The impact of individually removing corridors on the increase in the number of inaccessible zones



(b) The impact of individually removing corridors on the increase in the number of inaccessible zones

Figure 27 The impact of individually removing corridors for access to hospitals.

3.5 Cases of applying Method B

3.5.1 Results analysis and comparison between Methods A and B

In the experiment of applying Method B, the time allowance factor N is set to 2, which indicates that the total travel time can be relaxed to twice the original shortest path travel time, as described in **Section 2.5**. Method B minimizes the number of used bridges, so people in some zones take a detour to share more bridges.

Figure 28–Figure 34 present the results applying Method B to different types of facility access. It is seen that all zones need 418 bridges in 97 corridors to access the closest hospitals, with an average travel time of 27.54 mins, 57 bridges in 27 corridors to access fire stations, with an average travel time of 9.21 mins, 208 bridges in 65 corridors to access police stations, with an average travel time of 18.68 mins, 516 bridges in 112 corridors to access Caltrans maintenance facilities, with an average travel time of 22.84 mins. Additionally, access to seaports and ferry terminals still requires many bridges and corridors (910 bridges in 133 corridors and 904 bridges in 132 corridors, respectively), as their facilities are limited in number, forcing remote areas to traverse many corridors to reach the nearest ones.

The results of applying Methods A and B are compared to illustrate the differences between the two methods, as shown in Table 3. Method A assumes that people from each zone use the shortest path to the nearest facility and then return via the shortest path to the zone. In contrast, Method B minimizes the number of bridges used, encouraging people to take detours in order to share bridges. As a result, Method A yields shorter travel times, while Method B results in fewer bridges being used. For instance, the average round-trip travel time for zones accessing hospitals using Method A is 26.23 mins, which is 1.31 mins less than that of Method B. However, the number of used bridges in Method A is 542, which is 124 more than in Method B. The same can be seen in other facility access. It is suggested that if decision makers have a limited budget, Method B is preferable; otherwise, Method A is recommended when shorter travel time is the priority.

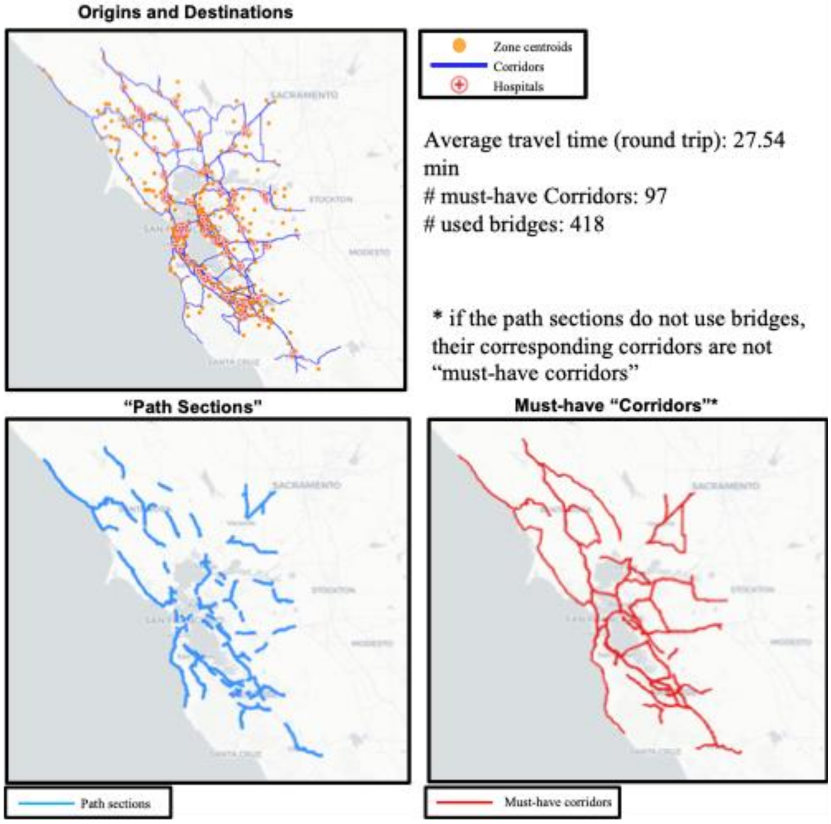


Figure 28 Results applying Method B for hospital access.

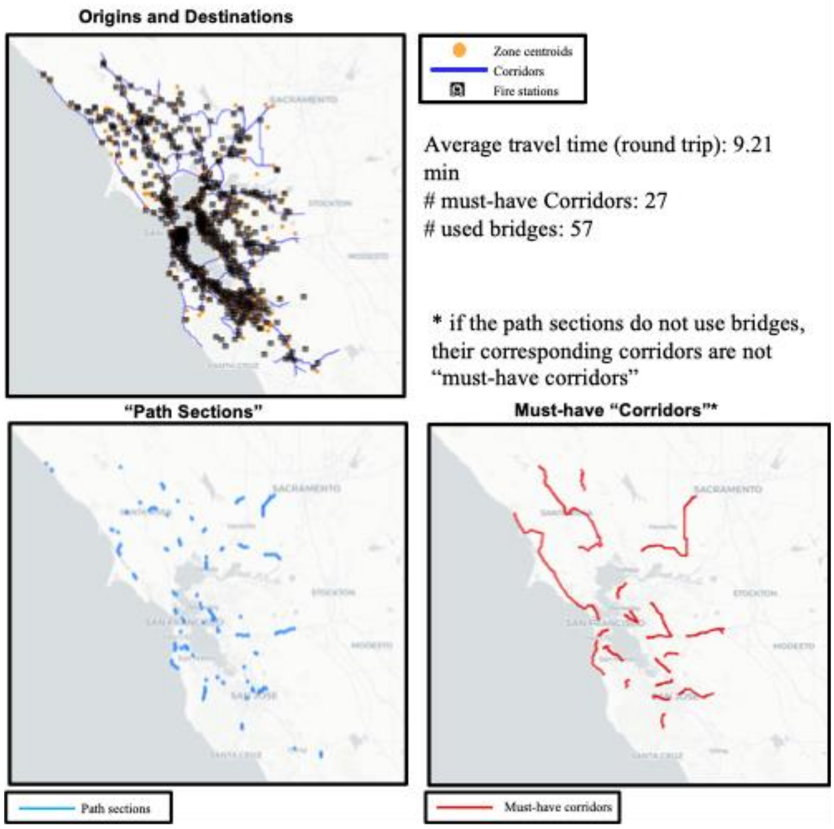


Figure 29 Results applying Method B for fire station access.

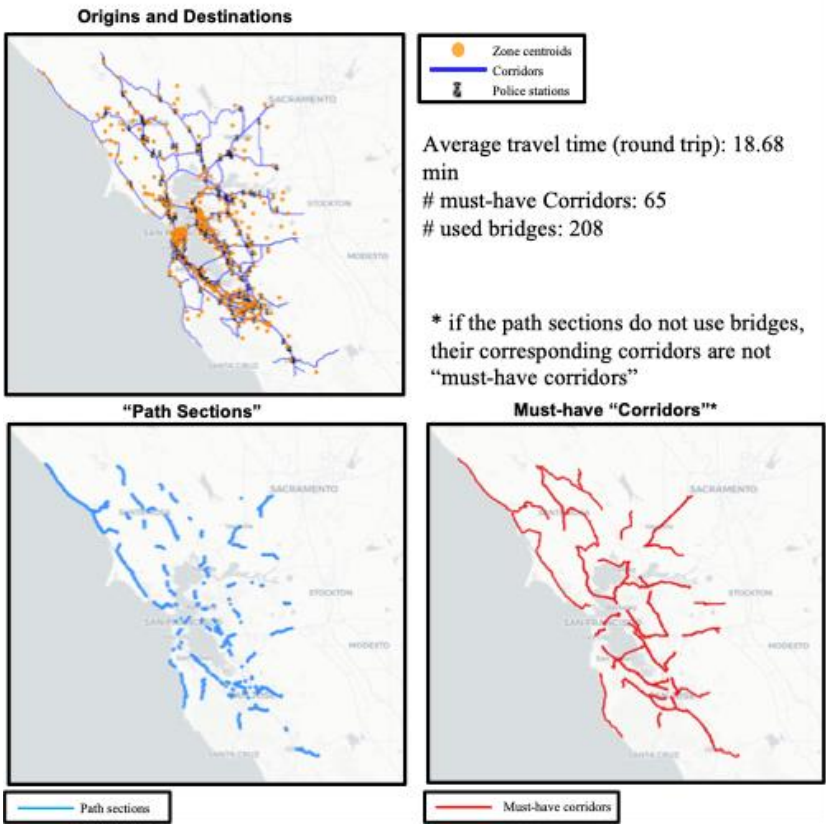


Figure 30 Results applying Method B for police station access.

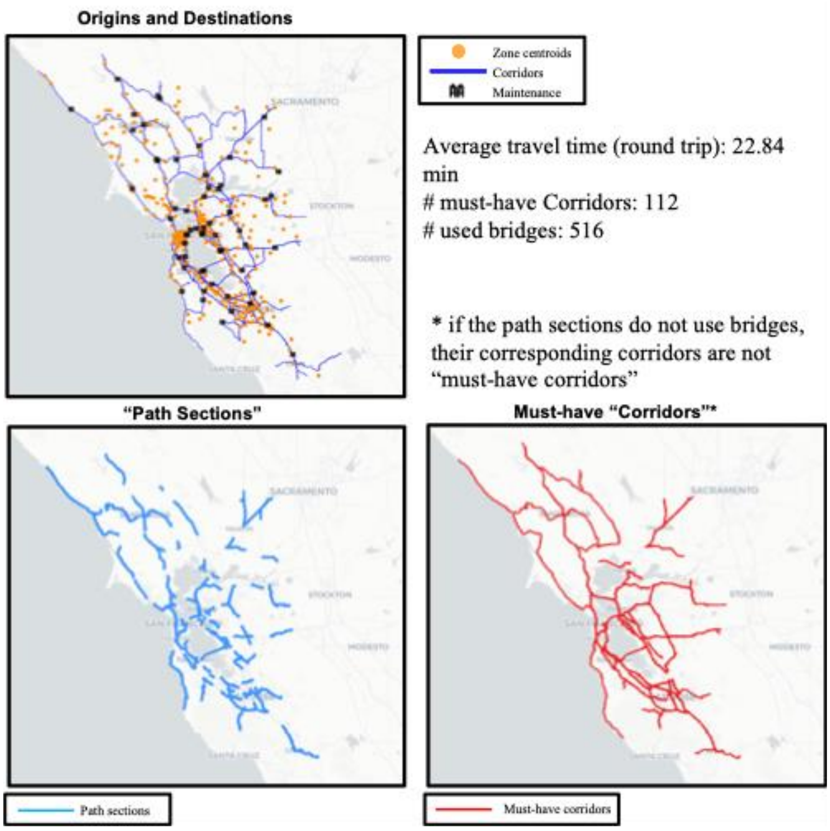


Figure 31 Results applying Method B for maintenance facility access.

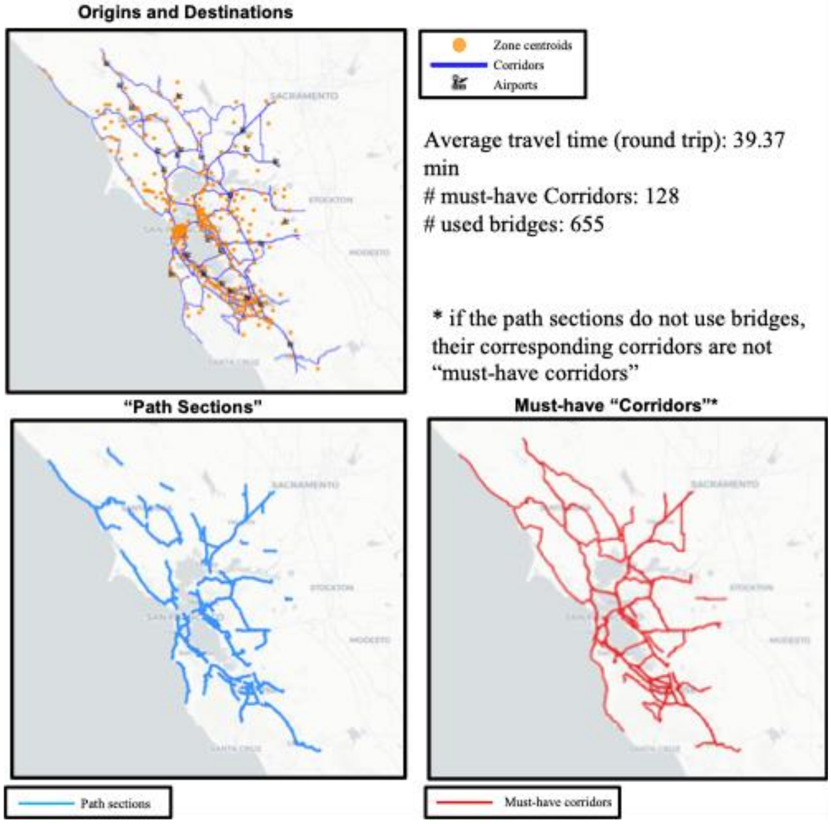


Figure 32 Results applying Method B for airport access.

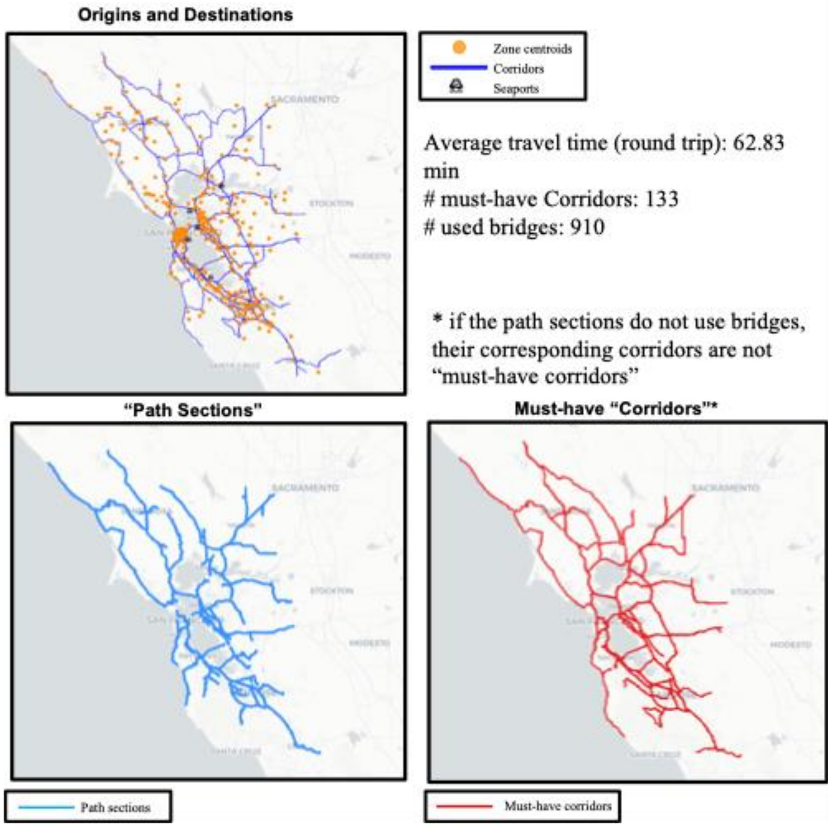


Figure 33 Results applying Method B for seaport access.

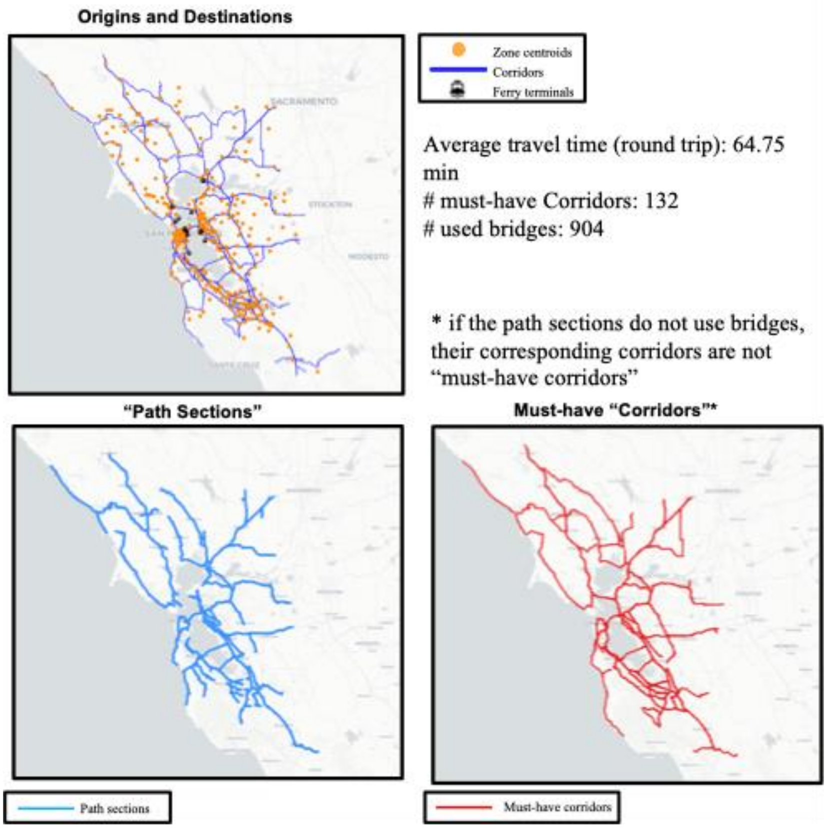


Figure 34 Results applying Method B for ferry terminal access.

Table 3 Comparison between Methods A and B.

Facility type	Method A			Method B		
	Average round trip travel time (min)	#bridge used	#corridors used	Average round trip travel time (min)	#bridge used	#corridors used
Hospital	25.84	542	115	27.54	418	97
Fire station	8.39	67	32	9.21	57	27
Police station	18.07	237	70	18.68	208	65
Maintenance facility	21.36	636	116	22.84	516	112
Airport	36.05	763	129	39.37	655	128
Seaport	58.20	935	134	62.83	910	133
Ferry terminal	61.78	973	134	64.75	904	132

3.5.2 Impact of N

In this section, the impact of the time allowance factor *N* on the number of used bridges is analyzed. It can be observed that as N increases, the number of used bridges decreases, shown in **Figure 35**. This is because a more relaxed travel time allowance increases the likelihood that people can share bridges, resulting in fewer bridges being used.

However, when N reaches 2, the number of used bridges is already much lower than that in Method A. Further increases in N do not significantly reduce the number of used bridges. For instance, the number of bridges used in Method A for hospital access is 542. When N increases to 2, the number of bridges used decreases to 418. However, further increasing N to 3 or 5 results in only a small reduction. This is because of a rule that the local road travel time must not exceed the travel time of the local road on the shortest path, which limits the choice of routes.

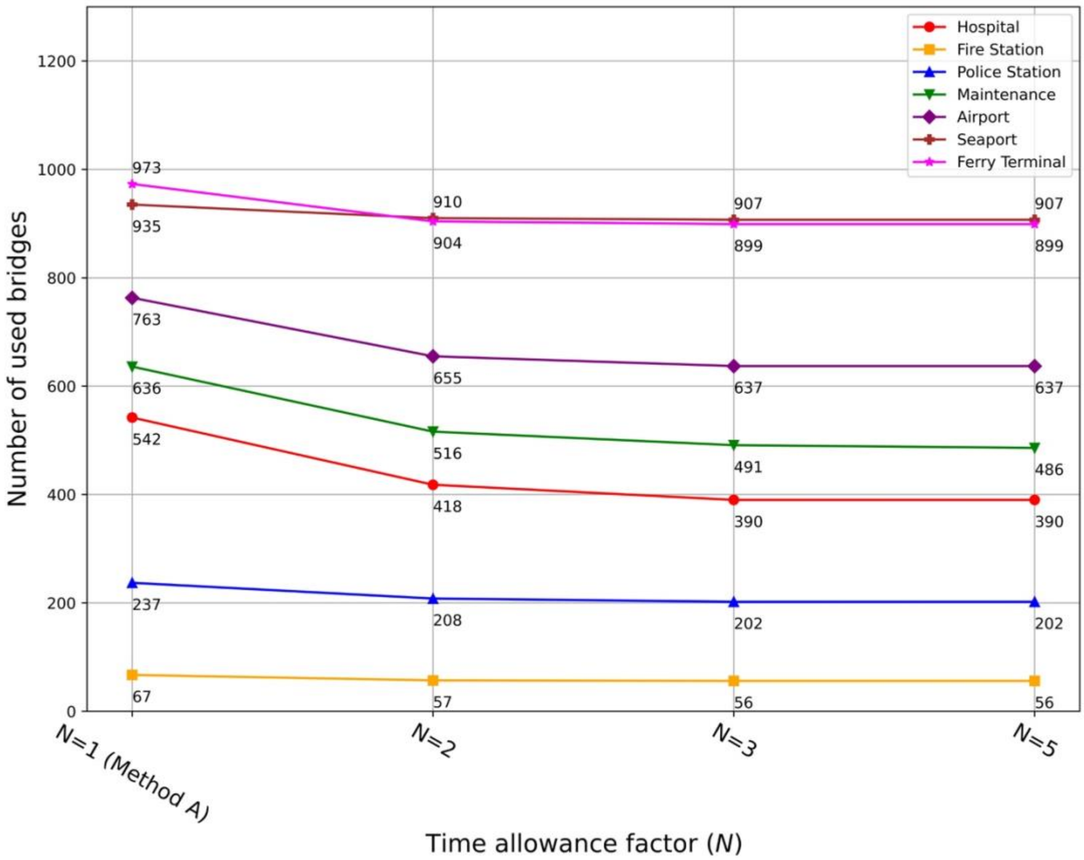


Figure 35 The impact of the time allowance factor N on the number of used bridges.

3.6 Validation of the developed method for the existing recovery bridges

There are two designated recovery bridges in California: one is located nearby the Golden Gate Bridge, and the other is located near Redwood National and State Parks. **Figure 36** shows the locations of these two recovery bridges. The recovery bridge network in this study only covers District 4; therefore this validation is for the Presidio Bridge.

We aim to evaluate whether the Presidio Bridge is widely used for access to the critical facilities listed in this study. Using Method A, it is found that only one zone uses it for seaport access, two zones use it for ferry terminal access, and no zone uses it for any other type of facility access. Additionally, the corridor where the Presidio Bridge is located ranks at the bottom among all corridors. Specifically, it is unranked in the scenarios of hospital access, fire station access, police station access, maintenance facility access, and airport access, as no zone uses it for these types of facility access, and ranks 30th for both seaport access and ferry terminal access.

It seems that the Presidio Bridge is being designated as a recovery bridge based on factors beyond essential facility access need. With discussion with Caltrans, the reason is because it is the main connection through Golden Gate Bridge between Marin and San Francisco Bay with heavy daily commute traffic. Using the traffic simulation model developed by Soga Research Group (https://github.com/cb-cities/residual_demand_simcenter) and modelled Origin-Destination data from Metropolitan Transportation Commission (https://data.mtc.ca.gov/data-repository/), it is estimated that the traffic on this bridge is around 70,000 vehicle/day/direction, ranking top 1% among all bridges in District 4.

Therefore, it is suggested that selecting of the Presidio bridge as a recovery bridge relies mainly on daily traffic counts.

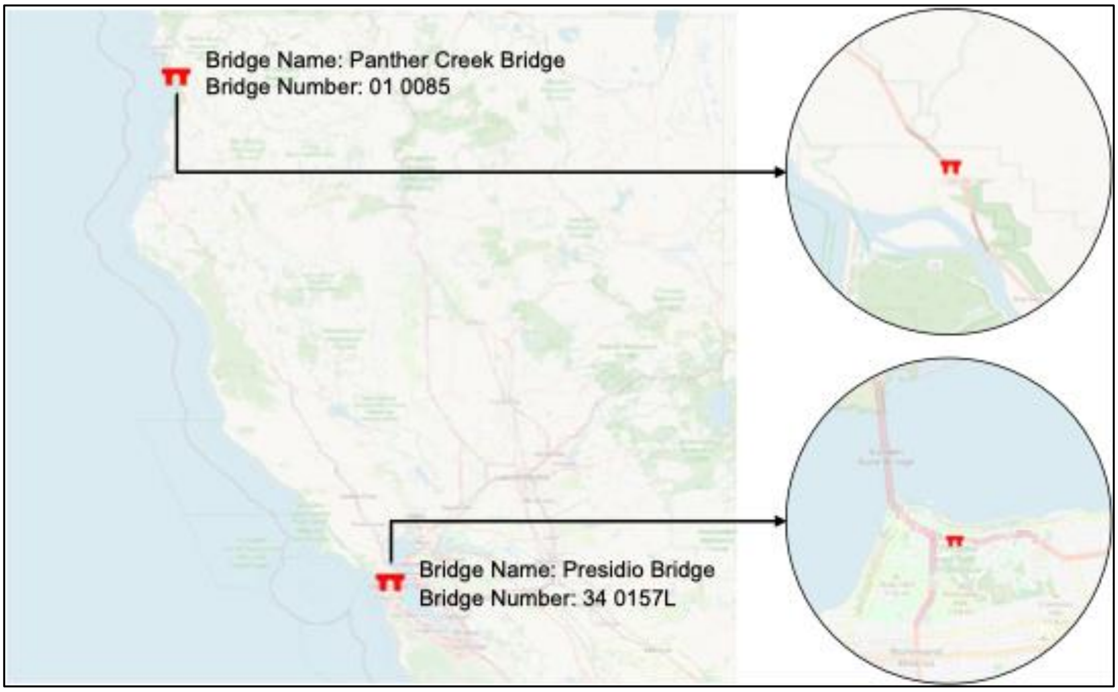


Figure 36 The location of the existing recovery bridges.

4 Development of the online application tool

The online application tool was developed to provide Caltrans with an integrated, user-friendly platform for evaluating bridge corridors, performing accessibility simulations, and visualizing results. The tool contains three coordinated applications, Networks, Simulation, and Visualization, which together support the full workflow from corridor ranking to scenario evaluation and mapping. The following sections primarily describe the functionality of each application; for detailed instructions on how to use the tool, please refer to **Section 8.8**.

4.1 The "Networks" application

The "Networks" application is designed to identify critical corridors under intact network conditions. Users can select the ranking method, assign weights to different facility types, and choose whether to consider population-based demand. After clicking "*Rank"*, the system computes corridor importance based on the specified ranking methods and displays the updated corridor map. The map interface supports several key functions, including:

- Filtering corridors within a selected ranking range,
- Searching for a specific corridor by ID,
- Viewing detailed corridor information such as ID, type, zone count, and rank.

A corresponding table is also generated to summarize the ranked corridors. Selecting a corridor from the table opens the bridge-level map, enabling further inspection of bridge usage and detour implications. The details can be seen in **Appendix 8.8.2**.

4.2 The "Simulation" application

The "Simulation" application evaluates how network performance changes when one or more corridors become unavailable. Users select a facility type, input the list of removed corridors, and optionally upload updated Caltrans nodes or links data for future network revisions.

After submitting the simulation, the system recalculates corridor rankings based on the modified network and generates a downloadable spreadsheet of results. The output includes corridor rankings, zone-to-facility travel times, lists of bridges used, and any zones that become inaccessible due to corridor removal. This module enables Caltrans to assess network resilience and quantify the consequences of disruptions under various earthquake damage scenarios. The details can be seen in **Appendix 8.8.3**.

4.3 The "Visualization" application

The "Visualization" application provides an interactive mapping interface for viewing simulation outputs. Users upload one or more result spreadsheets, assign weights to the selected facility types, and generate updated corridor maps similar to those in the "Networks" application.

This tool visualizes corridor importance and bridge usage under disrupted conditions, allowing comparison across multiple simulation scenarios. All major map-based functions from the Networks interface are supported, except for path-level displays, which are omitted to minimize computational cost. The Visualization application helps Caltrans interpret simulation results intuitively and examine how disruptions affect regional accessibility. The details can be seen in **Appendix 8.8.4**.

5 Future study

There are several directions that can be considered for further exploration.

- **Involve bridge damage probability**: the current study ranks corridors/bridges solely based on their usage for critical facility access. However, some corridors/bridges are already highly seismically resilient. Although this study provides a formula to involve the bridge damage probability (See **Appendix 8.6.6**) into the ranking, it is necessary to apply this in a case study to understand which corridors/bridges are more critical, considering both their usage and damage probability. To perform such an analysis, Caltrans would need to provide the necessary bridge damage probability data.
- **Develop an automated method to update the traffic network**: although the bridge traffic network does not change in the short term, it may evolve over time as some bridges are added or removed. When this occurs, the code needs to be re-run to update the bridge traffic network. Given that re-running the code may be somewhat complex for Caltrans, it is necessary to develop a simpler, automated method to update the network. Therefore, one potential direction is

to develop an automated tool (e.g., using a large language model) for updating the traffic network.

- **Combining Brace 2 and this project:** Bridge Rapid Assessment Center for Extreme Events (BRACE2) is where the current tool is hosted. BRACE2 monitors real-time bridge health, while this study provides a method to identify the critical corridors for pre-earthquake planning. However, the proposed method in this study can be also used for post-earthquake critical bridge identification. When an earthquake occurs, the BRACE2 platform provides information on inaccessible bridges. Using the Method A and an updated traffic network with inaccessible bridges removed, the zones that become accessible can be identified and critical bridges that should be prioritized for repair can be determined.

- **Expanding to other regions.**

The framework of this study can be easily expanded to other districts, such as Los Angeles, where the probability of occurring earthquakes is large.

- **Building damage**

Only bridge conditions are currently considered as a factor affecting transportation service. However, building collapses can also obstruct roads and disrupt transportation. Therefore, future studies could consider building damage as well, to evaluate the importance of each corridor more comprehensively.

- **Post-hazard OD estimation**

This study does not explore post-earthquake OD demand. However, this is an important issue, as post-disaster OD patterns can differ significantly from those before the event. Therefore, estimating post-earthquake OD is necessary to better identify which corridors are most critical.

6 Summary

This study explores a framework to identify the most critical corridors, which provides some suggestions on determining whether a bridge should be designed to a recovery bridge performance standard or an ordinary standard bridge performance standard. Firstly, an interchange-based method is introduced to group bridges into multiple corridors. Then, a shortest path-based method, Method A, is used to determine routes from each zone to its nearest emergency facility. The usage of each corridor for facility access is calculated, and total usage is used as the ranking criterion. Finally, bridges within the most critical corridors are analyzed and ranked based on their damage probabilities.

The shortest paths obtained in Method A, are compared to those obtained in Google Map, showing a dissimilarity rate of only 5.6%, which demonstrates that driving from the critical facilities to zones heavily relies on Caltrans routes if people want to have the shortest travel time. Additionally, it is observed that the must-have bridges and corridors vary with facility types. There are 563 fire stations in the 298 zip-based zones in the District 4, resulting in fire stations close to zones and only 31 zones need Caltrans bridges to access a fire station. In contrast, 159 zones need Caltrans bridges to access hospitals. Further, it is noted that the top-ranked corridor for each type of facility varies, as the spatial distributions of these facilities vary. Corridor 36 (04-SON-116-3) ranks the top for not only hospital and police station access, but for all facility types with equal weights. Moreover, a comparative analysis was conducted to assess the impact of including versus excluding population data in the corridor ranking process. The results indicate that when population is not considered, the highest-ranked corridors tend to be located in rural areas, as these roads often serve as the sole connections for multiple zones. Some top-ranked corridors are also found in urban regions with high facility density, where access routes are shared by many zones. On the other hand, incorporating population data shifts the top rankings toward corridors in densely populated areas. This suggests that different prioritization criteria can lead to significantly different corridor rankings. Therefore, it is important to clarify the intended planning objective—whether to prioritize coverage across all zones or focus on areas with higher population density—before selecting a ranking approach.

In addition, the possibility that some corridors cannot be improved due to various issues is also considered. This approach is referred to as Method A-alternative. In this method, selected corridors are removed from the network, and a new corridor ranking is generated by reapplying Method A. This method can be used for testing the impact of each corridor on travel time by removing them individually. It is found that removing corridors in rural areas leads to many inaccessible zones, as they are the only road out for zones around them. In contrast, removing corridors in urban areas does not lead to inaccessible zones or significant increases in travel time, demonstrating the strong redundancy of urban road network.

Furthermore, an alternative method–Method B–is proposed. Method B employs an optimization model aimed at minimizing the number of Caltrans bridges used. It provides Caltrans with an additional tool, especially if the goal is to reduce costs by designating fewer bridges as recovery bridges, assuming that some relaxation in travel time is acceptable.

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8 Appendix

8.1 Explanation of Method A

Simple Example:

In **Figure 37**, there are three zones and six hospitals. The solid black lines indicate available paths between zones and hospitals. The blue sections within the black lines are Caltrans sections (Corridors). The green numbers represent the travel times of every path, including the time used to travel local roads and Caltrans routes.

- For Zone 1, The closest facility is Hospital 1. The shortest path is the one that crosses Corridor A.
- For Zone 2, The closest facility is Hospital 2. The shortest path is the one that crosses Corridor B.
- For Zone 3, The closest facility is Hospital 2. The shortest path is the one that crosses Corridor C.

Therefore, Corridors A, B, and C are must-have corridors, each with a zone count of 1.

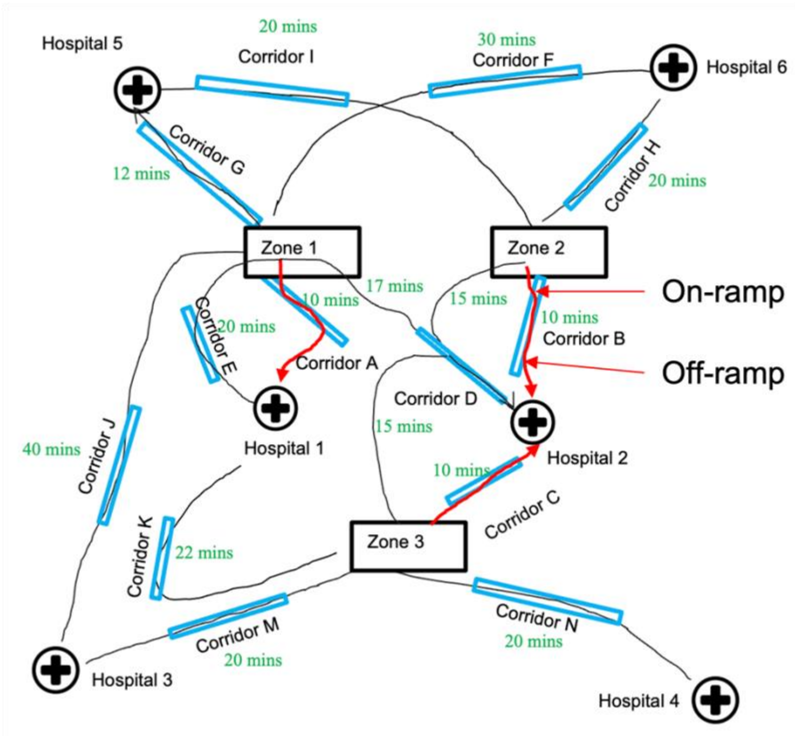

Figure 37 An illustrative example of Method A.

8.2 Explanation of Method A-alternative

<u>Simple example:</u>

The simple network used in the previous method is used. It is now assumed that Corridors A, B, and C cannot be improved due to some reasons. This means that the bridges on these corridors cannot be made as recovery bridges, shown in **Figure 38**. We remove these corridors and conduct Method A.

- For Zone 1,

  The closest facility is Hospital 5. The shortest path is the one that crosses Corridor G.

- For Zone 2,

  The closest facility is Hospital 2. The shortest path is the one that crosses Corridor D.

- For Zone 3,

  The closest facility is Hospital 2. The shortest path is the one that crosses Corridor D.

Therefore, Corridors D and G are must-have corridors. Corridor D has a zone count of 2 while Corridor G has a zone count of 1.

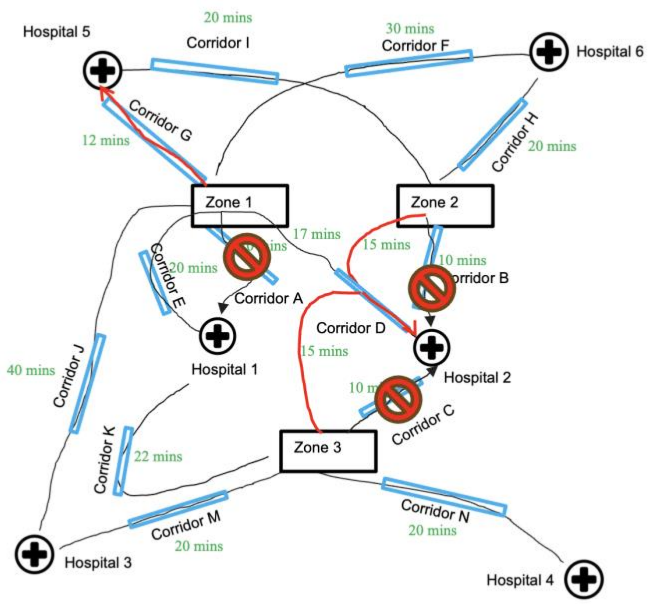

Figure 38 An illustrative example of Method A-alternative

8.3 Explanation of Method B

8.3.1 Method B: essential bridge identification.

In this method, people share as many bridges as possible to reduce the number of bridges/corridors that are needed. Therefore, the goal is to find the minimum number of bridges while ensuring that the travel time for each person is less than N*the original shortest path travel time.

Step 1: Define the time allowance factor **N** (N>1)

Step 2: For all the zones, find all paths to any facilities with the travel times $\leq$ **N** times the original shortest path travel time.

Step 3: Run an optimization model to find the minimum number of bridges that are needed so that all zones can reach to a hospital (can be a different critical facility identified in Method A). The corridors to which the identified essential bridges belong are the essential corridors.

<u>Simple example:</u>

Again, the network example used in Method A is utilized. Besides, we assume each corridor has one bridge on its center, shown in **Figure 39**. If we set N=2, this means the travel time should be less than or equal to 2 times the original shortest path travel time.

- For Zone 1,

  The original shortest path travel time is 10 mins (using Corridor A to reach Hospital 1).

  If we relax the travel time to 2 times, which is 20 mins. The following are the feasible options:

  - Corridor A to Hospital 1 (10 mins)
  - Corridor E to Hospital 1 (20 mins)
  - Corridor D to Hospital 2 (17 mins)
  - Corridor G to Hospital 5 (12 mins)
- For Zone 2,

  The original shortest path travel time is 10 mins (using Corridor B to reach Hospital 2).

  If we relax the travel time to 2 times, which is 20 mins. The following are the feasible options:

- Corridor B to Hospital 2 (10 mins)
- Corridor D to Hospital 2 (15 mins)
- Corridor I to Hospital 5 (20 mins)
- Corridor H to Hospital 6 (20 mins)

• For Zone 3,

The original shortest path travel time is 10 mins (using Corridor C to reach Hospital 2). If we relax the travel time to 2 times, which is 20 mins. The following are the feasible options:

- Corridor C to Hospital 2 (10 mins)
- Corridor D to Hospital 2 (15 mins)
- Corridor M to Hospital 3 (20 mins)
- Corridor N to Hospital 4 (20 mins)

Making the objective to minimize the number of bridges, it is shown that, if all the zones use the bridge on Corridor D to Hospital 2, all of them can reach a hospital within 2 x the original shortest path travel time. Therefore, for this plan, the bridge on Corridor D is the essential bridge and thus Corridor D becomes the must-have corridor and has a zone count of 3.

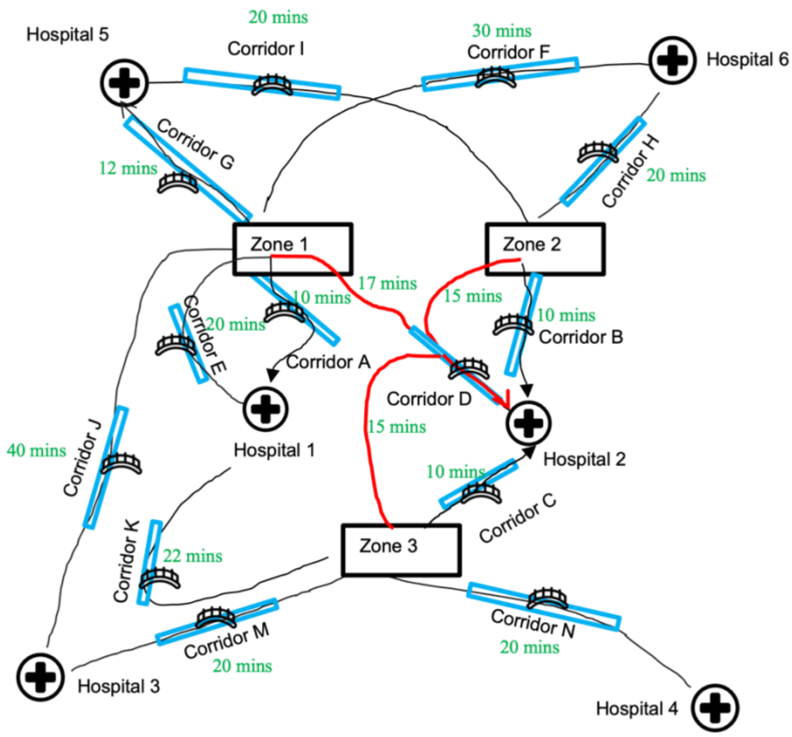

Figure 39 An illustrative example of Method B

8.3.2 Special attention on the local travel time for Method B

Firstly, it is important to understand that "travel time = local travel time from origin to on-ramp + highway travel time + local travel time from off-ramp to destination".

When it is stated that the travel time is relaxed to N times the original shortest path travel time, it implies that only the highway travel time is relaxed, while the local road travel time remains unchanged. This is because we want to rely as little as possible on the local road.

An example is given in **Figure 40**. Corridors A and B are Caltrans routes while the other links that are connected to zones or hospitals are local roads. Each local road is labelled with an ID (from I to XII).

- Firstly, calculate the shortest path to the closest hospital and its travel time: the shortest path from Zone 1 to the closest hospital is Zone 1 – Local Road I – Corridor A – Local Road VII – Hospital 2. The travel time is 21 minutes. Therefore, if the travel time is relaxed to 2 times the original shortest path travel time, it implies that the maximum travel time (including travel time on local and highway) is 21*2 = 42 minutes.
- For each zone-hospital pair, find the local road travel time on the shortest path to this hospital. For example,
    - for the pair "Zone 1- Hospital 2", the shortest path is Zone 1– Local Road I – Corridor A – Local Road VII – Hospital 2, where the travel time on Local Road I and Local Road VII is 5 mins and 6 mins, respectively. Therefore, if one person wants to go from Zone 1 to Hospital 2, the local road travel times from Zone 1 to on-ramps and from off-ramps to Hospital 2 should be less than or equal to 5 mins and 6 mins, respectively. Under this setting, this person can choose local roads from Local Roads I, III, V, and XII that connect Zone 1 to on-ramps and local roads from Local Roads VII and IX that connect off-ramps to Hospital 2. Following this, this person can try different combinations (e.g., Zone 1-Local Road III-Corridor A-Local Road IX-Hospital 2, Zone 1-Local Road III-Corridor A-Local Road VII-Hospital 2) that connects Zone1 to Hospital 2 while ensuring the travel time is less than or equal to 42 minutes.
    - for the pair "Zone 1 – Hospital 3", the shortest path is Zone 1–Local Road XII – Corridor B – Local Road XI – Hospital 3, where the travel time on Local Road XII and Local Road XI is 4 mins and 4 mins, respectively. Therefore, if one person wants to go from Zone 1 to Hospital 3, the local road travel times

from Zone 1 to on-ramps and from off-ramps to Hospital 3 should be less than or equal to 4 mins. Under this setting, this person can choose local roads from Local Roads XII, V, and III that connect Zone 1 to on-ramps and local roads from Local Road XI that connect off-ramps to Hospital 2. Following this, this person can try different combinations (e.g., Zone 1-Local Road V-Corridor B-Local XI-Hospital 3) that connects Zone1 to Hospital 3 while ensuring the travel time is less than or equal to 42 minutes.

In one sentence: the total travel time should be limited to N times the original shortest path travel time to the closest hospital. Additionally, the local road travel time on the path to each potential hospital should be less than or equal to the local road travel time on the shortest path to that hospital.

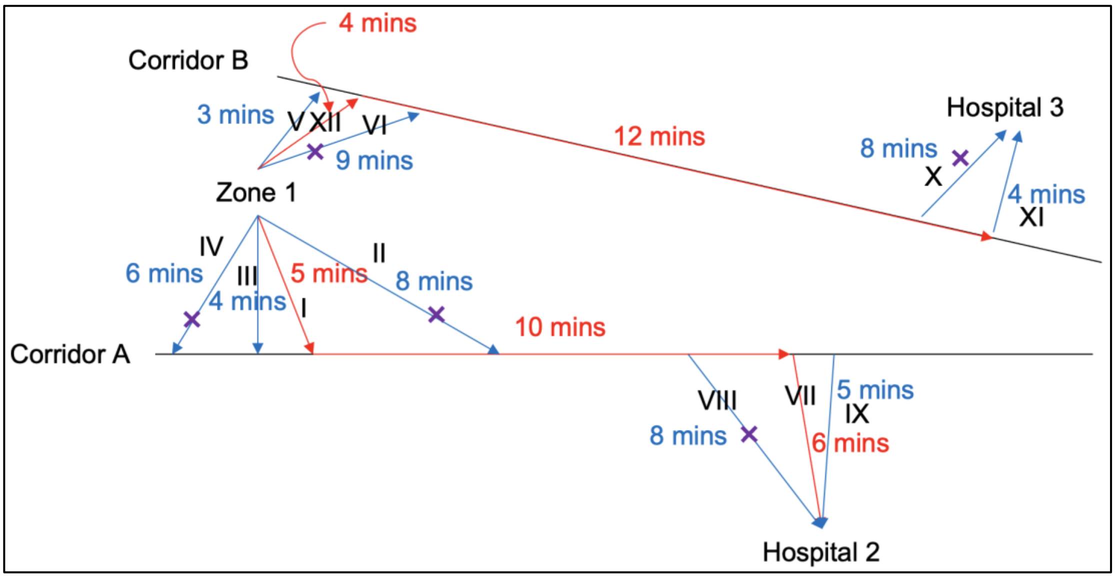

Figure 40 An illustrative example of local road selection.

8.4 Method B-alternative

There is another optimization model with a different goal: minimizing the total length of Caltrans route used, including roads and bridges. This method can be considered if Caltrans believe that attention should be paid not only to bridges, but also to pipelines or other infrastructure beneath the roads.

8.4.1 Objective function

The objective is to minimize the total length of Caltrans route used, given as follows:

$$minimize \sum_{r \in \mathbf{R}} x_r l_r \quad (19)$$

where $\mathbf{R}$ represents the road link set, and x_k is a binary variable, indicating whether road link l is selected or not.

8.4.2 Constraints

If an O-D pair chooses a path, the road links along that path need to be selected. Furthermore, since round trips are considered, if a D is selected for an O, there should also be a path going from this D back to this O. These constraints are expressed using the following mathematical formulations.

$$\left(\sum_{r \in \mathbf{R}} a_{odjr} - \sum_{r \in \mathbf{R}} a_{odjr} \cdot x_r\right) - M\left(1 - y_{odj}\right) \leq 0, \forall o \in \mathbf{O}, d \in \mathbf{D}, j \in \mathbf{P}^{(o,d)} \quad \mathbf{(20)}$$

$$\left(\sum_{r \in \mathbf{R}} a_{dojk} - \sum_{r \in \mathbf{R}} a_{dojk} \cdot x_k\right) - M\left(1 - y_{doj}\right) \leq 0, \forall o \in \mathbf{O}, d \in \mathbf{D}, j \in \mathbf{P}^{(d,o)} \quad \mathbf{(21)}$$

$$\sum_{j \in \mathbf{P}^{(o,d)}} y_{odj} \geq z_{od}, \forall o \in \mathbf{O}, d \in \mathbf{D} \quad \mathbf{(22)}$$

$$\sum_{j \in \mathbf{P}^{(d,o)}} y_{doj} \geq z_{od}, \forall o \in \mathbf{O}, d \in \mathbf{D} \quad \mathbf{(23)}$$

$$\sum_{d \in \mathbf{D}} z_{od} \geq 1, \forall o \in \mathbf{O} \quad \mathbf{(24)}$$

$$x_r \in \{0,1\} \quad (25)$$

$$y_{odj} \in \{0,1\} \quad (26)$$

$$z_{od} \in \{0,1\} \quad (27)$$

The constraints are the same as those in Method B. Here, you can think of a road link in this model as similar to a bridge in Method B, except that the length is optimized rather than the number.

8.5 Explanation of Corridor ranking

8.5.1 Corridor ranking for access to each facility type

Two simple examples applying Method A are given below to facilitate better understanding.

Example A: Hospital access

Figure 41 shows the corridor usage for the hospital access. It can be seen that Corridor A is used by Zone 1, with a zone count of 1. Corridor B is used by Zones 2, 4, 5, and 6, giving it a zone count of 4. Corridor C is used by Zone 3, resulting in a zone count of 1. The ranking of these corridors is: Corridor B > Corridor A = Corridor C. The other corridors rank last, as they are not used by any zones.

Example B: Fire station access

Figure 42 shows the corridor usage for the fire station access. It is noted that the shortest paths from Zones 5 and 6 to their closest fire stations do not use Caltrans routes. It can be seen that Corridor B is used by Zones 2 and 4, while Corridors C and G are used by Zones 3 and 1, respectively. Therefore, the zone counts for Corridors B, C, and G are 2, 1, and 1, respectively. The rankings are: Corridor B > Corridor C=Corridor G.

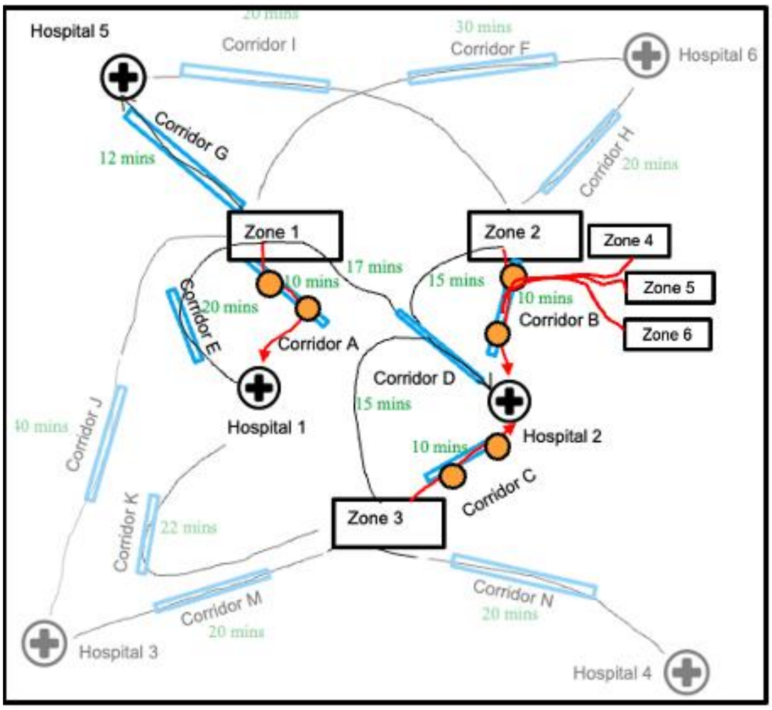

Figure 41 Corridor ranking in the example of hospital access.

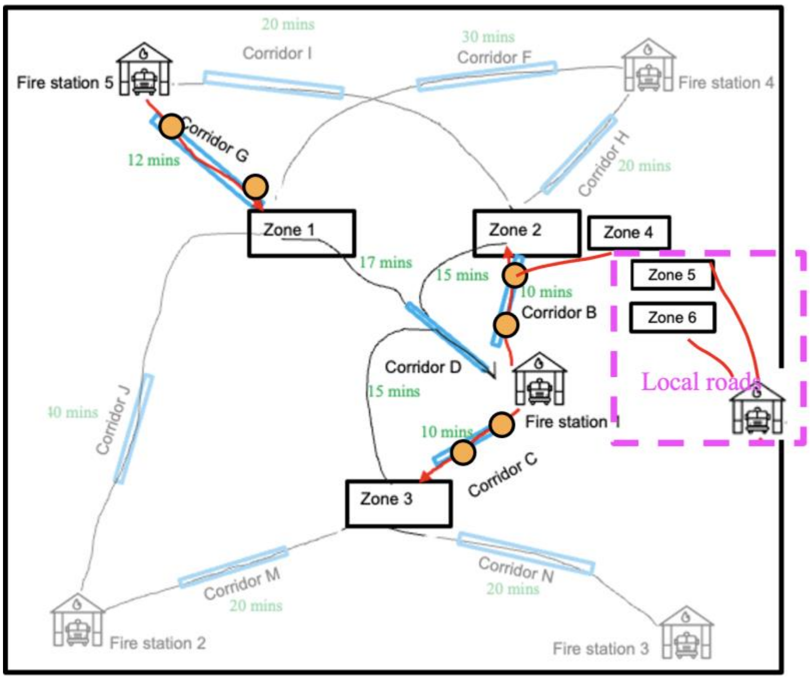

Figure 42 Corridor ranking in the example of fire station access.

8.5.2 Corridor ranking for access to multiple facility types

A simple example is given below to facilitate better understanding.

Example: Considering hospital access and fire station access.

The examples from **Figure 41–Figure 42** are applied. We assume that hospital access and fire station access are of equal importance, so that $w_{hospital}$ and w_{fire} are both set to 50%. The normalized zone count and score for each corridor are shown in **Table 4**. The ranking is: Corridor B > Corridor C > Corridor G > Corridor A.

Table 4 Corridor score

Corridor	**Zone count for hospital access**	**Normalized zone count for hospital access**	**Zone count for fire station access**	**Normalized zone count for fire station access**	**Corridor Score**
A	1	1/4	0	0/2	1/4*0.5+0/2*0.5=0.125
B	4	4/4	2	2/2	4/4*0.5+2/2*0.5=1
C	1	1/4	1	1/2	1/4*0.5+1/2*0.5=0.375

G	0	0/4	1	1/2	0/4*0.5+1/2*0.5=0.25

8.5.3 Bridge ranking

The example in **Figure 43** is used to show how to calculate the importance of each bridge. As Bridge C is not used, it does not attend the ranking. We assume that Bridges A, B, and D have damage probabilities of 0.3, 0.4, 0.2, respectively. The bridge usage of Bridge A is 2, as it is used by Path sections 1 and 2, while the bridge usages of Bridge B and D are both 1, as they each is only used by one path section. Therefore, $importance_A = 2 \times 0.3 = 0.6$, $importance_B = 1 \times 0.4 = 0.4$, and $importance_D = 1 \times 0.2 = 0.2$. Therefore, the ranking is: Bridge A > Bridge B > Bridge D. If the budget is only for one bridge, Bridge A could be prioritized as the recovery bridge.

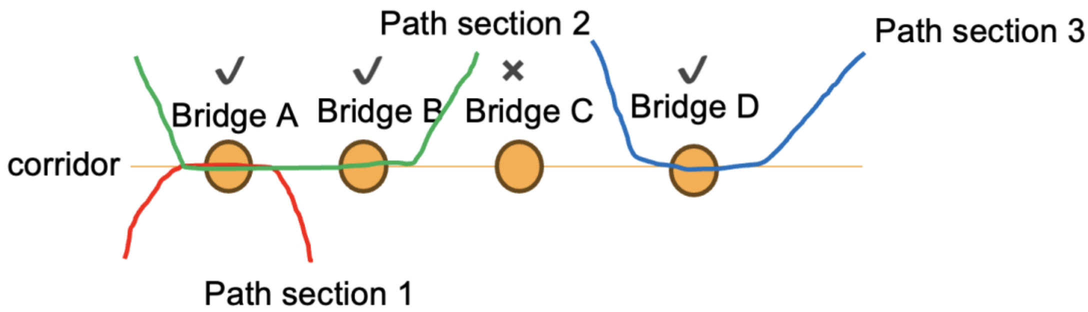

Figure 43 An example to show which bridges may become recovery bridges.

8.6 Simulation-free model

Simulation-free model is a model that we discussed before. However, this method is a little bit complicated, and the obtained results are not the actual traffic volume, which may be hard for understanding. Additionally, this method is more applicable to bridge ranking, rather than corridor ranking. Therefore, after discussion, we switched to traffic simulation methods, which are Methods A-B. Here, we provide it for reference. The core of this model is a Markovian random walk on a graph. Given a graph and a starting vertex, we choose a neighbor of the current node based on a transition probability and move to this neighbor and continue in this fashion. It is a Markov process such that the next node to visit only depends on the current node and is independent of the history. The output of the model is the visit probability of each node. With the visit probabilities of all nodes, we can identify the most likely visited bridges/roads. Besides, the product of the visit probability and damage probability for each bridge is a measure of the importance of this bridge. Therefore, we can identify the critical bridges and critical corridors.

8.6.1 Traffic network

Let a weighted graph G represent a traffic network with roads and bridges. The nodes are bridges, intersections of roads, and vertices of a spatial mesh of roads; the links are roads connecting adjacent nodes. The topological adjacency matrix $\boldsymbol{A}$, which describes the topology of the graph, is defined as

$$\boldsymbol{A}(i,j) \coloneqq \begin{cases} 1 & \text{there is a link from node } i \text{ to } j \\ 0 & \text{there is no link from node } i \text{ to } j \end{cases}, \tag{28}$$

If $\boldsymbol{A}$ is symmetric, G is undirected, i.e., all the roads are two-way; otherwise G is directed. The discussions hereafter will assume G is finite, directed, and connected. The weight adjacency matrix $\boldsymbol{W}$, which encodes the distance between adjacent nodes, can be defined as

$$\boldsymbol{W}(i,j) \coloneqq \begin{cases} \dfrac{1}{l_{ij}} & \text{there is a link from } i \text{ to } j \text{ with average travel time } l_{ij} \\ 0 & \text{there is no link from node } i \text{ to } j \end{cases}, \tag{29}$$

Clearly, $\boldsymbol{A}$ can be inferred from $\boldsymbol{W}$; we explicitly define both for later use.

8.6.2 Origin-destination distribution

The demand of a traffic network can be represented by a joint probability mass function (two-dimensional probability table) $\boldsymbol{P}_{OD}$. The entries $\boldsymbol{P}_{OD}(o,d)$ denote the joint probability of node o being the origin and node d being the destination. The matrix $\boldsymbol{P}_{OD}$ can be approximated from an origin-destination dataset.

$$\boldsymbol{P}_{OD}(o,d) = \frac{trip_{o,d}}{\sum_{o\in O, d\in D} trip_{o,d}}, \tag{30}$$

where $trip_{o,d}$ represents the number of trips that originate from o to d.

8.6.3 The impact of earthquakes

We assume the direct/instantaneous impact of an earthquake on a traffic network is dominated by the seismic impact on bridges. Let the states of bridges be represented by discrete random variables $X_i \in \{0,1\}, i = 1,2,\dots,n_b$, where n_b is the number of bridge nodes on G, and $X_i = 0$ indicates safe and $X_i = 1$ failure. The joint probability mass function $p_{\boldsymbol{X}}(x_1, x_2, \dots, x_{n_b})$ (alternatively denoted by $p_{\boldsymbol{X}}$ for simplicity) fully describes the seismic behavior of bridge nodes. The seismic behavior of a bridge is the result of the local ground motion filtered by the bridge structure. Therefore, the statistical dependency encoded in $p_{\boldsymbol{X}}(\boldsymbol{x})$ is contributed by: i) the correlation of ground motions; ii) the similarity between bridges.

To obtain $p_{\boldsymbol{X}}(\boldsymbol{x})$, the ideal approach is a regional simulation of physics-based bridge models. However, the computational resource is limited. Therefore, a simplified approach was applied by using fragility curves and seismic intensity maps. Specifically, let $[IM_1, IM_2, \dots, IM_{n_b}]$ denote the local seismic intensity measures at bridge locations, $p_{\boldsymbol{X}}(\boldsymbol{x})$ is approximated by

$$p_{\boldsymbol{X}}(x_1, x_2, \dots, x_{n_b}) \approx \prod_{i=1}^{n_b} p_{X_i}(x_i | IM_i), \tag{31}$$

where $p_{X_i}(x_i|IM_i)$ is obtained from the fragility curve of the *i*-th bridge. It is important to note that Equation (31) captures the correlation of ground motions via the spatial pattern/correlation of IM_i.

8.6.4 Stochastic matrix

For a specified origin-destination pair (e.g., a random sample from $\boldsymbol{P}_{OD}$), let the random walk be represented by a stochastic matrix $\boldsymbol{S}^{(o,d)}$; for all origin-destination pairs from $\boldsymbol{P}_{OD}$, the average stochastic matrix is

$$\boldsymbol{S} \coloneqq \mathbb{E}_{\boldsymbol{P}_{OD}}[\boldsymbol{S}^{(o,d)}] = \sum_{(o,d)\in\Omega_{OD}} \boldsymbol{P}_{OD}(o,d)\boldsymbol{S}^{(o,d)}, \tag{32}$$

where Ω_{OD} is the sample space of $\boldsymbol{P}_{OD}$. Since $\sum_{(o,d)\in\Omega_{OD}} \boldsymbol{P}_{OD}(o,d) = 1$, $\boldsymbol{S}$ is a valid stochastic matrix as long as $\boldsymbol{S}^{(o,d)}$ are valid. Provided with $\boldsymbol{P}_{OD}$, to construct $\boldsymbol{S}$ the main question is to model $\boldsymbol{S}^{(o,d)}$.

We assume $\boldsymbol{S}^{(o,d)}$ involves a trade-off between following the shortest path and kth shortest path. An individual may deviate from the shortest path due to traffic congestion, non-commute travel, inherent preference and uncertainty, and others. The deviation varies from individual to individual, situation to situation; we coarse-grain the deviation into a probability of initiating deviation from the shortest path. Specifically, $\boldsymbol{S}^{(o,d)}$ is modeled by

$$\boldsymbol{S}^{(o,d)} = \sum_{k=1}^{k_{max}} \alpha_k^{(o,d)} S_k^{(o,d)}, \tag{33}$$

$$\alpha_k^{(o,d)} = \frac{e^{-l_k^{(o,d)}}}{\sum_{k=1}^{k_{max}} e^{-l_k^{(o,d)}}}, \tag{34}$$

where $l_k^{(o,d)}$ is the travel time for the kth shortest path of the pair (o,d), $\boldsymbol{S}_k^{(o,d)}$ is the stochastic matrix of the kth shortest path walk.

The entries of $\boldsymbol{S}_k^{(o,d)}$, denoted by $\boldsymbol{S}_k^{(o,d)}(i,j)$, are defined as

$$\boldsymbol{S}_k^{(o,d)}(i,j) \coloneqq \begin{cases} 1, & i \neq d \text{ and the } k\text{th shortest path passes } i \\ 0, & \text{no shortest path passes } i \\ 0, & i = d, j \neq o \\ 1, & i = d, j = o \end{cases}, \tag{35}$$

where the last two lines enforce the random walk to "teleport" to the origin o after reaching the destination d. The teleportation is introduced so that the stationary distribution will correctly reveal the long-term node visit probabilities for the specified origin-destination. Without the teleportation mechanism, the stationary distribution will be independent of the origin-destination (proportional to the degree distribution for undirected graphs) and thus be unrealistic. Noticeably, $\boldsymbol{S}^{(o,d)}$ can have rows whose sum is not equal to 1 as some k shortest paths do not pass through those nodes. For those rows whose sums are between 0 and 1, a re-normalization is performed to make these rows sum up to one; for those rows whose sums are 0, we can just keep them as they are since there is no vehicle passing through these nodes. After the re-normalization $\boldsymbol{S}^{(o,d)}$ and consequently $\boldsymbol{S}$ are valid stochastic matrices. The k shortest paths are calculated based on weighted adjacency matrix $\boldsymbol{W}$.

8.6.5 Visit probability of each node

Consider a probability vector $q^{(t)} = \left[q_1^{(t)}, q_2^{(t)}, \dots, q_n^{(t)}\right]$, where $\sum_{i=1}^{n} q_i^{(t)} = 1$ and $\forall i \in \{1,2,\dots,n\}$, $q_i^{(t)} \geq 0$, describing the likelihood of a random walk visiting each node at a given time point $t \in N^+$. Provided with the stochastic matrix $\boldsymbol{S}$, the dynamics of the probability vector $\boldsymbol{q}^{(t)}$ is described by the forward propagation equation

$$\boldsymbol{q}^{(0)}\boldsymbol{S}^t = \boldsymbol{q}^{(t)}, \tag{36}$$

where $\boldsymbol{q}^{(0)}$ is the initial condition.

Given G is connected and $\alpha^{(o,d)} \neq 0$, the stationary distribution $\boldsymbol{q}^*$ exists and is unique. It also coincides with the limiting distribution, i.e., the underlying Markov chain is ergodic. The stationary distribution $\boldsymbol{q}^*$ can be solved from the eigenvalue equation

$$\boldsymbol{q}^*\boldsymbol{S} = \boldsymbol{q}^*, \tag{37}$$

$$\sum_{k=1}^{n} q_k^* = 1, \tag{38}$$

where $\boldsymbol{q}^*$ is normalized to be a probability vector. The stationary/limiting distribution $\boldsymbol{q}^*$ describes the long-term node visit probabilities and is an ideal building block for the importance metric.

As for how to calculate $\boldsymbol{q}^*$, the method of matrix inversion was applied. Equations (37)-(38) were converted into the following equations.

$$\boldsymbol{q}^*(\boldsymbol{S} - \boldsymbol{I}) = 0, \tag{39}$$

$$\boldsymbol{q}^*\boldsymbol{E} = \boldsymbol{1}, \tag{40}$$

where $\boldsymbol{I}$ is an identity matrix and $\boldsymbol{E}$ is an all one matrix. Combing Equations (39)-(40), Equation (41) can be obtained and $\boldsymbol{q}^*$ is calculated in Equation (42).

$$\boldsymbol{q}^*(\boldsymbol{S} - \boldsymbol{I} + \boldsymbol{E}) = 1, \tag{41}$$

$$\boldsymbol{q}^* = (\boldsymbol{S} - \boldsymbol{I} + \boldsymbol{E})^{-1}, \tag{42}$$

8.6.6 Importance of each bridge

Inspired by the conceptual definition of risk as $risk = likelihood \times consequence$, a bridge is critical iff:

- severe consequence: the failure will significantly impact the functionality of the traffic network,

- high likelihood: the failure probability is relatively high.

For example, the Golden Gate Bridge satisfies the first criterion but not the second. This is because a long suspension bridge is flexible and can absorb large ground motions. Therefore, the Golden Gate Bridge is not critical.

Under this context, the likelihood is the damage probability of each bridge, and the consequence is the visit probability. The risk-informed importance metric for an individual bridge is defined as

$$\mu_k \coloneqq q_k^* \times p_{X_k}(x_k|IM_k), \tag{43}$$

where k takes index values for bridge nodes on G. Since both q_k^* and $p_{X_k}(x_k|IM_k)$ are probabilities, the metric has $\mu_k \in [0,1]$, i.e., well-bounded.

8.7 Corridor Information

Information for all 161 corridors is provided in **Table 5**. Their locations can be viewed at https://structures.live/. Instructions for logging in can be found in **Appendix 8.8**.

Table 5 Corridor information

Corridor Number	Corridor ID	Corridor Number	Corridor ID	Corridor Number	Corridor ID
D4-1	04-SCL-085-4	D4-55	04-SOL-505	D4-109	04-SCL/SM-101
D4-2	04-SM/SCL-280	D4-56	04-SOL-080-5	D4-110	04-SM/ALA-084
D4-3	04-SCL-017-1	D4-57	04-SOL-080-6	D4-111	04-SCL-280-1
D4-4	04-SCL-085-1	D4-58	04-SOL-080-4	D4-112	04-SCL-082
D4-5	04-SCL-017-2	D4-59	04-SOL-113	D4-113	04-SCL-085-5
D4-6	04-SCL-009	D4-60	04-SOL-012-2	D4-114	04-SCL-237-1
D4-7	04-SM-084-1	D4-61	04-SOL-012-1	D4-115	04-SCL-237-2
D4-8	04-SM-001-1	D4-62	04-SOL-080-3	D4-116	04-SCL-101-9
D4-9	04-SM-001-2	D4-63	04-SOL-080-2	D4-117	04-SCL-101-8
D4-10	04-SM-092-1	D4-64	04-SOL-680	D4-118	04-SCL-087-2
D4-11	04-SM-001-3	D4-65	04-SOL-780	D4-119	04-SCL-101-7
D4-12	04-SM/ALA-092	D4-66	04-CC/SOL-080	D4-120	04-SCL-880-3
D4-13	04-SM-280-2	D4-67	04-CC-080-2	D4-121	04-SCL-880-2
D4-14	04-SM-280-3	D4-68	04-CC/SOL-680	D4-122	04-SCL-101-6
D4-15	04-SM-380	D4-69	04-CC-004-1	D4-123	04-SCL-680-2
D4-16	04-SM-280-4	D4-70	04-CC-004-2	D4-124	04-SCL-237-3
D4-17	04-SM-001-4	D4-71	04-CC-004-3	D4-125	04-SCL/ALA-680
D4-18	04-SM/SF-035	D4-72	04-CC-160	D4-126	04-ALA-680-1
D4-19	04-SM/SF-001	D4-73	04-CC-004-4	D4-127	04-ALA-680-2
D4-20	04-SF-280-1	D4-74	04-CC-680-2	D4-128	04-ALA-680-3
D4-21	04-SF-001	D4-75	04-CC-242	D4-129	04-ALA-580-2
D4-22	04-SF-101	D4-76	04-CC-680-1	D4-130	04-ALA-580-3
D4-23	04-SF/MRN-001	D4-77	04-ALA/CC-680	D4-131	04-ALA-084-2
D4-24	04-MRN-101-1	D4-78	04-ALA/CC-024	D4-132	04-ALA-084-1
D4-25	04-MRN/CC-580	D4-79	04-ALA-024	D4-133	04-ALA-880-2
D4-26	04-MRN-101-2	D4-80	04-CC-080-1	D4-134	04-ALA-880-3
D4-27	04-MRN/SON-037	D4-81	04-ALA-080	D4-135	04-ALA-880-1
D4-28	04-MRN/SON-101	D4-82	04-ALA-013	D4-136	04-SCL/ALA-880
D4-29	04-SON-116-1	D4-83	04-ALA-580-5	D4-137	04-ALA-262
D4-30	04-SON-101-1	D4-84	04-ALA-580-4	D4-138	04-CC-004-5
D4-31	04-SON-101-2	D4-85	04-ALA-580-1	D4-139	04-SCL-087-1
D4-32	04-SON-116-2	D4-86	04-ALA-238-2	D4-140	04-SCL-280-3
D4-33	04-SON-012-2	D4-87	04-ALA-880-4	D4-141	04-SM-001-5
D4-34	04-SON-012-1	D4-88	04-ALA-880-5	D4-142	04-SCL-280-2
D4-35	04-SON-101-3	D4-89	04-ALA-185-2	D4-143	04-SCL-017-3

D4-36	04-SON-116-3	D4-90	04-ALA-980	D4-144	04-SCL-880-1
D4-37	04-MRN/SON-001	D4-91	04-ALA-580-6	D4-145	04-SCL-085-2
D4-38	04-SON-001	D4-92	04-SF/ALA-080	D4-146	04-SCL-085-3
D4-39	04-SON-101-4	D4-93	04-ALA-880-6	D4-147	04-SCL-101-5
D4-40	04-SON/NAP-128	D4-94	04-ALA-061	D4-148	04-SCL-101-4
D4-41	04-NAP-029-4	D4-95	04-SF-280-2	D4-149	04-SCL-152-1
D4-42	04-NAP-029-3	D4-96	04-SF-280-3	D4-150	04-SCL-101-3
D4-43	04-NAP-128-1	D4-97	04-SM/SF-101	D4-151	04-SCL-152-2
D4-44	04-SON/NAP-012	D4-98	04-SCL-130	D4-152	04-SCL-025
D4-45	04-SON-121	D4-99	04-SM-101-2	D4-153	04-SCL-152-3
D4-46	04-SON/SOL-037	D4-100	04-SM-092-3	D4-154	04-SCL-101-1
D4-47	04-SOL-037	D4-101	04-SM-101-1	D4-155	04-SCL-680-1
D4-48	04-NAP-029-1	D4-102	04-SM-082-2	D4-156	04-ALA-238-1
D4-49	04-NAP-012	D4-103	04-SM-092-2	D4-157	04-SOL-080-1
D4-50	04-NAP-221	D4-104	04-SM-280-1	D4-158	04-ALA-185-1
D4-51	04-NAP-121-2	D4-105	04-SM-084-2	D4-159	04-SCL-035
D4-52	04-NAP-121-1	D4-106	04-SCL/SM-082	D4-160	04-SCL-101-2
D4-53	04-NAP-029-2	D4-107	04-SM-082-1	D4-161	04-SM-035
D4-54	04-NAP-128-2	D4-108	04-SM-084-3		

8.8 User Manual

8.8.1 Preparation-log in the platform

Step 1: Open your browser and go to https://structures.live/. The login page will appear as shown below:

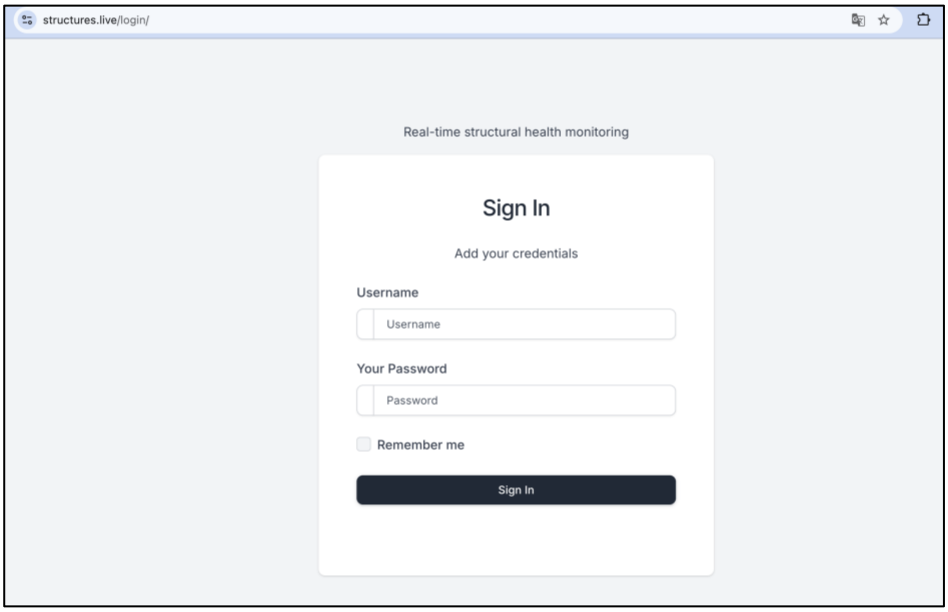

Figure 44 Login interface.

Step 2: Enter your username and password.

Step 3: The website interface will appear as shown below.

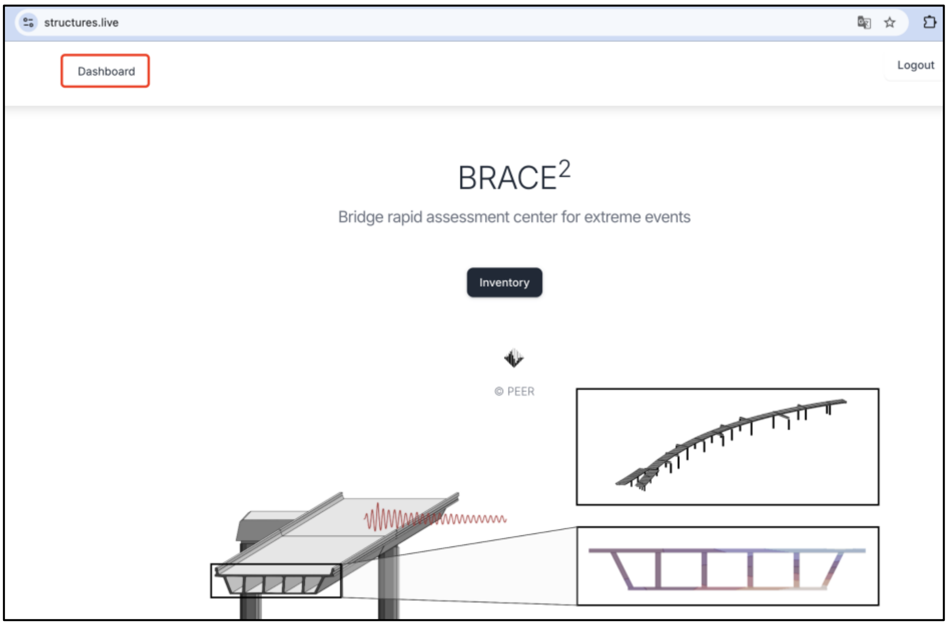

Figure 45 Interface after logging in.

Step 4: The website interface will appear as shown below.

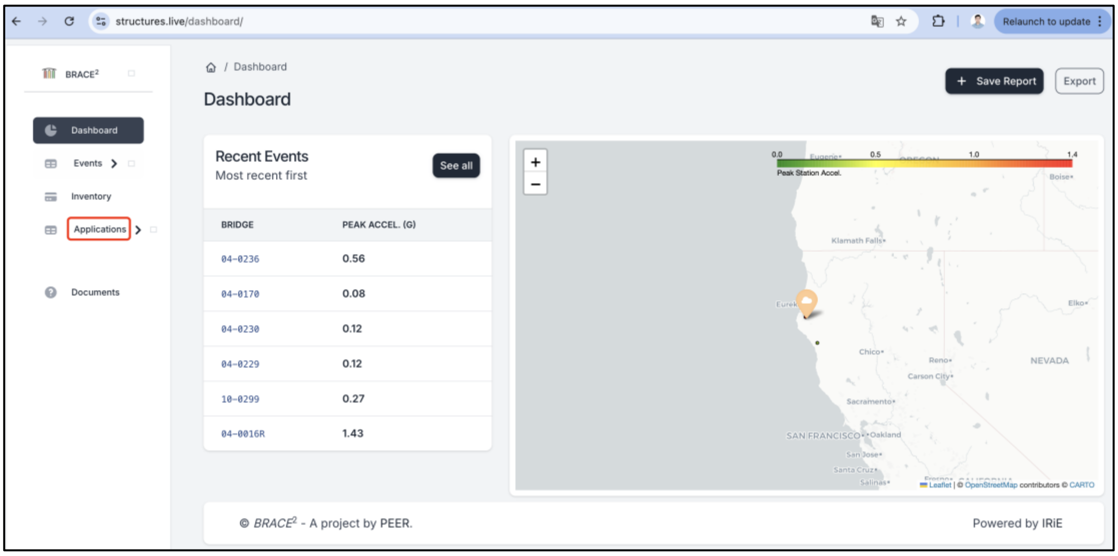

Figure 46 The Dashboard interface.

Step 5: Click the Applications in the sidebar to reveal three tools: Networks, Simulation, and Visualization.

- Networks: View the top ranked corridors based on the set weights for different types of facility access. It is noted that this is for intact networks, where all bridges can be used/touched.
- Simulation: You can remove any corridor and run the simulation to obtain new rankings.
- Visualization: Visualize the results obtained in Simulation.

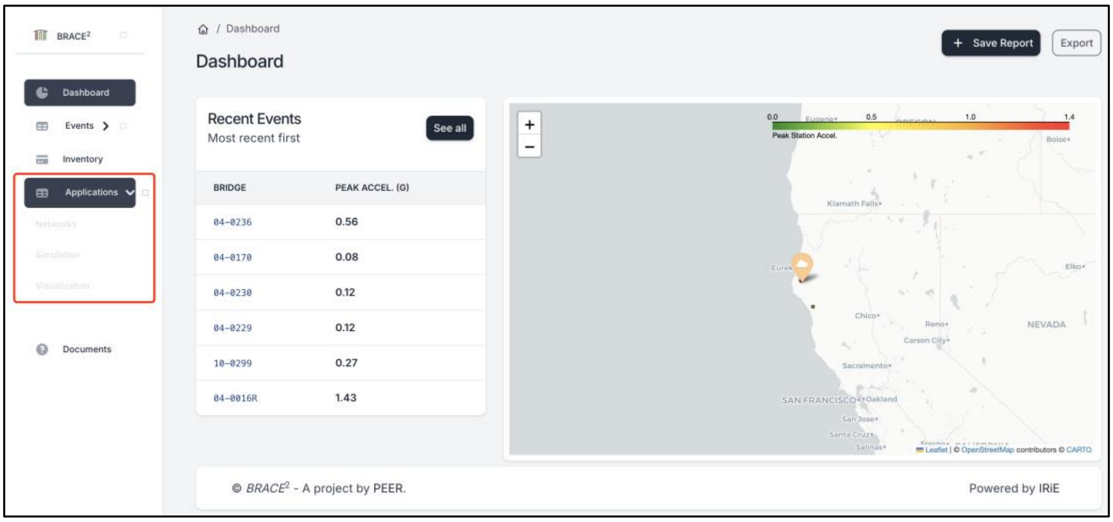

Figure 47 Three tools.

8.8.2 the "Networks" Application

- Forms

After clicking Networks, the interface changes, as shown in **Figure 48**. On the left is a form where you can select a method, assign weights to different types of facility access, and choose whether to consider population.

The currently available method is Method A. Method A means that each zone uses the shortest paths to and from the closest facility. The weights assigned to each facility access can be any non-negative integer, and when you click the "Rank" button, these weights are automatically normalized to sum to 100%.

Additionally, for "Consider population", selecting "*No*" means that each zone is treated equally, assuming one unit of demand per facility type. Selecting "*Yes*" means that zones with higher population are considered to have greater demand, which results in the top-ranked corridors being concentrated around these zones.

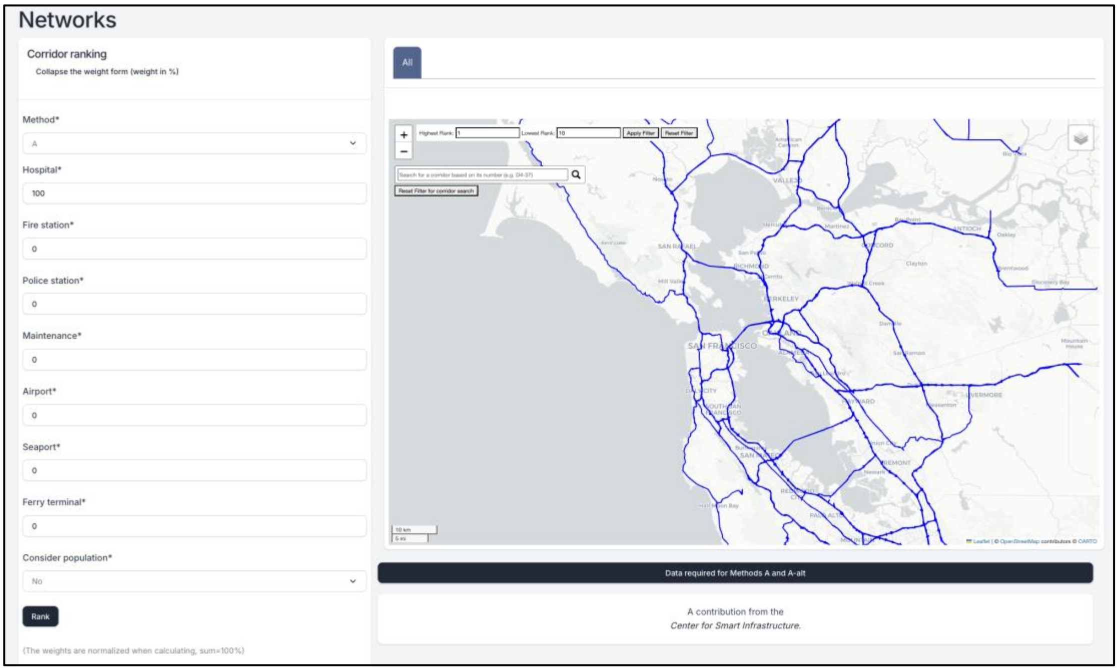

Figure 48 Networks interface.

- Corridor maps

After filling out the form, click the "Rank" button. The corridor map on the right will be automatically refreshed. For instance, in **Figure 48**, Method A is selected, the weight for hospital access is set to 100%, while the weights for other facility types are set to 0, and population is not considered. After clicking the "Rank" button, the map on the right in **Figure 48** is obtained.

Figure 49 describes the components in the map: highlighting the corridors within a certain ranking range, searching for a specific corridor based on its number, showing corridor information, and showing the strategic highway network (Strahnet).

- For the component of highlighting the corridors within a certain ranking range, which is within the green rectangle, there are two fields to fill in: one for the "highest rank" and the other for the "lowest rank." After filling them out and clicking the "Apply Filter" button, the corridors within this ranking range will be displayed on the map. For instance, if we want to know the locations of corridors within the ranking range of 1-5, the highest rank is set to1 while the lowest rank is set to 5. **Figure 50** shows the corridors, highlighted in red, in this range. If you want to re-select corridors in another range, click the "Reset Filter" button and then do the same.
- For the component of searching for a specific corridor by its number, located within the purple rectangle, you can find the location of each corridor by entering its number. For instance, to locate Corridor D4-37, enter "D4-37" in the search field, and the map will automatically zoom to that corridor, as shown in **Figure 51**.
- For the component of showing the Strahnet, place mouse on the layer icon on the upper right of the map and you can see two layers, corridor and Strahnet. If you want to view the Strahnet, check the box next to it.
- For the component of showing the corridor information, place the mouse over the corridor you want to view and click it. Its information, including corridor number, corridor ID, corridor type, zone count, corridor score, corridor rank, and whether it belongs to Strahent, will pop up. For instance, **Figure 49** shows the information of Corridor D4-37. Its corridor ID is 04-MRN/SON-001, corridor type is "other", zone count is 8, corridor score is 0.615, corridor rank is 3 out of 10, and it does not belong to Strahnet.

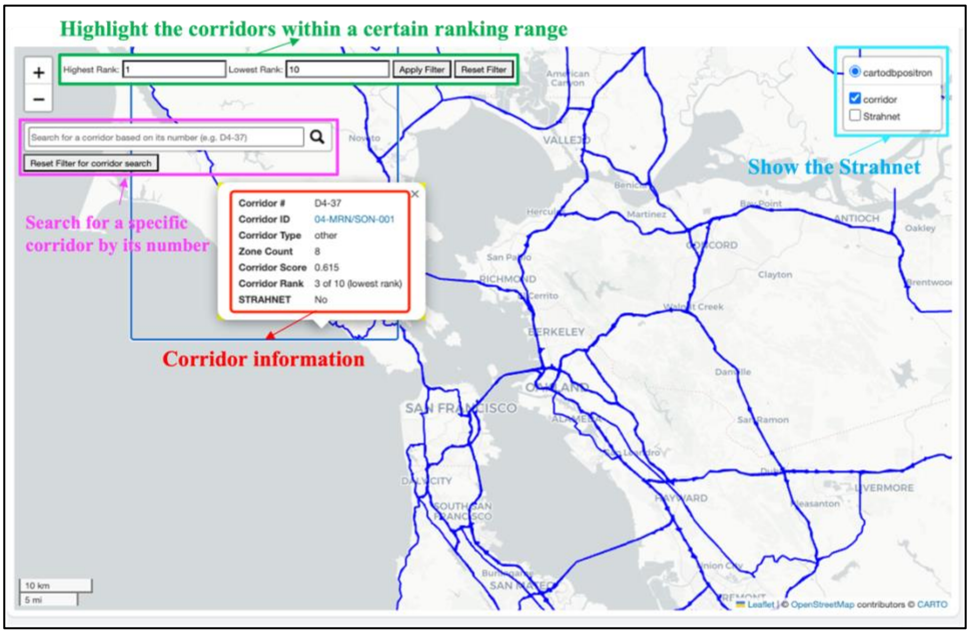

Figure 49 Description of each component in the map.

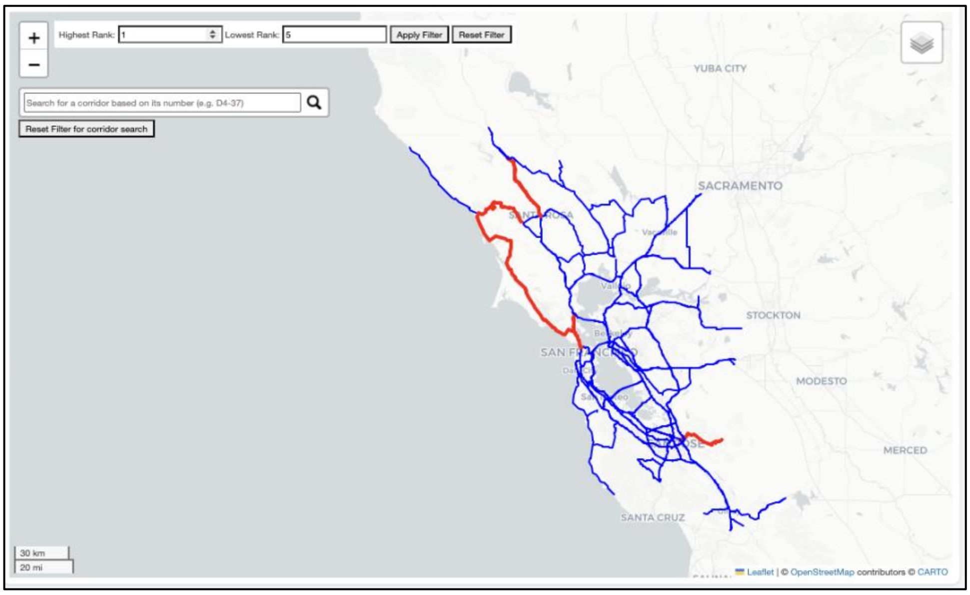

Figure 50 An example showing the top 5 corridors.

Figure 51 An example searching for Corridor D4-37.

- Bridge Maps

After filling out the form and clicking the "Rank" button, not only is the corridor map updated, but a table containing the corridor information also appears below the form, as shown in **Figure 52**. This table presents three columns, corridor number, corridor ID, and corridor rank. If you want to view the detailed information of a specific corridor, click on the row of that corridor, and the bridge map will show on the right. For instance, if you want to view the detailed information about Corridor 36 (04-SON-116-3), place the mouse over that row and click it. A bridge map will be shown on the right next to the corridor map, as shown in **Figure 53**.

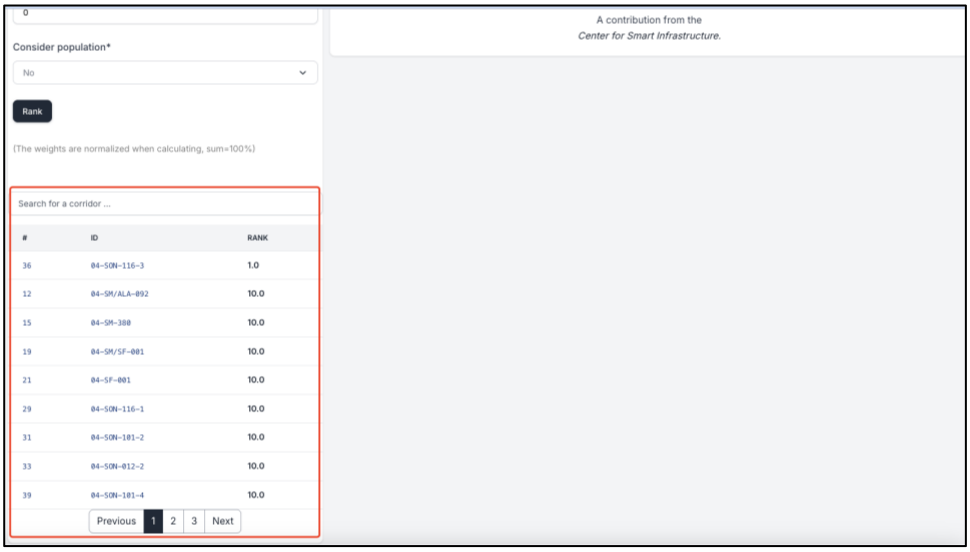

Figure 52 A table that appears below the form after clicking the "Rank" button.

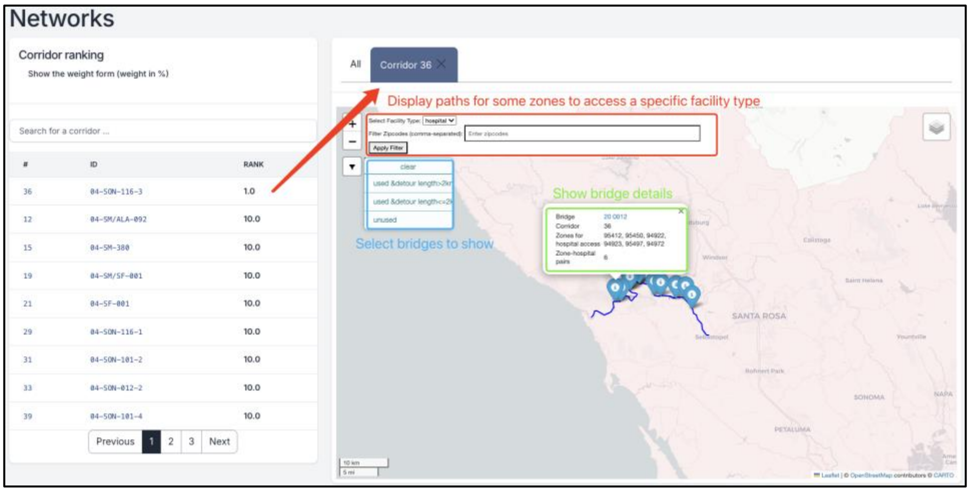

Figure 53 An example of the bridge map after clicking Corridor 36 (04-SON-116-3) in the corridor table.

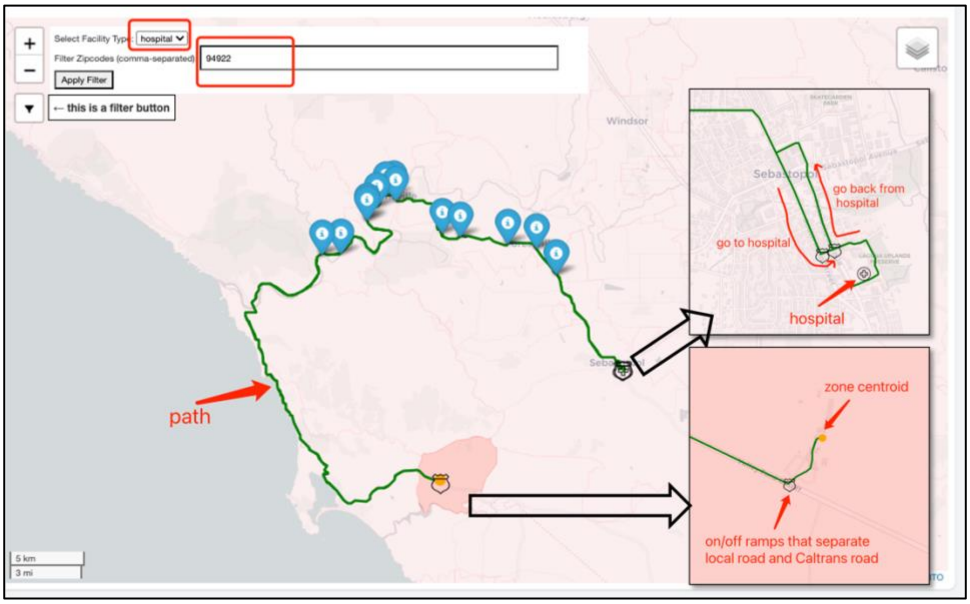

Figure 54 An example of showing paths from a zone to its closest hospital and back.

8.8.3 the "Simulation" Application

In the "Networks" application, the results are based on the intact network. If you want to understand the impact of removing a specific corridor, or if certain corridors cannot be upgraded in practice, you need to remove them and re-rank the corridors based on the updated network. This can be achieved by the "Simulation" application.

Figure 55 shows the interface of this application. There is a form including four parts: choose a facility type, input removed corridor numbers, upload updated Caltrans road nodes data, and upload updated Caltrans road links data.

- For “Choose a facility type”, there are seven options: hospital, fire station, police station, maintenance facility, airport, seaport, and ferry terminal. The selected facility type indicates that the simulation will run for access to that facility type. **Figure 55** provides an example in which “hospital” is selected.
- For “Input removed corridor numbers”, enter a set of corridor numbers ranging from 1 to 161, separated by commas. If no corridors are to be removed, enter “intact” in the field. For example, to remove bridges on Corridors 1, 2, and 10, enter “1,2,10”.
- For “Upload updated Caltrans road nodes data and links data”, these are advanced features. In the future, as some bridges are constructed or removed, both the bridge inventory and the Caltrans road network will need to be updated accordingly. We plan to develop a large language model to automate this process, allowing Caltrans to update the network without writing any code, simply by interacting with the model.

After filling out this form, click the “Run Simulation” button. When the simulation progress reaches 100%, a “Download Result” button will appear, as shown in **Figure 56**. Click the “Download Result” button to download a spreadsheet containing the results. The spreadsheet includes the following 8 columns:

- Rank: the ranking of the corridor,
- Corridor id,
- Count: the number of zones that use the bridges on this corridor,
- Zone: the zones that use the bridges on this corridor,
- OD travel time round trip [min]: the round-trip travel time from each zone to its closest facility,
- Bridge in this corridor that is used: the bridges used on this corridor,
- Inaccessible zones: zones that become inaccessible after the specified corridors are removed,
- Removed corridor list: the list of removed corridors.

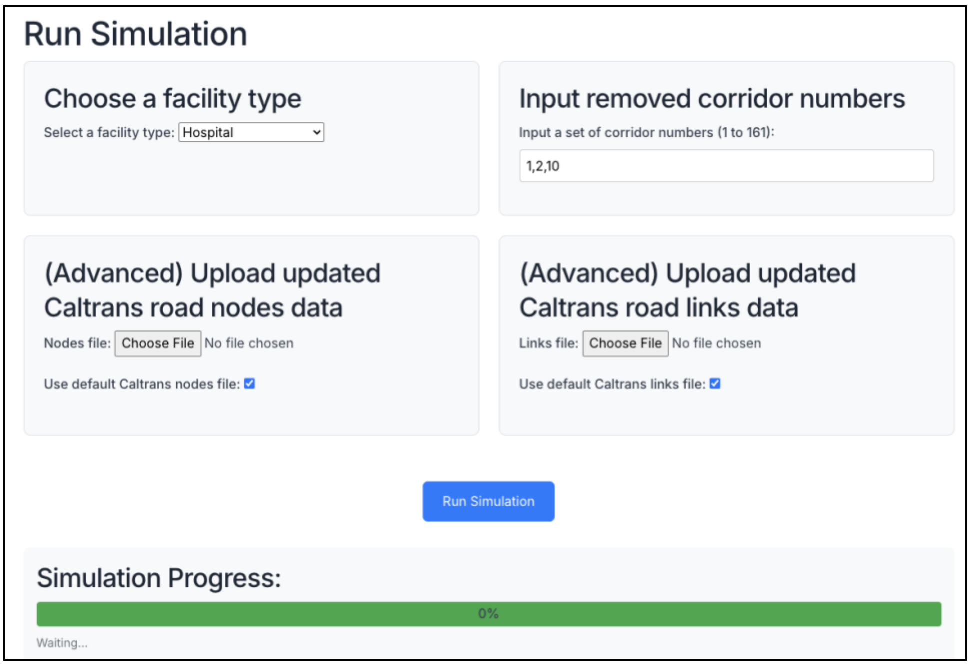

Figure 55 Simulation interface.

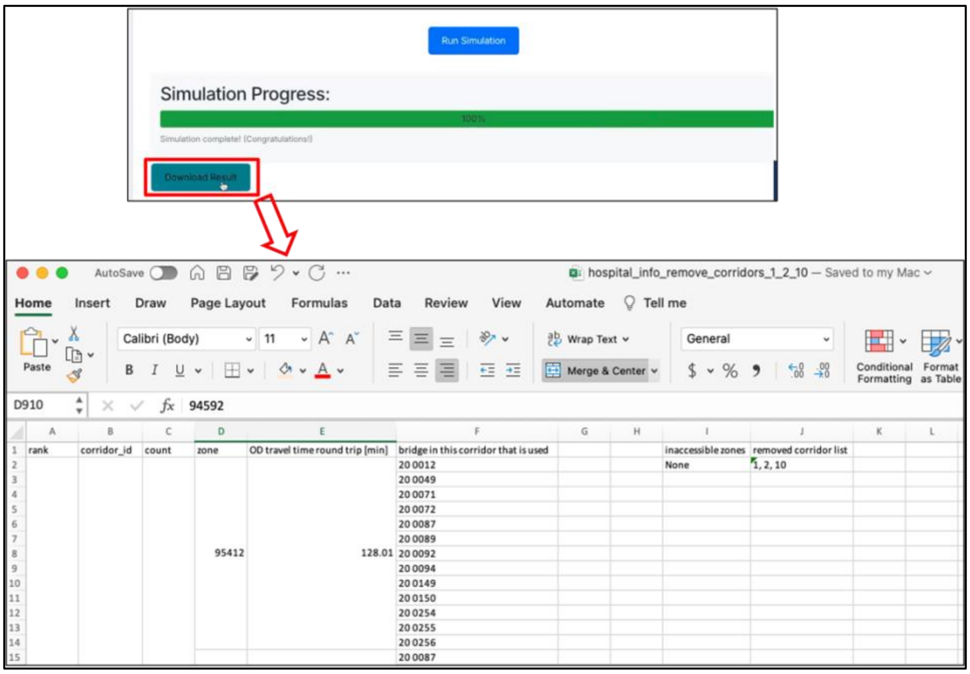

Figure 56 Simulation results.

8.8.4 the "Visualization" Application

Since the simulation generates a spreadsheet, the results may not be very user-friendly to interpret. To provide a visualization like what is shown in "Networks", another application called "Visualization" is created. By uploading the generated spreadsheet there, you can view maps of corridors and bridges just like in the "Networks" interface. **Figure 57** presents the visualization interface. You need to upload the spreadsheet corresponding to the selected facility type and set the weight. For instance, spreadsheets about hospital access and maintenance facility access with Corridor 36 (04-SON-116-3) removed are uploaded and their weights are set to 50%. It indicates that only hospital and maintenance facility access are considered for ranking the corridors and they are of equal importance. Then, click the "Rank" button, and the corridor map on the right will be updated. The other functions are the same as in the "Networks" application, except that paths are not shown on the bridge map, as generating them consumes significant computational time and memory.

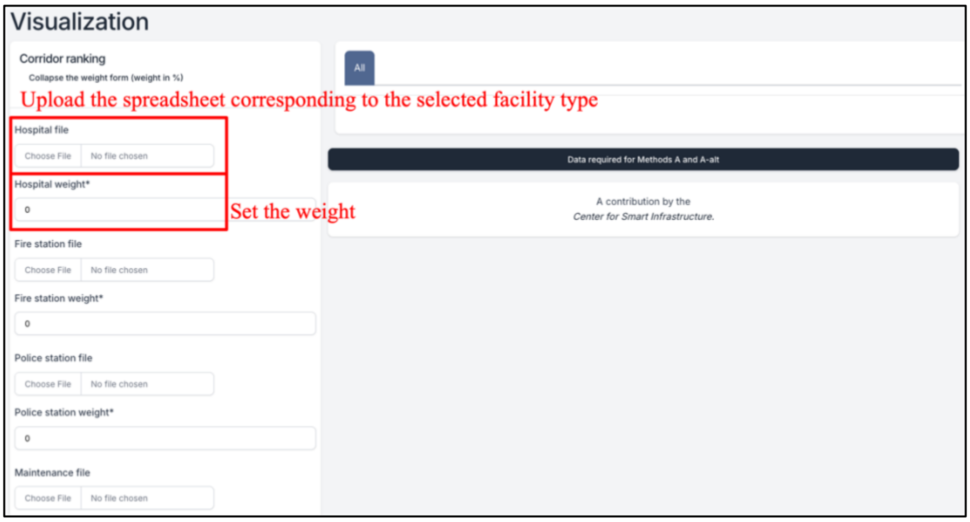

Figure 57 Visualization interface.

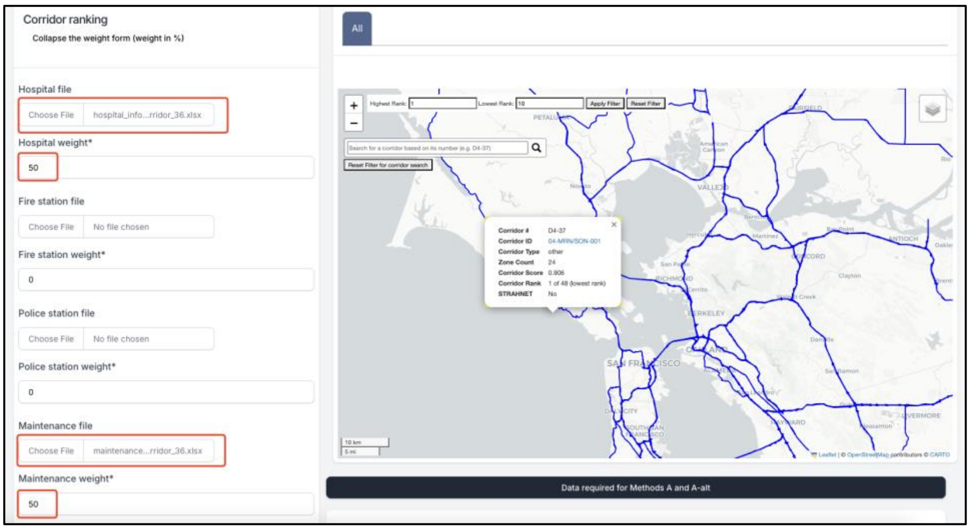

Figure 58 A visualization example.