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The existing reliability measures are useful for assessing different factors related to the performance of the transportation network. However, none of the existing measures addresses the issue of adequacy of network capacity to accommodate demand. That is, whether the available network capacity relative to the required demand is sufficient. This measure provides important information for efficient flow control, capacity expansion, and other relevant works to enhance the reliability of a road network. It may also have the potential of providing a tool to design road networks that are resistant to traffic disturbances. Only recently, the capacity was reliably introduced as a new performance measure to evaluate the performance of a degradable road network. It was defined as the probability that the network can accommodate a certain traffic demand at a required service level, while accounting for drivers' route choice behavior. Travel time reliability can also be obtained as a side product while evaluating the capacity reliability. However, a comprehensive analysis of the capacity reliability was not provided. It can be observed from the past that most of the researches primarily focus at safety issues of transportation systems. Literature emphasizing on transportation reliability is scarce. Since no paper is directly dealing with reliability issues. This study aims to introduce a successful technique for calculating critical paths of the proposed California transport network by analyzing reliability of the network, creating a high-level design of the software, utilizing tools and technologies, and describing the modular implementation of the software, testing, and experimentation. More specifically, this work aims to achieve accurate real-time calculation of betweenness centrality index with a unique combination of reliability analysis and path failure strategies to predict critical paths of a transport network.

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INTRODUCING THE RESILENCE INTO THE STATE TRANSPORTATION NETWORK

January 2018

A Research Report from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

CALIFORNIA STATE UNIVERSITY LONG BEACH 1949

About the National Center for Sustainable Transportation

The National Center for Sustainable Transportation is a consortium of leading universities committed to advancing an environmentally sustainable transportation system through cutting-edge research, direct policy engagement, and education of our future leaders. Consortium members include: University of California, Davis; University of California, Riverside; University of Southern California; California State University, Long Beach; Georgia Institute of Technology; and University of Vermont. More information can be found at: ncst.ucdavis.edu.

Disclaimer

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NCST

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EXECUTIVE SUMMARY

California has been a leader in adopting policies to reduce greenhouse gas emissions. Meanwhile, for too long, businesses have been warning of key routes that are stretched to breaking point. In many places across California, it takes only a single incident to cause chaos – for instance, car accident across the intersection of I-5, I-10, and I-101. Fast-pace California businesses demand a transport network that can cope better with accidents, severe weather - not to mention ubiquitous earthquake threats. Therefore, the state requires to provide and to maintain an acceptable level of service in face of faults and any challenges to normal operations. Sacramento should be tasked to immediately identify all the places where the road and rail networks need urgent attention in their state-wide long-range transportation plans.

Transportation network is a key component to provide a better transport service for both people and goods. Reliability, vulnerability and robustness are the major characteristics that can be used to analyze a transport network. The reliability of a transport network is defined as the possibility of moving people or goods from one place to another successfully. Exploring the reliability of a road network has attracted a significant attention due to increase in natural disasters. Such natural disasters not only damage connections of the roadways, but paralyze transportation system for a remarkable period of time. To overcome this disadvantage, reliability of a transport network can be maintained by closely monitoring and ensuring the safety of critical paths in the network so that the users can always have a reliable route for their commute.

Critical paths of a transportation network are the most dependable/used paths of that network. Failure of certain paths, or sub-networks which is caused by car accidents, road maintenance, or serious road congestion has a severe impact on the reliability of the transportation network. Several methods exist to analyze reliability of the transport network such as concept of connect reliability, network reliability technique to monitor the current traffic status.

In this study, a network model is developed to calculate reliability by considering the critical paths of a transportation network using the UCINET simulation tool. The implementation of this network model used two path failure strategies (selective and random) using the Betweenness Centrality as a metric. Our preliminary results show that the UCINET tool can be used to successfully estimate the reliability and to further identify the critical paths of a highway transportation network in California.

Introduction

Transportation system is a network system normally composed of three parts: road, railway, and bridge. This system is a critical lifeline for land transport, for evacuations, for sending disaster fighters and disaster engines, and for matter transport. If any earthquake occurred, the bridge and road would suffer different degrees of damage, which will be a bad influence on its service function and will threaten people's lives. For example, the great Tang San Earthquake in China in 1976, the San Fernando Earthquake in American in 1971, and the Earthquake in Japan in1995, caused great damages to their transportation system. These damages included complete blockage of the freeways, bridge collapse and cracks in the road. Since the seventies, the studies of lifeline earthquake engineering systems have been developed to investigate network system damage, function destructiveness analysis, and reduction disaster policy analysis. Therefore, it is important to analyze the reliability of our transportation system at California.

For the past four decades, network reliability prediction has been explored extensively. Numerous prediction models and algorithms have been proposed and applied by researchers. With modern technology developments, reliability analysis has become most popular in the research area due to its essential role in the Intelligent Transportation Systems (ITS). As one of the most fundamental inputs in the ITS, critical path information in the recent future is crucial for both 1) the travelers so that they can make a trip decision and 2) the traffic management center that develops strategies for operation control. Therefore, a critical path calculation model is needed to analyze reliability of a network.

The existing reliability measures are useful for assessing different factors related to the performance of the transportation network. However, none of the existing measures addresses the issue of adequacy of network capacity to accommodate demand. That is, whether the available network capacity relative to the required demand is sufficient. This measure provides important information for efficient flow control, capacity expansion, and other relevant works to enhance the reliability of a road network. It may also have the potential of providing a tool to design road networks that are resistant to traffic disturbances. Only recently, the capacity reliability was introduced as a new performance measure to evaluate the performance of a degradable road network. It is defined as the probability that the network can accommodate a certain traffic demand at a required service level, while accounting for drivers' route choice behavior. Travel time reliability can also be obtained as a side product while evaluating the capacity reliability. However, a comprehensive analysis of the capacity reliability was not provided. It can be observed from the past that most of the researches primarily focus at safety issues of transportation systems. Literature emphasizing on transportation reliability is scarce. Since no paper is directly dealing with reliability issues; this project is an effort towards providing operational reliability assessment model for road transportation system. The scope of this paper is limited to assessment of reliability from the source to the destination route. The activities and the major factors affecting the operations since departure of a vehicle from source to destination have been considered. Network system safety is also one of the issues of concern that too is considered in the analysis. The whole transportation system is composed of several sub and sub–sub systems; as a result, the complexity of the entire system is at high dimension level. The major challenge is how to model the decision variables and assess the operational reliability of the transportation system in the domain of the scope as mentioned. The problem can be tackled in case statistical data or information could be obtained about the relevant variables. Availability of statistical data is a primary hindrance here as well, as always in any large-scale system. However, the complexity of the problem magnifies in case of lack of statistical data or availability of imprecise or vague data. Hence, the fundamental thought of this paper is based on modeling vague or ambiguous information and evaluation of subjective operational reliability. The model proposed in this project, since it depends on expert opinions or their judgment in the form of linguistic terms, is titled as an efficient approach for reliability analysis based on path failure strategies.

Overall, this study aims to introduce a successful technique for calculating critical paths of the proposed California transport network by analyzing reliability of the network, creating a high-level design of the software, utilizing tools and technologies, and describing the modular implementation of the software, testing, and experimentation. More specifically, this work aims to achieve accurate real-time calculation of betweenness centrality index with a unique combination of reliability analysis and path failure strategies to predict critical paths of a transport network.

Literature Survey

Road network reliability [1], which evaluates the size of the road network endurance in the daily and occasional incidents, is used as an evaluation index described by the access probability from one node to another. However, it has only been two decades since the concept of the reliability really began to be applied into the traffic system and its research content is continuously improved associated with the changes of traffic technology and modes.

Connectivity was first proposed by H. Main et al. [1], which reflects the probability to maintain connectivity between nodes in transport networks. Y. Asakura et al. [2] puts forward the concept of travel time reliability in 1991, which is another measure method of network reliability, fully taking into account the travel needs of the road network and traveler behavior. In 1994, A. J. Nicholson et al. [3] defined the recession reliability of the traffic flow, namely the probability for the decline of Origin-Destination (OD) pair or the traffic flow in the network not exceeding a certain value, and pointed out that one or more road network OD pairs will be directly affected when recession occurs in one road section. W. Lam et al.proposed the conception of demanding satisfaction reliability in 2000, which reflects the ability of providing the potential travel demand for road network, and describes the probability for the travel demand satisfaction rate not less than a particular value [4]. In 2002, M. Bell et al. expanded the travel time reliability to the travel cost reliability [5], including travel time, travel distance, vehicle charges, and public transport costs; if the cost for completing a trip is less than a given threshold value, the corresponding road section is believed to be reliable. In China, based on the growth rules of the simulating tree, Zhu et al. proposed the channel generation method [6], of which all channels are efficient and suitable for large-scale network, discussed the effective channels, sensitivity of road sections and the reliability; for the fallibility factors of the road traffic network, J. Jin explored the reliability of the evaluation system of urban road traffic networks, and researched the redundancy and the economy of time and space of road transport network from the viewpoint of dynamic degeneration [7]. In 2005, H. Lin et al. studied the reliability of transport networks in emergencies and gave out the three probability problems usually considered in unexpected situations: the destruction of properties of nodes and sections, repair characteristics of nodes and sections, and the connectivity reliability in emergencies [8]. H. Fan et al. gave out the evaluation indexes of network reliability and the calculating model of reliability based on the network topology [9], and determined the arc, path, node, and the calculation method of reliability of the network structure; P. Yuan et al. considered the state of uncertainty of the transportation network under realistic traffic conditions [10], and proposed the change of choice of behavior from uncertain to deterministic network state and the route choice of model based on travel time reliability.

The traditional connect reliability evaluation method is mainly based on the analysis of the transportation network graph theory, But the transportation network of high density and large scale not only requires a tremendous amount of calculation, but also presents an insensitive reflection of the real situation. Different links of the transportation network have various degrees of influence and possibilities for the function of the whole network. The most influential links with the most possibilities to be destroyed was vital for connect reliability of the transportation network. Hence, to facilitate the connect reliability of the whole network, the improvement of the key links should be put on top of the agenda. The evaluation methods for connect reliability based on above ideas are put forward by some scholars. A. J. Nicholson et al. have defined two key points about vulnerability concept, using the method of sensitivity analysis and reliability analysis with the identification of the key unit of transportation network and provides the reliability of network system by improving the key unit [3]. G. D'Este et al. proposed a reliability evaluation method for the key point of a transportation network whose small portion was disastrous [11]. P. Hossain et al. referred the Birnhaum probability importance and defined the route importance based on the index of consumers' surplus reliability with which he used to improve network performance through heuristic algorithm as well, but still an enormous calculation for a large scale net [12]. According to B. Sanso et al., the most important system state should be prioritized to evaluate the reliability of transportation network [13]. It is vital importance to find out the key link to facilitate the network and optimize the performance with the consideration of random accidents. The so-called critical link refers to those roads with an enormous impact on network performance once they closed, especially under the conditions of natural disasters. S. Sanchez et al. defined accessibility index node as the objective of network performance optimization [14]. But the accessibility index cannot reflect the change of demand elasticity. In 2006 L. Haixu et al., based on the key links, raised transportation network optimization theory holding that the key link for the probability of being selected is bigger than a predetermined threshold section [15]. L. Haixu built a transportation network reliability improvement model based on key links using the heuristic method which can identify key links proposed by Taylor, and the improved model is established based on the key links of the transportation network reliability without measure methods on critical link; G. Yong et al. combined the city basic traffic data and started from the actual operation, putting forward a kind of connect reliability evaluation method based on key links and managed to avoid too much computation, but this method did not analyze the influencing factors, which caused the result [16]. It is a kind of afterward result according to experience for improvement to certain extent but not for prediction for transportation network performance. H. Liwen et al. considered direct measurement of the relative importance was not feasible, and then he figured out the solution to find key links based on connect reliability [17]. But the computation of network connect reliability is difficult.

Connect reliability analysis method based on the key point is a new way for researching connect reliability, but the key point identification method is not yet mature and it is still in the earlier research stage. Recent years, the rise and development of complex network science provided the theoretical support for varieties of networks existence and also provided a way for the study of the transportation network reliability. To distinguish it from general networks, transportation network is weighted network. The network with the same structure but the traffic volume is different, the important degree obviously varies. We can make use of the dual graph theory to identify the key link with the identification of the key point.

Through the analysis of the literature, we can see that the study of reliability of road network has transformed from the study only considering the physical structure of the road network to that of consideration of loading traffic flow and the mutual influence between travel demand and the capacity of road network, as well as the travel behavior of road users; the corresponding reliability indexes are connectivity reliability and travel time reliability. During this period, some scholars have proposed demand satisfaction reliability, the weak point reliability, performance index reliability, and suffered reliability. In China, research is conducted on the basis of foreign studies, and is the supplement or continuation of foreign study results; there is no significant breakthrough in the road network reliability indexes, and most of the researches are on connectivity reliability and travel time reliability. But domestic researches have explored the connectivity reliability and travel time reliability from different perspectives and conditions, which widen the thoughts and provide a foundation for further study on this area.

Accurate calculation of critical links of a transportation network under various traffic conditions would help us to make better decisions and respond to the trip requirements under adverse traffic condition. This research would focus on two parts: one is to develop an accurate and reliable model for finding critical paths of a transportation network; and the other is to analyze the reliability of a transportation network during natural disasters using path failure strategies.

The California Transportation Network and Its Description

The California State Transportation Agency (CALISTA) is solely responsible for the transportation and its related departments within the state. It's a large organized system which is composed by world's best highways, yet its transportation network is slightly confusing as well as vigorous. The California State has a large number of interstates and streets in the process of the subdivision. The densely populated areas of it are found with few metros, worker rail, and the light rail. Apart from the highly developed roadways, it also has the transportation through water called as the Marine Transportation, the transportation through the air is called as the aerial communication and finally, rail transport which is boon to the middle-class people. The creation of the transportation network is not an easy task in the state of California due to its large and dense population and its wide range of available transportation systems. The intercommunication between the critical links plays a vital role in assessing the information of the entire network.

The California transport agencies handle the cargo shipments at the Pacific Rim and beyond to transport the goods. Apart from the transportation, it is composed of the air transportation with a large number of terminals. The little size terminals to the global terminals help to connect with the international airports such as Los Angeles and the San Francisco airports. Both the water and air transportation have its own place in the California State transportation. The California State is known for its lavish lifestyle and the cars are the biggest craze in it. The number of vehicles owned by the registered owners is higher than the registered license holders (driving). This situation makes the California traffic as the world's most congested traffic and also possess the worst roads of the USA in it. The unauthorized vehicle procession by the local residents of the California has increased the traffic in unimaginable level and this situation throws a challenge to the researchers who maintaining the network transportation of it. The extensive number of Highways, expressways, freeways and the vast terrains are all maintained by the California department of transportation and the patrolled by the California Highway Patrol (CHP).

The leadership came together in 1990 to support Propositions 108 and 111 which created the Transportation Blueprint for the last decade of the 20th century. Prop. 111 increased the gas tax from 9 to 18 cents, and Prop. 108 provided bonding for transit development and expansion. The first effort was to help pass the Transportation Blueprint in 1990. That was the first significant attempt to address the new demands of transportation infrastructure in California since Gov. Pat Brown’s administration. As ambitious as those measures were, however, no one could have anticipated improvements in fuel efficiency that have decreased the effectiveness of the gas tax, nor could anyone have anticipated the current economic and population boom that’s putting enormous pressure on the system, and consequently on people and those who supply them with goods and services. These pressures were pretty clear by the mid-’90s when the Northridge Earthquake shook up the funding mix. Caltrans had to use virtually all the money going into the highway fund for earthquake retrofit in Northern and Southern California — canceling or delaying projects approved in the 1990 plan.

Transportation California mobilized to the lead the fight for Prop. 192 for earthquake retrofitting. By creating separate funding for earthquake retrofitting, funds once again flowed into the state highway account for improvement and maintenance. In 1998 the state passed Prop. 2, a measure designed to protect the dollars in the state highway fund from diversion. This was approved by 75 percent of California voters. Now the state's politicians are not able to raid the gas tax funds as they did during the 1990s–diverting more than $1.2 billion in badly needed transportation dollars to non-transportation purposes.

In 1999 the focus was project delivery, an emphasis that resulted from a big backlog of highway improvements that had been approved and funded, but not even started. This year-long effort also was successful. On Oct. 10, Gov. Davis signed into law AB1012, the project delivery bill that will help expedite transportation projects. The legislation creates a loan program to draw down the huge balance in the State Highway Account. It also includes a "use it or lose it" provision for certain federal transportation funds. In 2000, the coalition supported Prop. 35 which reversed the limiting trend and specifically allowed government agencies to contract out necessary design services.

In March 2002, Transportation California took the lead on Proposition 42, a measure that will permanently dedicate the sales on tax on gasoline for transportation purposes only. The measure's passage will boost transportation funding by $1.2 to $1.5 billion annually – as much as $30 billion over the next 20 years. And in 2005, Transportation California was asked to spearhead the Fund Prop. 42 coalitions, mounting a statewide awareness campaign and working with the Administration to reverse its proposal to suspend Proposition 42, and ultimately to achieve full funding for Proposition 42 at $1.2 billion.

In 2006, Transportation California joined with the California Alliance for Jobs, Governor Schwarzenegger and Senate President pro Tempore Don Perata in the successful drive to enact and win voter approval of a comprehensive infrastructure bond package–Propositions 1A-1E. Most important to Transportation California were Proposition 1A to provide additional constitutional protections for transportation funds and Proposition 1B, which authorized $19.3 billion for vital transportation infrastructure projects.

As California confronted a series of severe fiscal crises in the first decade of the 21st Century, Transportation California has led industry and labor efforts to make the case to the Governor and Legislature for full funding of transportation programs, which are vital to the state's economy. While State spending has undergone significant retrenchment in the past decade, existing transportation programs have more than held their own, yet they still face massive shortfalls resulting from decades of underinvestment.

Now Transportation California is tackling the job of developing significant new revenue streams that are needed to make sure our transportation system is up to meeting the needs of California's economy and its people.

Model Development and Implementation

Based on the earlier literature review, this section proposes a novel way of calculating critical paths across a given transport network. The characteristics of reliable routes are discussed in the first section, which is further followed by the strategies to calculate the centrality index of all the nodes in the given transport network. The strategy specifies the working methodology and steps used to find the betweenness centrality index of each node. The strategy discussed here has two modules, constructing transportation network model and calculating path betweenness centrality index of transportation network model using the concept of Adjacency matrix, which are essential steps in predicting network reliability. The results of this module are further used in the identification criteria.

Characteristics of Reliable Routes

Some of the elements that the analyses in the previous section should take explicitly into account in order to incorporate considerations of reliability are:

- The probability of non-failure of a given project, given various external circumstances (i.e., the reliability).
- The probability of external circumstances not occurring (i.e., probability of no threat)
- The robustness of the system (i.e., the probability that the system will continue to function even if a threat eventuates at a vulnerable point)
- How long it will take (and how expensive it will be) to repair the system if the threat occurs and the system fails at its vulnerable point
- What the costs are to the general economy of such a failure (i.e., goods and passengers not getting to their destinations, or getting there late, transportation carriers being forced to use expensive detours, etc.)
- The contribution of a given project to improving the robustness (and hence reliability) of the system (or possibly the costs of a project in reducing robustness if a project involves taking an existing piece of the transportation system out of service: e.g., replacing a bus system with a subway)
- What degree of risk aversion that should be applied in deciding what weight to place on the risk (i.e., level of threat times vulnerability) that has been identified?

Constructing Transportation Network Model

The concept of adjacency matrix is used to model the transportation network. An adjacency matrix is a (0, 1) square matrix used to represent a finite graph. The elements of the matrix indicate whether pairs of vertices are connected or not in the graph. The value zero indicates no connection and the value one indicates direct connection. After collecting the network routes data, the next step is to convert the data collected into the adjacency matrix.

		1	2	3	4	5	6	7	8	9	10	11
		Sacramento	Napa Valley	Stockton	Yuba City	Ukiah	Chico	Willows	Redding	Eureka	San Jose	San
1	Sacramento	0	0	0	0	0	0	0	0	0	0	0
2	Napa Valley	0	0	1	0	1	0	0	0	0	1	0
3	Stockton	0	1	0	0	0	0	0	0	0	0	1
4	Yuba City	0	0	0	0	0	1	0	0	1	0	0
5	Ukiah	0	1	0	0	0	0	0	0	0	0	0
6	Chico	0	0	0	1	0	0	1	0	1	0	0
7	Willows	0	0	0	0	0	1	0	0	0	0	1
8	Redding	0	0	0	0	0	0	0	0	0	0	1
9	Eureka	0	0	0	1	0	1	0	0	0	0	0
10	San Jose	0	1	0	0	0	0	0	0	0	0	1
11	San	0	0	1	0	0	0	1	1	0	1	0
12	Oakland	0	0	1	0	0	0	0	0	0	1	1
13	Berkeley	0	0	0	0	0	0	0	0	0	1	1
14	Bakersfield	0	0	0	0	0	0	0	0	0	0	0
15	Fresno	1	0	0	0	0	0	0	0	0	1	0
16	King City	0	0	1	0	0	0	0	0	0	1	0
17	Paso Robles	0	0	0	0	0	0	0	0	0	0	0
18	Los Angels	0	0	0	0	0	0	0	0	0	0	0
19	San Diego	0	0	0	0	0	0	0	0	0	0	0
20	Long Beach	0	0	0	0	0	0	0	0	0	0	0
21	Anaheim	0	0	0	0	0	0	0	0	0	0	0
22	Santa Ana	0	0	0	0	0	0	0	0	0	0	0
23	Riverside	0	0	0	0	0	0	0	0	0	0	0
24	Irvine	0	0	0	0	0	0	0	0	0	0	0
25	San	0	0	0	0	0	0	0	0	0	0	0

FIGURE 1. Adjacency Matrix Graph of Road Model.

This adjacency matrix is given as an input for the simulation tool, UCINET and the transportation network graph is generated based on the data provided in the matrix. Figure 1 represents the adjacency matrix where the 'x' and 'y' axis represents the names of the cities of the network, while the data '0/1' represents the connection between corresponding cities.

Figure 2 represents the transformation of the adjacency matrix into network graph, where the blue squares represents cities and the directed arrowheads between them show the connection between them. It can also be seen from the Figure 2 that some of the connections are unidirectional and some are bidirectional, this concept is later briefly discussed in the following sections.

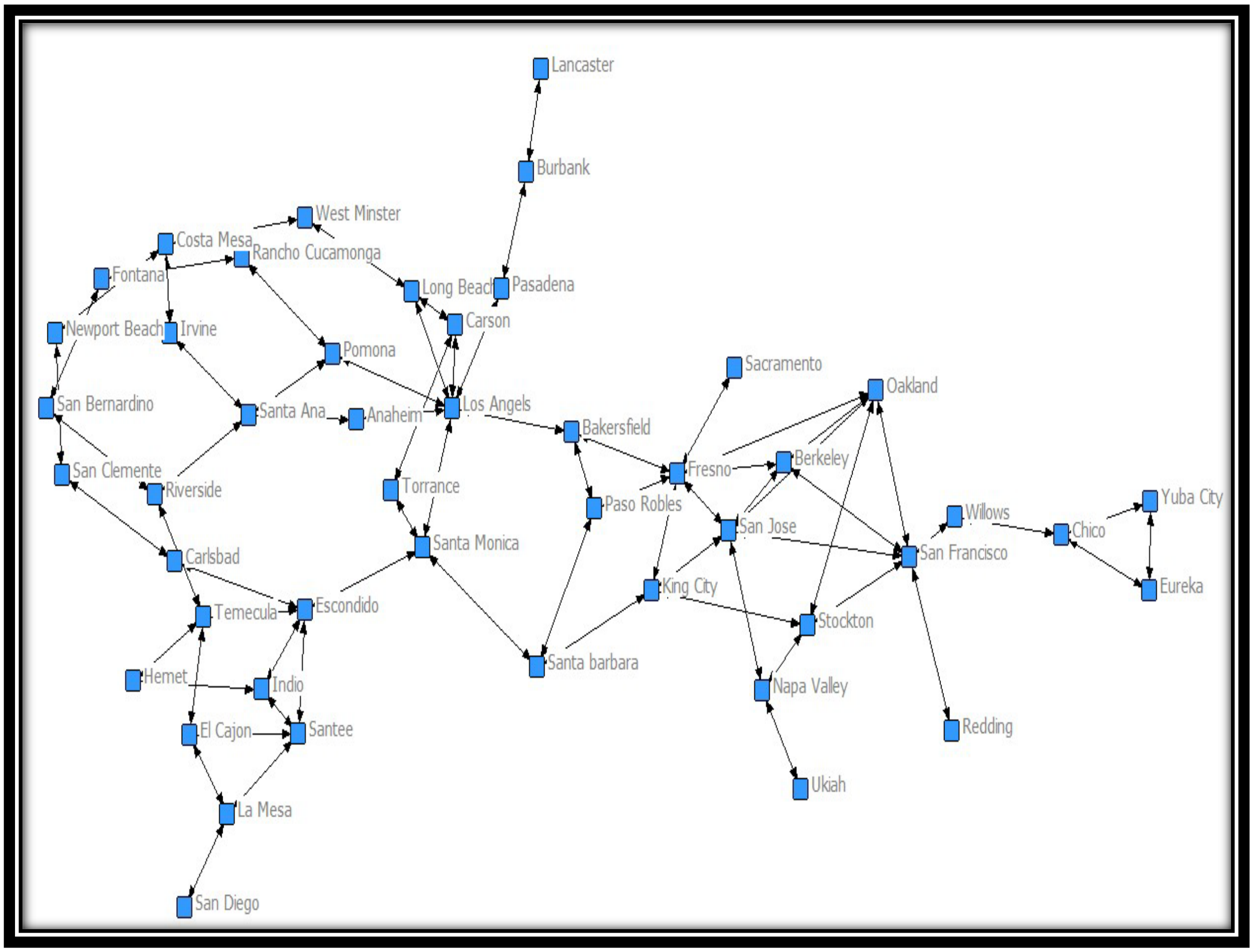

FIGURE 2. Network Graph of Road Model.

Path Betweenness Centrality Index of Transportation Network Model

Path Betweenness Centrality Index of highway and transportation network model means the time that the path belongs to one shortest route of any double nodes [7]. The index can tell us that one path has the control superiority for the connectivity shortcut of the whole network. With UCINET program, the Path Betweenness Centrality Index of each path of the network model can be calculated as shown in the Figure 3. The statistics can be elicited as seen in Figure 3 if all the path Betweenness Centrality Indexes are arranged in order. It can be seen from the Figure 3 that the Betweenness Centrality Index of the path (Bakersfield, Los Angles) is evidently larger than others. This means that the number of shortcuts of each pair of nodes passing the path is more and a lot of shortcuts will change if the path is interrupted because of some kind of reasons. So, the path (Bakersfield, Los Angles) is very important in the Road model. While the Betweenness Centrality Index of the path (Ukiah, Napa Valley) is smallest, and the value is 16.738, that means the number of shortcuts of each pair of nodes passing the path is smallest. It can be seen from Figure 2 that city Ukiah lies in the edge of the network model. So, the important of the path (Ukiah, Napa Valley) is lesser to the connectivity of the network model.

	Sacram	Napa V	Stockto	Yuba Ci	Ukiah	Chico	Willows	Reddin	Eureka	San Jos	San Francisco	Oaklan	Berkele	Bakersf	Fresno	King Cit	Paso R	Los Ang	San Die	Long B	Anahei	Santa A	Riversic	Irvine	San Be
Sacramento	0	0	0	0	0	0	0	0	0	0	0	0	0	0	101.84	0	0	0	0	0	0	0	0	0	0
Napa Valley	0	0	38.632	0	16.738	0	0	0	0	67.539	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stockton	0	38.632	0	0	0	0	0	0	0	0	87.304	36.913	0	0	0	77.036	0	0	0	0	0	0	0	0	0
Yuba City	0	0	0	0	0	23.464	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ukiah	0	16.738	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chico	0	0	0	23.464	0	0	58.992	0	23.464	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Willows	0	0	0	0	0	58.992	0	0	0	0	100.938	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Redding	0	0	0	0	0	0	0	0	0	0	65.41	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eureka	0	0	0	0	0	23.464	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Jose	0	67.539	0	0	0	0	0	0	0	0	116.211	65.82	62.361	0	152.64	105.94	0	0	0	0	0	0	0	0	0
San Francisco	0	0	87.304	0	0	0	100.94	65.41	0	116.21	0	80.429	76.97	0	0	0	0	0	0	0	0	0	0	0	0
Oakland	0	0	36.913	0	0	0	0	0	0	65.82	80.429	0	26.579	0	116.86	0	0	0	0	0	0	0	0	0	0
Berkeley	0	0	0	0	0	0	0	0	0	62.361	76.97	26.579	0	0	113.4	0	0	0	0	0	0	0	0	0	0
Bakersfield	0	0	0	0	0	0	0	0	0	0	0	0	0	0	190.34	0	94.957	268.15	0	0	0	0	0	0	0
Fresno	101.84	0	0	0	0	0	0	0	0	152.64	0	116.86	113.4	190.34	0	156.98	108.3	0	0	0	0	0	0	0	0
King City	0	0	77.036	0	0	0	0	0	0	105.94	0	0	0	0	156.98	0	0	0	0	0	0	0	0	0	0
Paso Robles	0	0	0	0	0	0	0	0	0	0	0	0	0	94.957	108.3	0	0	0	0	0	0	0	0	0	0
Los Angels	0	0	0	0	0	0	0	0	0	0	0	0	0	268.15	0	0	0	0	0	209.28	194.42	0	0	0	0
San Diego	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Long Beach	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	209.28	0	0	0	0	0	0	0
Anaheim	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	194.42	0	0	0	59.323	0	0	0
Santa Ana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59.323	0	82.101	56.736	0
Riverside	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82.101	0	0	45.106
Irvine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	56.736	0	0	0
San Bernardino	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45.106	0	0
Fontana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.622
Rancho Cucamonga	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lancaster	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pomona	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	225.22	0	0	0	90.129	0	0	0
Escondido	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Torrance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pasadena	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	213.14	0	0	0	0	0	0	0
Costa Mesa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30.161	0

FIGURE 3. Path Betweenness Centrality Index of Transportation Network.

Simulation Results

In this section, the numerical results are presented using the reliability evaluation procedure, which is further discussed later in the section. The procedure is applied to a network graph representing the California state transport network. The network represents forty-seven cities and major freeways connecting them in California.

Defining the Network Model Reliability

At present, there is not an acknowledged definition of highway and transportation network reliability in academe. There are some kinds of definition in current researches. In this research, the reliability study is defined as the probability of connecting the points in the network, namely, researching in point of view of the topology structure and the traffic organizing. The reliability index formula is described in equation 8:

$$R = 1 - \frac{V}{N(N-1)/2} \tag{1}$$

In the formula,

- R = Reliability index
- V = Number of nodes pair which are not joined by any path
- N = Size of the model

Describing the Different Paths Failure Strategy

There are two paths failure strategies. The first strategy is Selective Paths Failure strategy which can be described that choosing one path among all the paths selectively and letting the path failure. The second strategy is Random Paths Failure strategy which can be described that choosing one path among all the paths randomly and letting the path failure.

Describing the Model Reliability Simulation Algorithm in Different Paths Failure Strategy

The first model reliability algorithm with the selective paths failure strategy:

- Step 1: Choosing two paths whose Path Between-ness Centrality Index degree are maximal, and removing them.
- Step 2: Calculating the reliability index of the new model.
- Step 3: Repeat until all paths fail.
- Step 4: Calculate the mean value of the reliability index every time when each two paths fail.

The second model reliability algorithm with the random paths failure strategy:

- Step 1: Choosing two paths randomly from all the paths, and removing them.
- Step 2: Calculating the reliability index of the new model.
- Step 3: Choosing two paths randomly from all the paths, and removing them.

- Step 4: Calculating the mean value of the reliability index every time when each two paths failure.

Analysis of Transportation Network of Northern and Southern Part of California

To analyse the reliability of transportation network, selective and random path failure strategies is applied as mentioned in the thesis. To apply this strategy, the edge between Bakersfield and Los Angeles is removed as shown in Figure 4 and calculated the reliability(R) of the network as shown in Equation (2).

$$R = 1 - \frac{0}{47(46)/2} = 1 \quad (2)$$

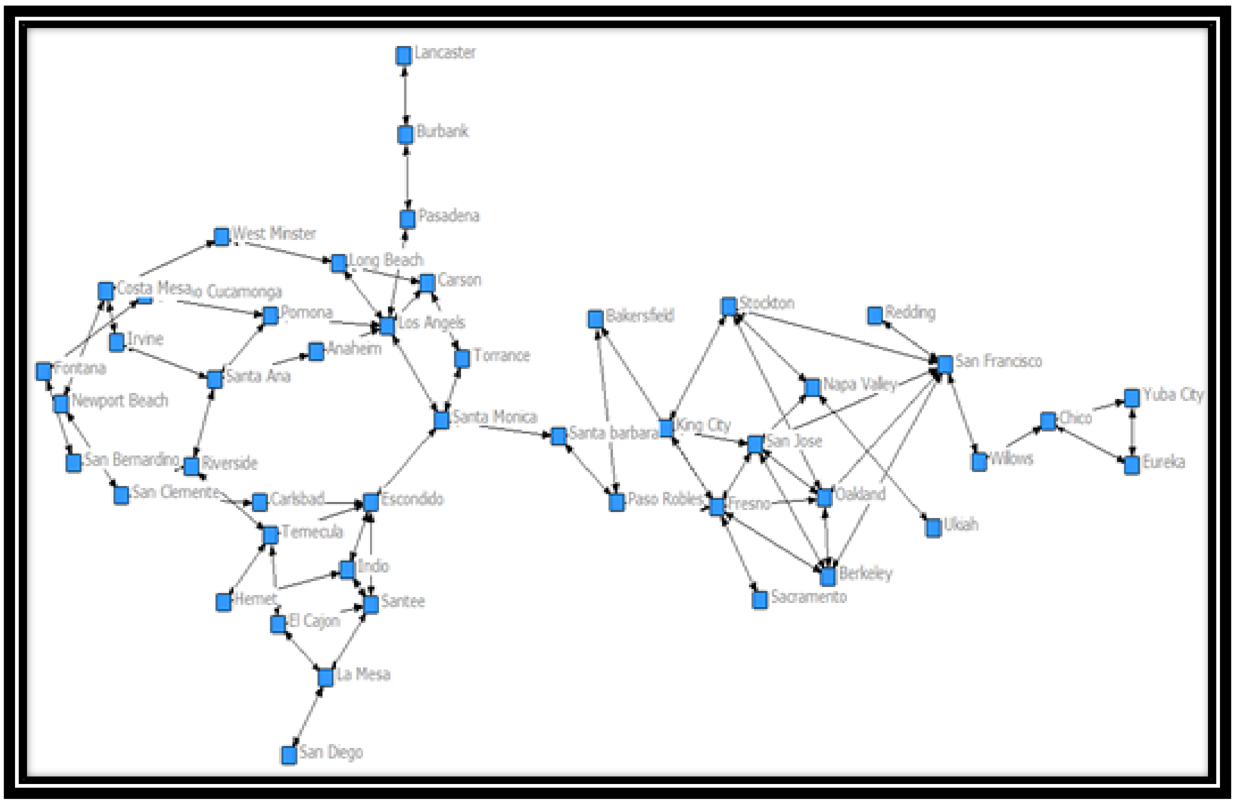

FIGURE 4. Network Graph with One Path Failure.

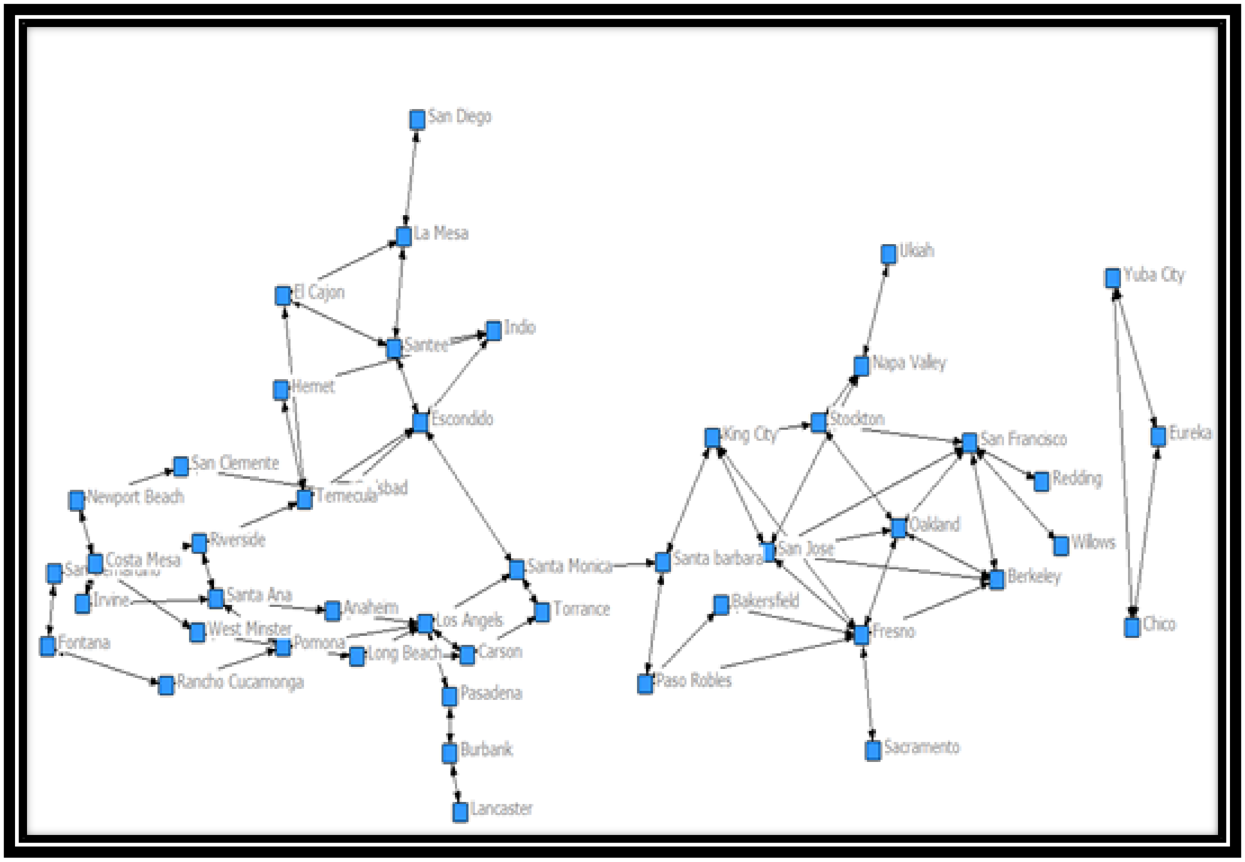

FIGURE 5. Network Graph with Two Paths Failure.

FIGURE 6. Network Graph with All Paths Failure.

Next, the edge between Willows and Chico is marked as failed and is removed from the graph as shown in Figure 5 and the reliability of the network is calculated as shown in Equation (3). This makes graph disconnected and It reduces the network reliability.

$$R = 1 - \frac{44*3}{\frac{47(46)}{2}} = 0.88 \tag{3}$$

Figure 6 gives the Graphical representation of a scenario where, if all the paths are failed in the graph, it will become totally disconnected and reliability of the network goes down to 0 as calculated and in Equation (4).

$$R = 1 - \frac{46+45+\cdots..+1}{\frac{47(46)}{2}} = 0 \tag{4}$$

Reliability of Road-model with Different Paths Failure Strategy can be seen from Figure 7 that the reliability index of Road-model is increasingly definitional with more paths invalidating. But the changing trend is the big difference. With random paths failure strategy, the reliability index descends smoothly. The index descends from 1 to 0.88 when ten paths failure, and the index descends to 0.52 when twenty paths failure and so on. While with selective paths failure strategy, the reliability index descends gently at the very start.

In this simulation experiment, the reliability index keeps unchanged as 1 until ten paths failure. The reason is that some shortcuts of Road-model are disappeared when the paths whose Path Betweenness Centrality Index degrees are maximal are selected and removed, but nodes can be connected by other routes. So, the reliability index does not change at the very start. But the reliability index descends sharply when certain number of paths failure. So, if enemy accurate strike few key paths of highway and transportation network with precision-guided weapons, the reliability index will descend greatly.

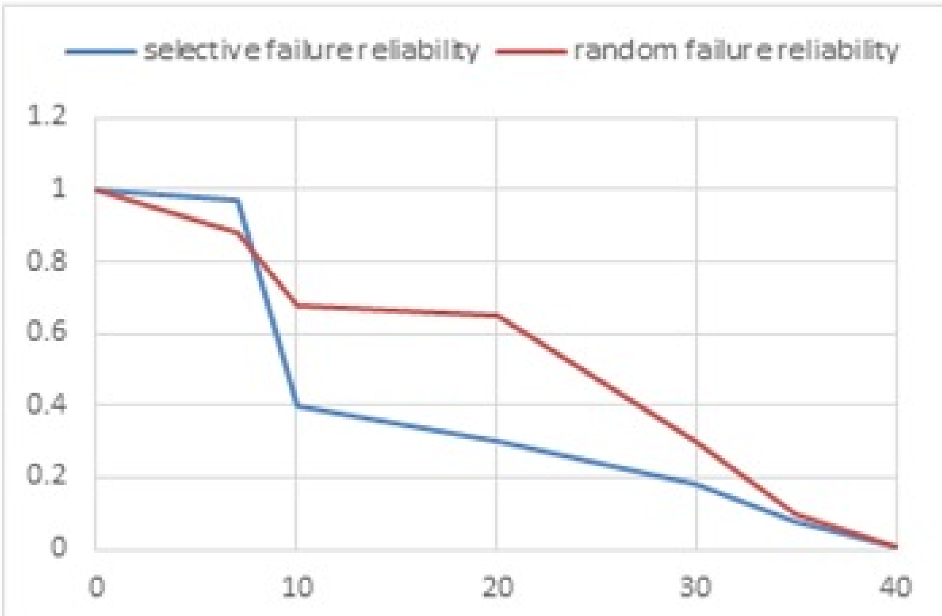

FIGURE 7. Reliability of Road Model under Different Paths Failure Strategies.

Conclusion

Past research shows that a better understanding of the reliability of transportation networks can improve response to a disaster and lead to increased network resilience. Improving the reliability of transportation networks is especially important in leading to faster recovery times after uncertain disruptions on roads that serve as critical paths. This study focused on the quantification of the improved reliability of highway transportation networks in California. Network reliability for the constructed California transportation network graph is estimated under both random path failure strategy and selective path failure strategy using UCINET by considering uncertainties in link-failure. The preliminary results can be considered to protect the important paths of the California transportation network.

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16. ABSTRACT

The existing reliability measures are useful for assessing different factors related to the performance of the transportation network. However, none of the existing measures addresses the issue of adequacy of network capacity to accommodate demand. That is, whether the available network capacity relative to the required demand is sufficient. This measure provides important information for efficient flow control, capacity expansion, and other relevant works to enhance the reliability of a road network. It may also have the potential of providing a tool to design road networks that are resistant to traffic disturbances. Only recently, the capacity was reliably introduced as a new performance measure to evaluate the performance of a degradable road network. It was defined as the probability that the network can accommodate a certain traffic demand at a required service level, while accounting for drivers' route choice behavior. Travel time reliability can also be obtained as a side product while evaluating the capacity reliability. However, a comprehensive analysis of the capacity reliability was not provided. It can be observed from the past that most of the researches primarily focus at safety issues of transportation systems. Literature emphasizing on transportation reliability is scarce. Since no paper is directly dealing with reliability issues. This study aims to introduce a successful technique for calculating critical paths of the proposed California transport network by analyzing reliability of the network, creating a high-level design of the software, utilizing tools and technologies, and describing the modular implementation of the software, testing, and experimentation. More specifically, this work aims to achieve accurate real-time calculation of betweenness centrality index with a unique combination of reliability analysis and path failure strategies to predict critical paths of a transport network.

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