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Strategic Implications for Civil Infrastructure and Logistical Support Systems in Post-Earthquake Disaster Management: The Case of St. Louis

Giacomo Fraioli, Abhijit Gosavi, and Lesley H. Sneed

***Abstract*— An important role of post-earthquake emergency management is to minimize the restoration time, which is the sum of the travel time and the response time. The travel time is the time needed to reach the affected area from the dispatch location, while the response time is the time required to bring the situation under control after reaching the affected area. A number of built environment variables, e.g., building collapse probability, and natural variables, e.g., flooding probability, are known to affect the restoration time. Data from St. Louis, Missouri, USA are used in conjunction with a discrete-event-based simulation model to identify the statistically significant variables via an analysis of variance. The experimental results show that in order to reduce the loss of life, the volume of resources and the building collapse and flooding probabilities are significant factors that should be accounted for in the emergency-response planning for an earthquake.**

***Index Terms*—Earthquake, emergency management, training, built environment (BUE).**

I. INTRODUCTION

THE post-earthquake emergency management response constitutes the activities by emergency response crews dispatched to the affected area. When an earthquake strikes, emergency responders are typically notified immediately. However, a time delay, called travel time, is usually experienced between the notification and the arrival of the responders at the affected site(s). An additional amount of time, called response time, is needed to perform the reparative work. Restoration time, which is the sum of the travel time and response time, is defined as the time taken to bring the situation under control after an earthquake strikes once the responders are notified. Restoration time includes activities related to transferring the injured to hospitals and resuming basic services, e.g., electricity and water, to residents in the affected area. Another concept, not considered in this paper, is the recovery time, which is related to reconstruction of damaged buildings and structures [1] and can take several years.

The restoration time depends on many built environment (BUE) variables related to the vulnerabilities of the existing infrastructure in the region and the coordination and makeup of the logistical support systems, as well as natural variables, such as the probability of flooding in the region. These variables can be studied via a discrete-event model. The first use of discrete-event system modeling in emergency management is described in Swersey [2]. Seminal work in estimating the so-called transition probabilities in these systems is from Clini et al. [3]. More recent related work (see Wei et al. [4] and Ghosh and Gosavi [5]) employs Markov chains for analysis.

This paper uses an analysis of variance (ANOVA) to determine key factors that have a significant impact on the restoration time. A discrete-event-based simulation (DEBS) model based on existing work from the literature [6] is used to evaluate the restoration times for data from the city of St. Louis, Missouri, USA. Minimizing the restoration time can help reduce the loss of human life, and hence identifying those variables is imperative in modern smart cities.

A significant advantage to employing a high-fidelity simulation model (i.e., the aforementioned DEBS model) is that it can be used *offline* to identify the critical BUE and natural variables and develop a deeper understanding of their impact on restoration times. This knowledge can help emergency managers make important strategic decisions in planning, preparing, and training for an emergency such as an earthquake and belongs to a class of models that perform probabilistic risk assessment [7, 8]. Other means to develop such an understanding include gathering historical data from actual emergencies [9]. Unfortunately, the availability of historical data from existing earthquakes is often limited, and furthermore, earthquake impact is highly dependent on variables such as the site of occurrence, population density, and existing infrastructure, making extrapolation to other regions questionable. Hence, using a high-fidelity simulator that accounts for the regional variables discussed above can be very helpful in strategic analysis. Planning and preparedness efforts are critical for managing any hazardous event [10], especially when the event is of a low probability but a high consequence or impact [11] and human life is involved. Five-hundred-year

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floods and pandemics, e.g., COVID-19, are some examples of low-probability high-consequence events. An earthquake in an area such as St. Louis is also a low-probability high-consequence event and, as such, requires analyses from numerous angles, including an evaluation of the region's critical infrastructure and the logistical systems that provide emergency management.

II. PROBLEM FORMULATION

In this section, first an overview of the DEBS model is presented. This is followed by a description of the BUE and natural variables and the data used from the city of St. Louis implemented within the model. Finally, the experimental setup for the ANOVA is presented.

A. DEBS Model

DEBS is a simulation-based model that estimates the restoration time, defined as the time needed to bring the situation under control after the earthquake occurs; estimation of this nature is typically performed for a given volume of resources of emergency response and a given set of values for the BUE and natural variables considered. When the earthquake occurs, an appropriate response center is selected and responders travel from the response center to the affected site in a finite amount of time (travel time). Once they reach the affected area, rescuers need a finite amount of time (response time) from the beginning of the reparative works until a stable state is reached when all the injured have been transferred to hospitals and no further danger exists for the region. The DEBS model seeks to estimate the mean restoration time, which is the sum of the travel time and the response time computed for each earthquake scenario.

Four basic incidents caused by an earthquake are considered in the DEBS model: Fire (F), Gas leakage (G), Building Collapse (BC), and FLooding (FL). The system goes through a sequence of states in the discrete-event model. The state is a combination of one to four basic incidents; the only exception to this is the starting state in which none of these incidents is present and the system is considered stable. A *primary* state is one into which the system transitions randomly immediately from the starting (stable) state after the earthquake strikes. The primary states do not contain the flooding incident. *Secondary* states are those that are more severe in terms of the hazard, and each of these contains the flooding incident. The primary and secondary states along with the associated basic incidents are defined in Table I. The system transitions from a primary state to a secondary state while the responders are traveling from the dispatch station to the affected site. After the responders complete their work, the system returns to the stable state. The transition from the stable state to a primary state and the transitions from a primary state to a secondary state are simulated within the discrete-event simulator using probabilities obtained from subject matter experts.

The restoration time, *ReT*, for a given trajectory is defined as follows:

$$ReT = TT + RT_c(\eta) \qquad (1)$$

where TT is the travel time associated to the simulated earthquake, η denotes the random secondary state reached at the end of the simulation trajectory, and $RT_c(\eta)$ denotes the response time associated to secondary state η. The response time is a function of the state as well as the volume of resources available and is defined as:

$$RT_c(\eta) = \sum_{d \in U(\eta)} RT(d)\phi. \qquad (2)$$

In the above, ϕ denotes the combined response time correction factor, where $\phi \geq 1$, $U(\eta)$ denotes the set of basic incidents associated to state η, and the response time associated to each incident, d, is defined as:

$$RT(d) = A + \frac{B}{X} \qquad (3)$$

where $A > 0$ is a fixed minimum portion of the response time; B/X denotes the variable part of the response time in which X denotes the level of resources taking values from a set of positive integers; and $B > 0$. The model was developed in [6]. Table II defines the values of A and B for the different basic incidents. The dependent variable in the analysis performed in the next section is *ReT*, which is evaluated by the DEBS model.

TABLE I
PRIMARY (2 THROUGH 8) AND SECONDARY (9 THROUGH 15) STATES

State (S)	Set of incidents contained in the state (U(S))
1	{Stable}
2	{G}
3	{F}
4	{G , F}
5	{BC}
6	{G, BC}
7	{F, BC}
8	{G, F, BC}
9	{G, FL}
10	{F, FL}
11	{G , F, FL}
12	{BC, FL}
13	{G, BC, FL}
14	{F, BC, FL}
15	{G, F, BC, FL}

G = Gas Leakage; F = Fire; BC = Building Collapse; FL = Flooding

TABLE II
VALUES OF *A* AND *B* IN THE RESPONSE TIMES

Incident (d)	*RT(d)*
G	$7 + \frac{5}{X}$
F	$21 + \frac{15}{X}$
BC	$35 + \frac{25}{X}$
FL	$120 + \frac{80}{X}$

B. BUE and Natural Variables for St. Louis

The metropolitan area of St. Louis is in proximity (approximately 240 km) to the New Madrid Seismic Zone (NMSZ). From 1811 to 1812, the zone has been affected by three large earthquakes, each of which had an estimated magnitude between 7.0 and 7.5 and was followed by at least four aftershocks with an estimated magnitude of 6.0 or larger [8]. Damage to man-made structures was very limited due to the sparse population in the epicentral area at that time, however a large area of land sank and was covered and flooded with water that erupted through fissures [12]. More recently, an earthquake of magnitude 5.4 was recorded in 1968. Considering the much denser population of the metropolitan area of St. Louis today, proximity to the NMSZ generates high-risk conditions in which a high-fatality rate is possible not only due to building collapse but also due to lack of access from the surrounding area. This is especially critical since the roads and bridges in the region are vital for connectivity to the surrounding area. Often referred to as "The Gateway to the West," St. Louis is connected to the nation through multiple interstate highways and railways. The eastern border of the city is adjacent to the Mississippi River, and the bridges that connect St. Louis with East St. Louis, Illinois, are in an area susceptible to flooding and soil liquefaction, creating a potentially disastrous situation. Figure 1 is a map of the St. Louis region that shows the areas susceptible to flooding.

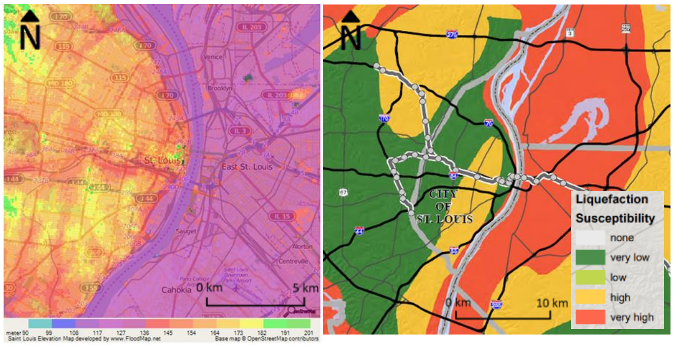

Fig. 1. (Left) Elevation map of inner St. Louis showing the areas more susceptible to flooding [9], (Right) liquefaction susceptibility of the St. Louis Metropolitan Area [10]

The DEBS model takes into account the effect of one natural input variable (flooding probability) and the following four BUE input variables: 1) traffic conditions, 2) bridge condition, 3) building age, and 4) fire department location. Traffic conditions, along with the distance between the dispatch point and the affected area, have a large impact on the travel time. Traffic congestion is usually relatively high twice each weekday during the hours when most people commute to and from work. This phenomenon, i.e., the "rush hour," can considerably increase travel time on the streets of St. Louis. Figure 2 shows the predicted travel time during the rush hour on the roads that connect the Fire Department Engine House No. 2 to 1654 Tower Grove Avenue [19]. For the three proposed routes, the predicted travel time varies twofold.

The literature studies the impact of earthquakes on structures, including bridges, buildings, and dams (see, e.g., [15-18]). Bridges that do not meet current seismic design requirements can behave in unpredictable ways during an earthquake. The Missouri Department of Transportation (MoDOT) rates the condition of bridge structures using a scale ranging from Level 9 (Excellent) to Level 0 (Failed). Bridges considered to be structurally deficient are classified at Level 4 (Poor) or lower [20]. Herein, the term *poor* implies a condition requiring replacement or major rehabilitation. Bridges in this condition can create inconvenience and a dangerous situation for travelers on the overpass and the underpass, leading to a slowdown or completely blocked traffic. According to MoDOT, the city of St. Louis has several bridges rated as poor, and the majority are located on interstates [21], as shown in Figure 3. The possible closure of these bridges due to a seismic event may cause the interruption of important routes, leading to an increase in traffic congestion on secondary streets, and the isolation of the city from the surrounding region.

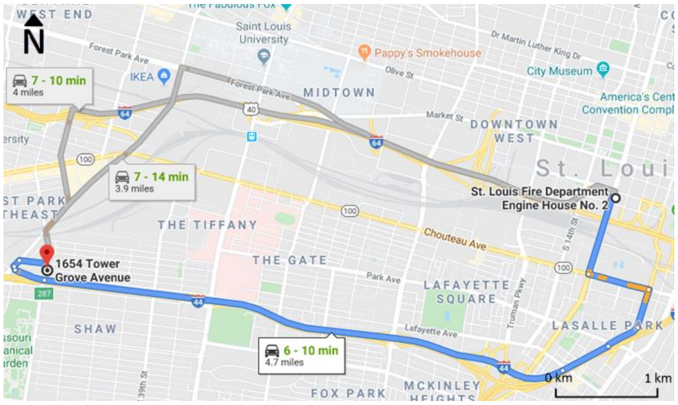

Fig. 2. Prediction of travel time in St. Louis during rush hour (Tue at 4:30pm) from Fire Department Engine House No. 2, 314 S Tucker Blvd., MO, to 1654 Tower Grove Ave, St. Louis, MO [19]

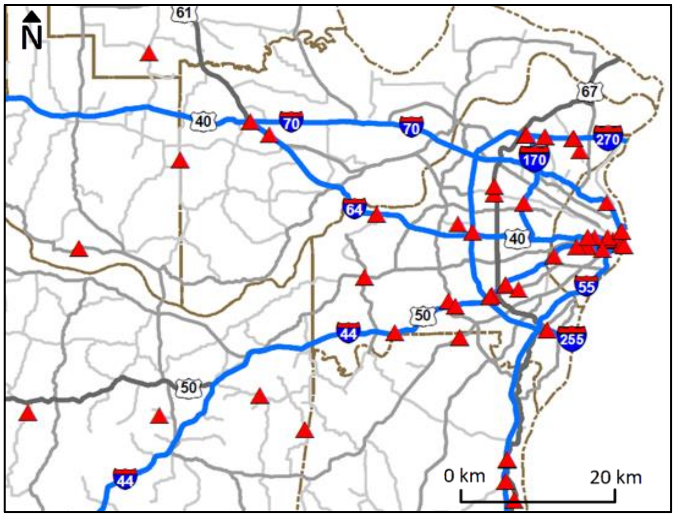

Fig. 3. Map of "poor" bridges in the St. Louis from MoDOT [21]

The third BUE variable analyzed is the age of the buildings. Building age can provide qualitative information about the capacity to withstand a seismic event. Seismic design criteria have evolved over time, and many older and historic buildings were either not designed for seismic loading or were designed using provisions that are inadequate based on current design standards. Therefore, the older the building, the higher the likelihood of damage from an earthquake. Moreover, debris from damaged buildings could occupy the roadways creating obstacles for motorists and emergency vehicles, thereby increasing the travel time. Figure 4 shows the year of construction of the buildings in St. Louis.

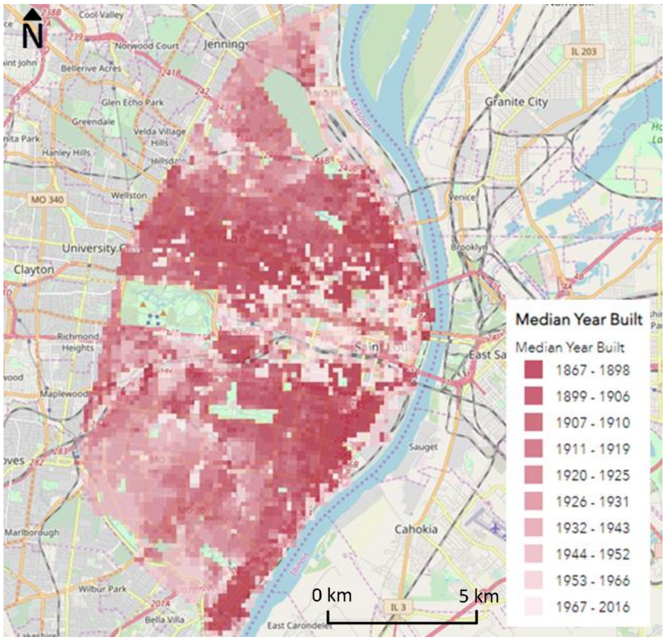

Fig. 4. Median year built for buildings in the inner St. Louis, Missouri, U.S. metropolitan area [22]

The fourth BUE variable is the location of nearby fire departments. Fire departments are the local response centers and are generally the first to be involved in case of emergencies. Optimal location of these response centers minimizes the travel time allowing fast responses across the city. Figure 5 shows the location of the 30 fire departments located in inner St. Louis. However, not all the response centers have the same number of vehicles and rescue squads. Some of them have three fire trucks [23], whereas the majority of the other fire departments have only one fire truck.

C. *Experimental Setup*

The setup for the ANOVA uses data collected from inner St. Louis, Missouri, USA. The ANOVA employs three factors: volume of resources, building collapse, and flooding. Since the city has a high percentage of older buildings and structures designed without consideration for seismic loading (i.e., buildings built before 1970) and it is difficult to predict their behavior during a seismic event, two levels were considered for building collapse: low damage level and high damage level. The impact of building collapse directly influences the restoration time and also the travel time, since the resulting debris is likely to slow down traffic. Further, damage to streets and bridges can also lead to a modification of the travel paths needed, leading to increased travel time. The building collapse probability (*BCP*) for the two levels is shown in Table III. For the flooding, two levels, low flooding level and high flooding level, were considered that are shown in Table IV.

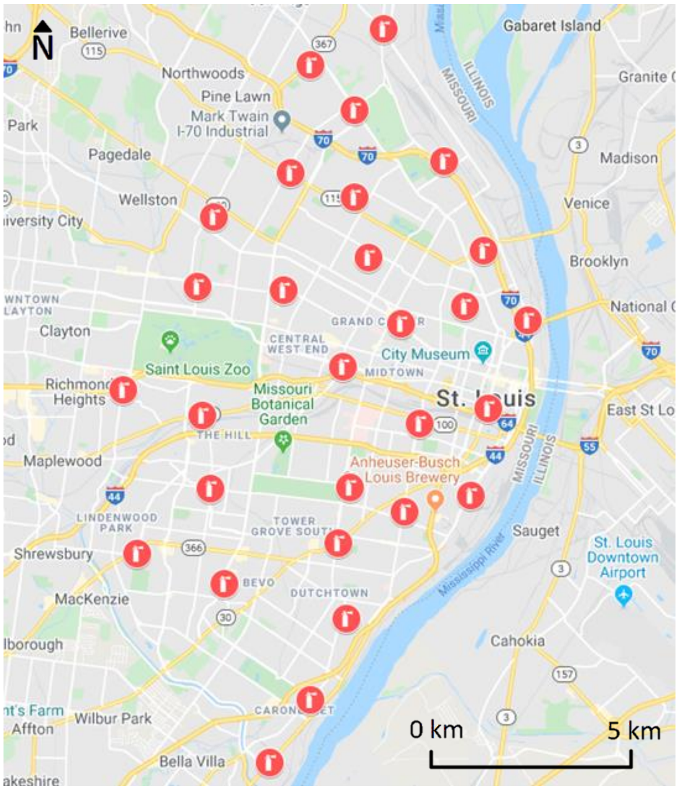

Fig. 5. Location of the fire departments in the inner St. Louis, Missouri, U.S. metropolitan area [23]

TABLE III
BUILDING COLLAPSE PROBABILITY (*BCP*)

Scenario	*BCP*
Low Damage Level	7/16
High Damage Level	11/16

TABLE IV
FLOODING PROBABILITY *(FLP)*

Scenario	Low Damage Level	High Damage Level
Low Flooding Level	0.25625	0.37500
High Flooding Level	0.49688	0.58125

Three different levels of resources corresponding to three different and real response centers are used in the ANOVA. The level of resources $X = 1$ is assigned to Fire Department No. 35, which has one truck company, while a level $X = 2$ is assigned to one of the largest response centers in town, Fire Department No. 2, which has three truck companies [23]. Finally, level $X = 3$ is used to model the resources from a federal agency, such as the Civil Protection or the National Guard.

The emergency site considered is located at 1654 Tower Grove Ave, St. Louis, Missouri, USA for the case study. The choice of the emergency location makes it serviceable from both Fire Departments No.2 and No.35. Moreover, it is located in a district where the median year of building construction is 1920 and is in close proximity of major roads with a large number of bridges in poor condition. Figure 6 shows the configuration of the system used for data collection.

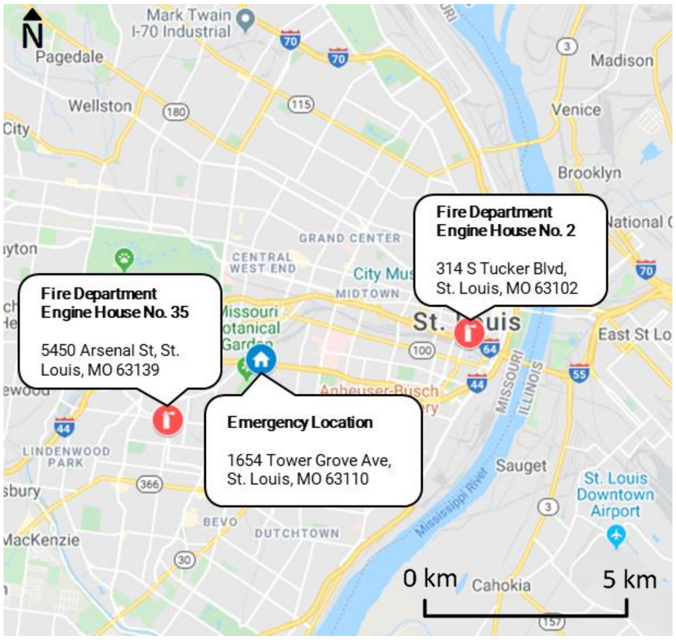

Fig. 6. The location of the fire departments and the emergency location in the inner St. Louis, Missouri, U.S.

The travel time *TT* is a function of the distance between the response center and the emergency site, as well as the conditions of traffic and infrastructure after an earthquake event. In particular, the condition of the infrastructure is a direct function of the damage suffered by roadways and bridges and an indirect function of the damage due to debris of collapsed structures [24]. Travel times needed to reach the emergency location from Fire Departments No. 2 and No. 35 were determined using Google maps, which provides estimates for both low and heavy traffic conditions. In this study, a triangular distribution, denoted by *TRIA (a,c,b)*,was assumed for *TT*, where the minimum value, *a*, represents the travel time under the lowest traffic conditions, and the maximum value, *b*, represents the travel time under the heaviest traffic conditions. Since St. Louis is not usually affected by congestion [24], the mode, *c*, was set to a value lower than $(a+b)/2$. For the resources supplied by a federal agency, a uniform distribution, denoted by *UNIF* (*a*,*b*), was assumed for the travel time, where *a* and *b* are as defined above. The reason for choosing the uniform distribution for the federal resources is that this is likely to occur in lower variability conditions, as federal resources are typically requested after traffic has stabilized.

For Fire Department No. 35, the travel time in the high damage level scenario was considered to be twice that of the low damage level scenario. It was not possible to extend the same approach to the Fire Department No. 2 for the reason that the bridges in poor condition on I-44 and I-64 will force a change of itinerary, thus increasing the minimum value of travel time. Figure 7 shows the increased travel time due to the change of itinerary for the same points of interest shown in Figure 2. Based on the configuration available from the map, the travel time in the case of high damage level scenario was set to approximately 1.33 times the travel time used for the low damage level scenario.

Six different values of travel time were considered, associated to three different locations of resources, and to two damage scenarios, which are shown in Table V.

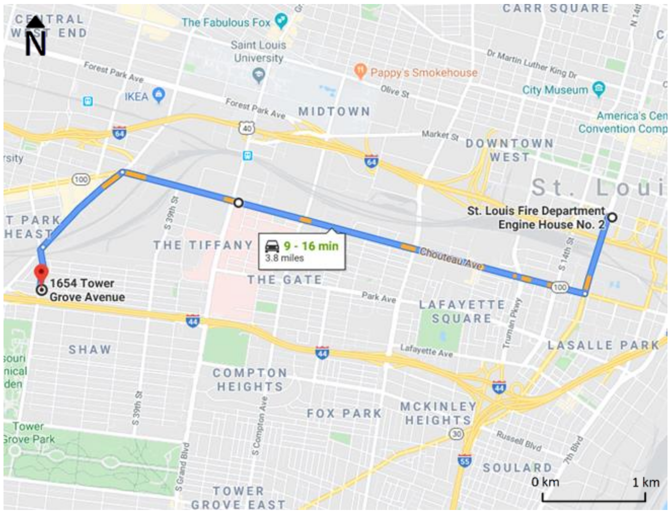

Fig. 7. Prediction of travel time in St. Louis from Fire Department Engine

House No. 2, 314 S Tucker Blvd., MO, to 1654 Tower Grove Ave, St. Louis, MO using an itinerary that avoids I44 and I64 [21]

TABLE V
TRAVEL TIME DISTRIBUTION (IN HOURS)

Location of Resources	Low Damage Scenario	High Damage Scenario
Fire Dept. No. 35	$TRIA\left(\frac{6}{60},\frac{7}{60},\frac{10}{60}\right)$	$TRIA\left(\frac{12}{60},\frac{14}{60},\frac{20}{60}\right)$
Fire Dept. No. 2	$TRIA\left(\frac{6}{60},\frac{10}{60},\frac{16}{60}\right)$	$TRIA\left(\frac{18}{60},\frac{20}{60},\frac{32}{60}\right)$
Federal	$UNIF(12, 24)$	$UNIF(16, 32)$

III. 3-way Analysis of Variance (ANOVA)

A 3-way ANOVA was used for statistical analysis [26]. The three factors (independent variables) considered are: the volume of resources, the building collapse probability, and the flooding probability. The volume of resources and the building collapse probability are impacted by the BUE variables named above, while the flooding probability is a natural variable. The volume of resources, X, has three levels ($X=1$ for Fire Department No. 35, $X=2$ for Fire Department No. 2, and $X=3$ for Federal). The ANOVA and the DEBS programs were coded in MATLAB. The computer program was run on a workstation with an Intel Xenon processor with a speed of 3.6 GHz on a 64-bit operating system. The program took approximately 5 minutes for each performance evaluation via DEBS, while the ANOVA took less than one second. The results of the ANOVA are summarized in Table VI.

TABLE VI
ANOVA RESULTS

Factor	SSE	dof	MSE	*F-value*	*p*-value
X	27035.5036	2	13517.7518	2250.1962	3.54E-16
FLP	318.5876	1	318.5876	53.0328	9.71E-06
BCP	2350.8146	1	2350.8146	391.322	1.59E-10
*X*FLP*	5.917	2	2.9585	0.49248	0.62294
*X*BCP*	44.7137	2	22.3569	3.7216	0.05527
*FL*BCP*	1.5955	1	1.5955	0.26559	0.61567
*X*FLP*BCP*	0.0033936	2	0.0016968	0.00028245	0.99972
Error	72.0884	12	6.0074		
Total	29829.2239	23			

The low *p*-values of the three factors indicate that each factor is statistically significant in impacting the restoration times. The same cannot be said for the two-factor or the three-factor interactions. The managerial and supply chain implications of these results for the city of St. Louis are as follows:

- **Implications for Capacity of Resources:** Care must be taken to have ample resources in the St. Louis region ready for emergency response, as this is an area where an earthquake is likely; this would be true of any area where an earthquake is likely.
- **Implications for Buildings:** St. Louis has numerous older buildings constructed without modern seismic design considerations that would not be able to withstand seismic loading; they need to be either retrofitted or demolished to avoid a possible catastrophe. This is probably the most crucial preventive intervention that needs to be performed in St. Louis.
- **Flooding Implications**: Since the ANOVA shows the flooding probability to be a significant factor, efforts should be made to reduce this threat as well, e.g., via effective flooding mitigation strategies.
- **Implications for Supply Chains:** The findings indicate that should an earthquake occur in this area, critical traffic flowing through the affected roads will be severely disrupted, as St. Louis remains a key connecting point from the eastern to the western part of the country. Another important implication here is that in order to enable the response and restore traffic, it is imperative that key ingress and egress routes into and from the affected area be identified. This will ensure that disruptions of supply chains of goods and emergency supplies flowing through St. Louis will be quickly mitigated.

This study discovered that because of many seismically deficient buildings, congested roads, a moderate likelihood of flooding, and a high likelihood of an earthquake, disaster St. Louis emergency managers need to undertake carefully considered steps to improve local logistical support systems and reinforce the infrastructure of the region. It appears that many key roads will become severely congested, and many buildings could collapse leading to a calamitous situation. While the population density was much lower the last time a major earthquake struck St. Louis, if no changes are made, the outcome is likely to be very different the next time with potentially a large loss of life.

IV. Conclusion

The paper developed a methodology to demonstrate how sensitive restoration times after an earthquake can be to BUE and natural variables. The methodology developed here can be applied to other regions after suitable data are gathered. For the specific data gathered for St. Louis, the strategic recommendation is that disaster managers should take necessary steps to ensure that an ample volume of emergency-response resources is available at all times and the probabilities of building collapse and flooding are reduced. The large number of older buildings constructed without modern seismic design considerations and lack of access to the downtown area of St. Louis during an emergency indicate that a high-magnitude earthquake in this region could have a significant death toll.

REFERENCES

[1] J. M. Nigg, “Disaster recovery as a social process”, *Wellington after the quake: The challenge of rebuilding cities*, pp. 81-92, 1995.

[2] S. Ghosh and A. Gosavi. “A semi-Markov model for post-earthquake emergency response in A smart city”, *Control Theory and Technology*, 15 (1), 13–25, 2017.

[3] A. J. Swersey. “A Markovian decision model for deciding how many fire companies to dispatch.” *Management Science*, 28(4):352–365, 1982.

[4] F. Clini, R.M. Darbra, and J. Casal. “Historical analysis of accidents involving domino effect”, *Chemical Engineering Transactions*, 19:335–340, 2010.

[5] W. Wei, L. Mao, and W. Li. “Dynamic optimization method of emergency resources deployment based on Markov decision process for Wenchuan earthquake,” In *Proceedings of 2nd International Workshop on Database Technology and Application*. IEEE, 2010.

[6] A. Gosavi, G. Fraioli, L. H. Sneed and N. Tasker, "Discrete-event-based simulation model for performance evaluation of post-earthquake restoration in a smart city," *IEEE Transactions on Engineering Management*, doi: 10.1109/TEM.2019.2927318.

[7] R. Van Coile, D. Hopkin, D. Lange, G. Jomaas and L. Bisby, “The need for hierarchies of acceptance criteria for probabilistic risk assessments in fire engineering”, *Fire Technology*, *55*(4), pp. 1111-1146, 2019.

[8] P. A. Korswagen, S. N. Jonkman and K. C.Terwel. “Probabilistic assessment of structural damage from coupled multi-hazards.” *Structural Safety*, *76*, 135-148, 2019.

[9] S. Zahran, S.D. Brody, W.G. Peacock, A. Vedlitz and H. Grover, *“*Social vulnerability and the natural and built environment: a model of flood casualties in Texas*”*, *Disasters*, *32*(4), 537-560, 2008.

[10] K. Poser and D. Dransch, “Volunteered geographic information for disaster management with application to rapid flood damage estimation”, *Geomatica*, 64, 1, 89-98, 2010.

[11] R. Waller, *Low-probability high-consequence risk analysis: Issues, methods, and case studies* (Vol. 2). Springer Science & Business Media, 2013.

[12] USGS. Summary of 1811-1812 New Madrid Earthquakes Sequence, April 2020. [Online]. Available: https://www.usgs.gov/natural-hazards/earthquake-hazards/science/summary-1811-1812-new-madrid-earthquakes-sequence?qt-science_center_objects=0No.qt-science_center_objects

[13] Floodmap.net. Saint Louis Elevation, May 2020. [Online]. Available: https://www.floodmap.net/Elevation/ElevationMap/?gi=4407066

[14] East-West Gateway Council of Governments. Liquefaction Susceptibility - St. Louis Metropolitan Area, May 2020. [Online]. Available: https://www.ewgateway.org/library-post/liquefaction-susceptibility/

[15] A. Malek, *“*Post-earthquake damage assessment and residual capacity of concrete and RC beams”, *PhD Dissertation, University of Canterbury*, New Zealand, 2018.

[16] M. D. Joyner and M. Sasani, “Building performance for earthquake resilience”, *Engineering Structures*, *210*, 110371, 2020.

[17] S. Zhao, S. Fan, and J. Chen, “Quantitative assessment of the concrete gravity dam damage under earthquake excitation using electro-mechanical impedance measurements”, *Engineering Structures*, *191*, pp. 162-178, 2019.

[18] R. Waqas, B. Uy and H. T. Thai, “Experimental and numerical behavior of blind bolted flush endplate composite connections”. *Journal of Constructional Steel Research*, *153*, pp. 179-195, 2019.

[19] Google Maps. St. Louis, MO, Typical Traffic, April 2020. [Online]. Available: https://www.google.com/maps/@38.6217426,-90.2266282,13.47z/data=!5m2!1e1!1e4

[20] MoDOT. Bridge Terms, May 2020 [Online]. Available: https://modot.org/common-bridge-terms,

[21] MoDOT. Poor and Weight-Restricted Bridges, May 2020. [Online]. Available: https://www.modot.org/Bridges

[22] Preservation Leadership Forum. Atlas of ReUrbanism | St Louis, May 2020. [Online]. Available: https://nthp.maps.arcgis.com/apps/webappviewer/index.html?id=ee08b5842d7e401cbb314561141f7f63

[23] Mydowntownstl.com. A Glimpse Inside Engine House No. 2 and St. Louis Historic Fire Department, May 2020. [Online]. Available: https://mydowntownstl.com/historic-fire-dept/

[24] A.J. Anastassiadis, and S.A. Argyroudis, *“*Seismic vulnerability analysis in urban systems and road networks. Application to the city of Thessaloniki, Greece*”*, *Sustainable Development and Planning*, Vol. 2, No. 3, pp. 287-301, 2007.

[25] Geotab. Gridlocked cities, May 2020. [Online]. Available: https://www.geotab.com/gridlocked-cities/

[26] D. C. Montgomery, *Design and analysis of experiments*. 8th edition, John Wiley & Sons, 2017.

Giacomo Fraioli received the B.S. and M.S. degrees in civil engineering from the University of Bologna, Bologna, Italy, in 2014 and 2017, respectively. He is currently a Ph.D. candidate in civil engineering at Missouri University of Science and Technology, Rolla, MO, USA. He is a Graduate Research and Teaching Assistant with the Department of Civil, Architectural & Environmental Engineering, Missouri University of Science and Technology, Rolla, MO, USA. His research interests include the repair and strengthening of concrete and masonry structures, seismic vulnerability, and disaster management.

Abhijit Gosavi received the B.S. degree in mechanical engineering from Jadavpur University, Kolkata, India, in 1992, the M.S. degree in mechanical engineering from the Indian Institute of Technology Madras, Chennai, India, in 1995, and the Ph.D. degree in industrial engineering from the University of South Florida, Tampa, FL, USA, in 1999. Since 2008, he has been employed at Missouri University of Science and Technology, Rolla, MO, USA. Since 2013, he has been an Associate Professor with the Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology. He has authored a Springer book entitled Simulation-Based Optimization, whose second edition appeared in 2015and has written more than 75 articles in journals and conference proceedings. Some of these articles have appeared in journals such as *Management Science*, *INFORMS Journal on Computing*, *Automatica*, and the *Journal of Retailing*. His research interests include simulation-based optimization, disaster management, total productive maintenance, and healthcare logistics.

Lesley H. Sneed received the B.C.E. and M.S.C.E. degrees from the Georgia Institute of Technology, Atlanta, GA, USA, in 1995 and 1997, respectively, and the Ph.D. degree from Purdue University, West Lafayette, IN, USA, in 2007, all in civil engineering. She has been employed at the Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO, USA, since 2008. She was promoted to the rank of Professor in 2020 and is currently the Stirrat Faculty Scholar with the Missouri University of Science and Technology. She has coauthored more than 90 peer-reviewed articles in journals and conference proceedings. Her research interests include innovative methods of repair and strengthening of structures subjected to seismic loading or other extreme hazards, and evaluation of existing structures. Dr. Sneed is a Fellow of the American Concrete Institute (AC) and is an Associate Editor of the *Journal of Composites for Construction* (ASCE) and *Engineering Structures* (Elsevier).