Bosporus Bridge Traffic Operation Techniques Using Real-time Earthquake Information to Mitigate the Risk Involved

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Abstract: One of the two bridges connecting Asia to Europe, Bosporus Bridge in Istanbul/Turkey, will be affected by the expected severe earthquake from the underneath of the Sea of Marmara in near future. As the traffic density on the bridge corresponds to the busiest in Turkey, utmost effort must be paid to keep the lives and casualties at the possible lowest level. No research hitherto has been conducted to explain the concept of risk management with regard to the lives of those people travelling on the bridge to be saved by combining both traffic management techniques and earthquake early warning system technology. This paper investigates the traffic operation techniques on Bosporus suspended bridge when a pre-known time period is available for the earthquake. Furthermore, this paper focused also on the issues of the strategies to manage the traffic by investigating the occurrence probability of the danger zone lengths and manipulating the average speeds of the vehicles on the bridge. Practical guideline and countermeasure strategies are offered through the use of real time earthquake information. The results indicated that to increase current average travel speed, 45 km/h, on the bridge would make tremendous changes to mitigate causalities.

I. INTRODUCTION

ISTANBUL, being the most crowded city in Turkey with a 15 million population, faces the major and complicated traffic problems to be solved. The city is located at a very high active seismic zone in the Marmara region on two continents, Asia and Europe (Figure 1). The traffic on and in the vicinity of Bosporus Bridge; one of the two suspension bridges that connects Asia and Europe, has probably the highest congestion level in Istanbul, thus in Turkey. When the traffic congestion is a matter, Bosporus Bridge-related traffic might be seen as the one having almost all the negative aspects of congestion. The high possibility of having a major earthquake in the near future adds the reliability dimension to the congestion problem of the bridge traffic already available.

The reliability of transportation systems mentioned has two main directions: Connectivity and Travel Time reliability (Bell, 1998; and Iida, 1999). While connectivity reliability concerns the physical connections of the nodes in the networks, travel time reliability deals with the performance of the networks by investigating the possibility of making journeys between origin and destination within an acceptable time limit.
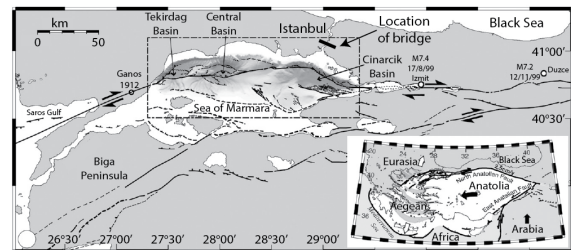

Figure 1. Tectonic models of the Marmara Sea region. (changed from Laigle et al, 2018)

The reliability of Bosporus Bridge in this research, however, is different from these two aspects of the transportation reliability concepts explained. It is basically related to the possibility of having least life-loses on acceptance of the fact that the expected earthquake is so strong that it might demolish the bridge in service to some extent. The main question remains as; can the traffic on the bridge be managed in a way that, the road users get the least possible adverse effects, especially in terms of lives to be lost, in case earthquake hits the bridge within a pre-known time period? Altough this question is asked for Bosporus Bridge in this particular study; it is valid for any bridge, tunnel, and metro passing a danger zone such as Marmaray

in Istanbul, Bay Area Rapid Transit (BART), Bay Bridge, and Golden Gate Bridge in San Fransisco or Rainbow Bridge in Tokyo etc (Aktas et al. 2010, Aslan et al. 2011, Kuyuk et al. 2011).

A. Seismicity of Marmara Region And Earthquake Early Warning System

The tectonic processes forming the Sea of Marmara and its surrounding area have been controlled by the North Anatolian Fault Zone (NAFZ). NAFZ is a dextral strike-slip fault zone, extending from the Karlıova region to the Gulf of Izmit along Anatolia, and south of Thrace as the Ganos Fault (Sengor A, 1985). There have been many micro and macro tectonic earthquakes occurred along NAFZ and its segments in the vicinity of Istanbul.

The occurrence and the hypocentral information of huge events in the area, one of the largest disasters affected the region was 17 August 1999 Golcuk earthquake with Mw 7.4, indicate that a likely earthquake is forthcoming in near future from the underneath of the Sea of Marmara (Figure 1). It is expected that the next earthquake would result in enormous undesirable consequences. On the other hand, fortunately, this seismically vulnerable city developed a reliable Earthquake Early Warning System (Figure 2, Erdik M., 2003) that could lessen the adverse consequences of the threatening earthquake.
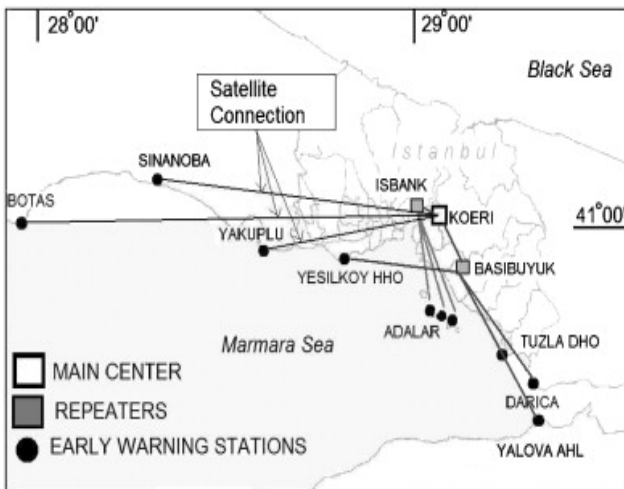

Figure 2. Distribution of early warning stations and 2.4 GHz spread-spectrum radio modem transmission through repeater stations (filled rectangles). (Alcık et al 2011)

Early warning systems give warnings of upcoming danger by rapid estimation of the earthquake source parameters (Kuyuk et al, 2014, Kuyuk and Allen, 2013a, 2013b). To do so, systems use the capability of modern real-time systems to process and transmit information faster than seismic wave's propagation (up to 8 km/s). The possible warning time is usually in the range of up to 70 seconds, depending on the distances among seismic sources, seismic sensors and user sites. As the city is getting now ready for further North Anatolian Fault System (NAFS) earthquakes, it is also vital to prepare traffic management plans and take precautionary actions to moderate the casualties.

Kuyuk (2010, 2015), investigated available time assuming possible hypocentres underneath of Marmara Sea. Available

time is defined as the time provided by EEWS before strong ground motion hits a place. He considered 486 simulated earthquakes with three different depths in the region. The available times to take action in case of earthquake range from 2.4 to 31.1 seconds. The average travel time based on available time in terms of time difference between S-wave arrival to Bosporus Bridge and P-wave arrival to front station is calculated according to Eqn. 1.

$$\Delta t_{avrg} = \sum_{i=1}^{n} \Delta t_i \Big/ \sum_{i=1}^{n} i \qquad (1)$$

where Δt_{avrg} is average available time, i is the earthquake number and Δt_i is available time depending on each i. The average available time is calculated as 13.45 seconds on assumption of the fact that the occurrence probability of each earthquake is equal. Although this average time seems small estimated by difference between P- and S-wave velocities, there would be additional couple of seconds before taking actions considering arrival of peak ground acceleration or total/partially collapse time of bridge.

B. Structural and Traffic Properties of The Bosporus Bridge

The Bosporus Bridge, in service since 1973, has a length and height of 1071 m and 165 m, respectively and 6 traffic lanes (3+3). The average daily traffic on both directions is about 190.000 veh/day throughout a year (www.kgm.gov.tr) The Figure 3 illustrates the fluctuating nature of the traffic volumes available on the bridge for different days of the months.
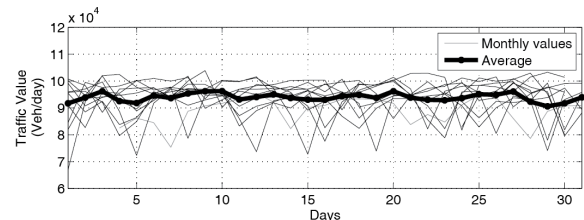

Figure 3. Light gray line shows average number of vehicles per day for one direction for twelve months. Red line shows average.

Red line shows the average daily traffic for one direction. One way traffic drops 70000 veh/day and rose above 100.000 veh/day during the different parts of the year. The same unstable nature of the traffic can be observed as far as the hourly volumes are concerned as shown in the Figure 4. Although the average hourly traffic (around 3850 veh/h) is already quite high, the peak hour traffic volume of 6000-6200 veh/h (1700 - 1800) corresponds the main proportion of the figure causing unbearable queues with extremely high travel times.
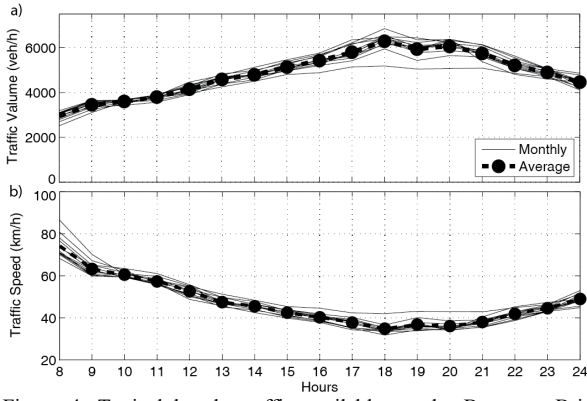
a)

Figure 4. Typical hourly traffic available on the Bosporus Bridge. Number of vehicles per hour for one direction. The average speed estimated from daily traffic volumes is seen the same figure from 8.00 to 24.00.

Apaydin, (2010) studied on the dynamic properties of the bridge and maximum transverse and vertical displacements of the bridge are calculated as 1.36 and 1.154 meter respectively at mid-span. The distribution of the bending moment at the apron was also calculated by Gundaydin, et.al (1997) and plotted in Figure 5. These findings verify that possible maximum damage will happen at the mid-span as expected. Thus expectable danger zone would be between 100 to 200 m in both directions from mid-span.

II. METHODLOGY

A. Setting up The Mathematical Structure and Cost Matrix of the Model

As to determine the best strategies in terms of the speeds on the bridge, a cost matrix was set up to illustrate the number of people to be affected if they are the ones on the danger zone when the earthquake hits the bridge. This matrix has the possible speeds of the vehicles as its rows and lengths of the danger zone as its columns. Danger zone describes the critical sections of the bridge in terms of failure and collapse.

Determination of the values of the matrix is based on the very well-known model suggested by Greenshields (1935). This model, being one of the macroscopic approaches to relate the speed and density of the traffic, hypothesized that a linear relationship existed between the two parameters of speed and density. The speed that is used in the algorithm is the space-mean speed which is the harmonic mean of the speeds of the vehicles passing a point on a highway during an interval of time. This speed is obtained through the division of the total distance on a section of highway by the total time required for two or more vehicles to travel this distance. The density, on the other hand is the number of vehicles travelling over a unit length of highway at an instant in time.

With these explanations, the mathematical structure is expressed by Greenshields as follows.

$$\bar{u}_s = u_f - \frac{u_f}{k_j}k \tag{2}$$

where;

$\bar{u}_s$ is the space-mean speed of the vehicles corresponding the density of k

u_f is the maximum speed when the density is at its minimum, i.e., 0

k_j is the jam density

The values of this matrix are determined through a design vehicle of 4.5m length with four (4) occupants travelling. Thus, the original matrix represents the numbers when related speed and corresponding length of danger zone are the case to represent the real cases as if the earthquake hit and those speed and length values occurred in real life. In other words, each cell value is determined by assuming that the probability of speed and danger zone for that specific value being one (1).

As one of the main objectives of this research is to investigate and establish the best set of possible strategies to manage the traffic to minimize the possible numbers of dead and injured people, the probabilistic distribution of both speed and length values was employed to include all different possibilities and scenarios. Hence, a new cost matrix was suggested to model these situations. Each expected cost element (EC) of this matrix is calculated through

$$EC = P_{v_{i_j}} P_{l_{i_j}} C_{ij} \tag{3}$$

where;

i represents the number of the speeds

j represents the number of the danger zones

$P_{v_{i_j}}$ is the probability of i.th speed when the length of j is the case

$P_{l_{i_j}}$ is the probability of length of the danger zone when the speed of the vehicle is i is the case

C_{ij} is the cost matrix values.

The cost matrix elements of the model of this research, thus, are related to the probabilistic distribution of the speeds and length of the danger zones. Four different types of cases were employed to represent the probabilistic occurrence of the length of the danger zones as shown in Figure 6. Probability distribution of danger zone distance is assumed to be an exponential function. This is due to the historical data related to the occurrence and magnitude of earthquakes and realistic evaluation of the fact that stronger earthquakes cause higher damages. The occurrence probability of 200m danger zone, for instance, is higher than 500 m danger zone because the probability of the occurrence of earthquake with Magnitude 5 is higher than the occurrence of earthquake with magnitude 7.5.
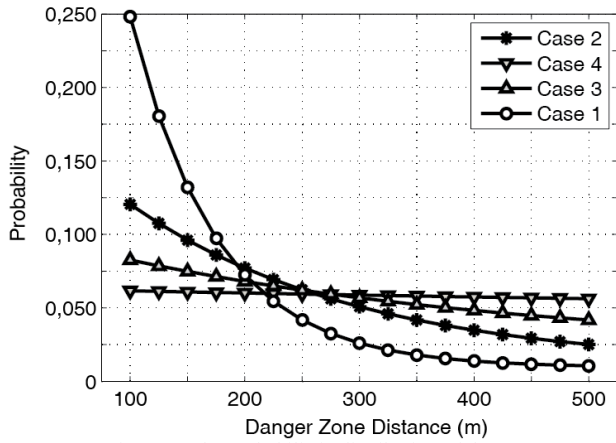
Figure 6. The probabilistic distribution of the Cases

While Case 1 covers this approach, other cases with different standard deviation and mean values, shown in Figure 6, are also assessed for comparison purposes and to investigate the boundaries of this approach. The Figure 7 depicts the lognormal structure of the averaged space-mean speed of the vehicles within the scope of this research. This approach finally produced the concept of "Total Expected System Cost" formulated in the following equation.
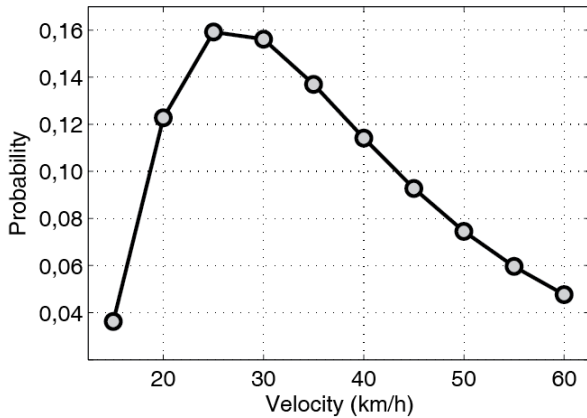

Figure 7. Lognormal distributions of the speeds

$$TEC = \sum_{i=1}^{n} \sum_{j=1}^{m} P_{v_{ij}} P_{l_{ij}} C_{ij} \qquad (4)$$

TEC, here is the total expected cost of the whole system.

III. RESULTS

The Table 1 indicates the calculated cost values for these real case scenarios estimated by Eq 2. Rows designate the speeds and columns depict possible danger zones. For instance, the number of causalities, cost value, is 291, for a 200 m danger zone with a 50 km/h speed. This means that when the average speed ascends to 90 km/h for the same danger zone, causalities will drop to 97, clearly diminishing the casualties by 67%.

In Figure 8, four different graphics sum the general pictures of the expected cost values of the problem in detail regarding the four different cases respectively. The darker red the cells get, the higher the expected cost of the system

is obtained as far as the combinations of the speed and danger zone distance probabilities are concerned.
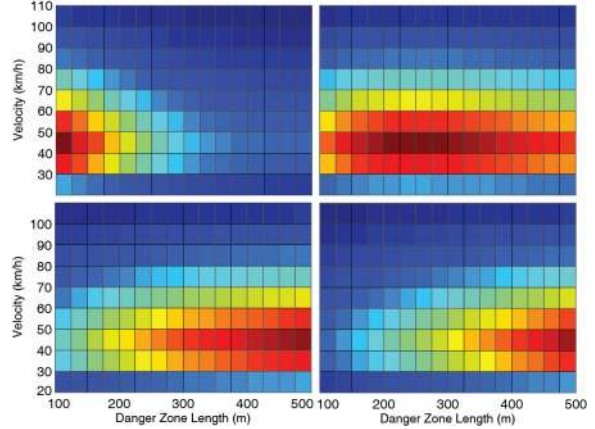

Figure 8. Illustration of the expected cost matrix values for each cell and scenario

The red cells are located in the left–bottom corner of the first item of the graph indicate the most dangerous combination of the probabilities in terms of Case 1. The red section moves to the down part of the right corner of the last item representing Case 4. The blue parts of the graphs are the sections with the safest combinations of the speed and danger-zone length probabilities. Therefore, the safest strategies to be implemented and operated by the engineers lie among the darker sections of the graphs. The total expected cost of the system can be shown as in Figure 9 for different probabilistic distribution of danger zone lengths. As this figure implies, Case 4 represents the worst case scenario with the total cost of 360 deaths. This was expected as Case 4 represents boundary condition assuming the probabilistic variation in danger zone length is almost the same regardless of the magnitude of the earthquake.
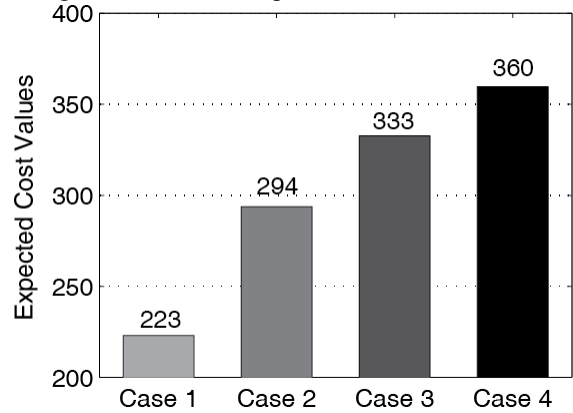
Figure 9. Total expected cost of the system for different cases of the danger zone distance probabilistic distribution

The other cases along with the most realistic approach of Case 1 resulted in lower expected cost values (total number of people in danger). Case 1, having the minimum value of expected cost, is in fact what is expected in real life due the fact that the probability distributions are determined using real data. The following Table 2 illustrates the probabilistic cost values of the matrix for the distribution type of Case 1.

Table 1: System Cost Matrix Values

Velocity (km/h)	Danger Zone Length (m)																
	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
20	218	273	327	382	436	491	545	600	654	709	764	818	873	927	982	1036	1091
30	194	242	291	339	388	436	485	533	582	629	678	727	775	824	872	921	969
40	170	212	255	297	339	382	424	467	509	551	594	636	678	721	763	805	848
50	145	181	218	254	291	327	364	400	437	473	509	546	582	619	655	692	728
60	121	151	182	212	242	273	303	333	364	394	425	455	485	516	546	576	607
70	97	121	145	170	194	218	242	267	291	315	339	364	388	412	436	461	485
80	73	90	109	127	145	164	182	200	218	236	255	273	291	309	328	341	364
90	48	61	73	85	97	109	121	133	146	158	170	182	194	206	218	231	243
100	24	30	36	42	48	55	61	67	73	79	85	91	98	104	110	116	122
110	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40

Table2. System cost matrix values in terms of probabilistic approach

Velocity (km/h)	Danger Zone Length (m)																
	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
20	0.95	1.06	1.14	1.19	1.22	1.23	1.23	1.22	1.20	1.18	1.16	1.13	1.10	1.07	1.04	1.02	0.99
30	2.87	3.19	3.43	3.58	3.67	3.71	3.71	3.68	3.63	3.55	3.48	3.40	3.31	3.23	3.14	3.06	2.99
40	3.26	3.63	3.90	4.07	4.16	4.21	4.20	4.18	4.11	4.04	3.95	3.86	3.76	3.66	3.57	3.47	3.39
50	2.73	3.04	3.27	3.41	3.50	3.54	3.54	3.51	3.47	3.40	3.32	3.25	3.16	3.09	3.00	2.93	2.86
60	2.00	2.22	2.40	2.50	2.56	2.59	2.59	2.56	2.53	2.48	2.43	2.37	2.31	2.26	2.20	2.14	2.09
70	1.33	1.49	1.59	1.67	1.71	1.72	1.72	1.71	1.69	1.65	1.62	1.58	1.54	1.50	1.46	1.43	1.39
80	0.82	0.90	0.97	1.01	1.04	1.05	1.05	1.04	1.03	1.01	0.99	0.96	0.94	0.91	0.89	0.86	0.85
90	0.43	0.49	0.52	0.54	0.56	0.56	0.56	0.56	0.55	0.54	0.53	0.52	0.50	0.49	0.48	0.47	0.46
100	0.17	0.19	0.21	0.22	0.22	0.23	0.23	0.22	0.22	0.22	0.21	0.21	0.20	0.20	0.19	0.19	0.18
110	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05

In this table, a lognormal - probability distribution of the vehicle speeds when crossing the bridge is assumed in accordance with the probability of occurrence of earthquake for the calculation of each cell.

IV. DISCUSSIONS REGARDING TRAFFIC MANAGEMENT OF THE BRIDGE

Once the earthquake information is released by EEWS, the proper messages are conveyed to the drivers on the bridge to guide them if they are required to stop in case they are in so-called safe zone area or to drive as fast as they can to reach the safest part of the bridge when they are in danger zone. Because the queues normally occur behind the danger zone, this seems to provide a quite good chance for the drivers in danger zone to have relatively free and fast forward movement opportunity for quick evacuation from the danger zone.

It should, however, be mentioned that the success of this strategy on the one hand depends heavily on the fact that the information obtained from EEWS is displayed on the Variable Message Signs existing on the bridge without losing even a single second, on the other hand the reasonable and effective responses of the drivers to the messages they get. This second one, without any doubt, requires teaching and training of the bridge users about how they should behave if they are the ones on the bridge when the earthquake hits.

During the peak hours, the queues occur right before the toll points back to the kilometers behind. Once the road users (no pedestrian access is available since 1978) get on the bridge, the average travel speed is at about 45km/h (12.5 m/sn) make the bridge to be passed completely at 86 seconds. As the pre-time available through EEWS system to evacuate the bridge entirely is not long enough (15-20 seconds), the basic strategy that can be applied to bridge traffic right before the destructive earthquake is to make sure that the vehicles close to the foots of the bridge stay where they are and the vehicles in the danger zone (Figure 10) move as quick as possible to pass the middle section possibly the weakest part of the bridge to leave or get the nearest possible most strong part of the bridge. The possible back turning movements just before the bridge seem to be infeasible as the traffic at the back is positioned bump-to-bump in the busiest times giving

no opportunity for vehicles to move backwards in order to make more space for the vehicles already on the foots of the bridge.
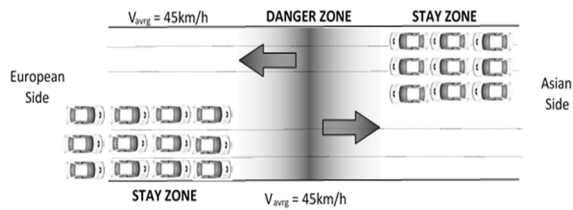

Figure 10. Illustration of the traffic movements on the bridge

The movement of the vehicles will be managed through variable sign messages located critical points of the bridge. The critical points correspond to the locations where the danger zone of the bridge starts. However, beyond the application of these signals on top of bridge, we advise to control entrance of bridge, too. This might be managed, as done Bay Bridge in California through Oakland to San Francisco, by stopping vehicles before entering bridge. Although one of the purposes in Bay Bridge is to merge lines before entering by red and green lights, this approach also increases the speed. This has two benefits 1) EEWS info can be conveyed via signalling, thus preventing any further vehicle movement into bridge 2) most critically, to increase average speed on the bridge so that danger zone will be passed faster. Unlike from Bay Bridge we think that it would be much advantageous to put signals 3-4 km before entrance. By doing this, the reaction time will be increased and there will be fewer cars between signals and bridge foots increasing the possibility to drive backward from the bridge. However this might not valid in busy hours.

The Figure 11 shows the required time to travel the corresponding distance in terms of different travel speeds. This figure clearly indicates the fact that with average travel speed of 12.5 m/s (45 km/h), the available time of 13.45 seconds provides 76.7 % of the vehicles on danger zone to get the safe sections of the bridge. If the average travel speed is assumed at about 8.33 m/s (30km/h) representing the rush hour 50.9 % of the vehicles can still be on the safe part of the bridge. On the other hand, with the speed of 19.44 m/s (70 km/h) assumed to be the average speed at the off-peak period, all vehicles can safely evacuate the danger zone. Nevertheless, all the proper measures should be taken to prevent the vehicles at the stay-zone from entering the danger zone.

Moreover, it should not be forgotten that, there will be more time than the estimated one for the evacuation of danger zone due to the fact that the bridge will not collapse with the arrival of initial S wave since the bridge will continue to oscillate even though the earthquake stops. On top of that, additional time for evacuation of danger zone would be available by installing high-tech sensor closer to the fault line underneath of the Sea of Marmara in future. Figure 11, gives possible seconds required to evacuate the bridge in terms of speeds and corresponding lengths of danger zones. Assuming the danger zone to be 200 m, the required time to evacuate this zone with the current average speed, (45 km/h) is about 16 seconds. On the other hand

increasing speed of vehicle to 90 km/h would decrease this required time by 50%.
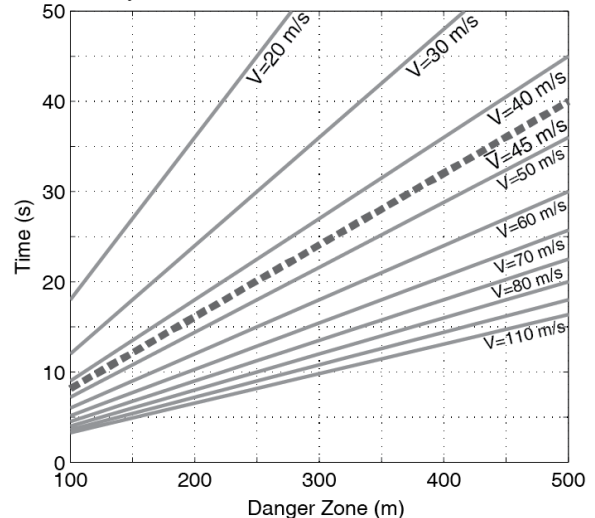

Figure 11. Distances vs travel times of the vehicle in terms of average speed

Another aspect of a warning system application to the bridge is to educate the bridge users through media tools. For instance, special pamphlets can be distributed when drivers buy or renew KGS, OGS electronic tooling cards. Moreover, drivers having email addresses in the system could be provided with easy and effective explanations regarding how to behave when they receive alerting massages. Special programs could also be broadcasted by radio channels dedicated to bridge itself.

Although various strategies could also be developed for different traffic scenarios for different times of the day, this is not directly related to the concept of this paper as in this research only the applicability and importance of EEWS to Bosporus Bridge traffic management concept is tried to be highlighted mainly for the worst case scenario. The guidelines presented here are thought to be applicable not only for Bosporus Bridge. Similar approaches are valid for other bridges in Japan, California, especially Bay Area, Golden Gate Bridge, tunnels; Bolu Tunnel, metros; BART, and Marmaray. Actions and precautions need to be taken are listed below;

1) Main strategy should concentrate on to increase average speed of vehicles on the bridge. This is crucially important because 10% increase would save hundreds of lives.

2) Re-arrangement of the position of tolls: Distance between tolls and bridge foots need to be as long as possible, to increase the entrance speed of vehicles to bridge as well as give vehicles an opportunity for possible backward manoeuvre.

3) Application of a signalized vehicle stopping system on both sides of the bridge entrances. Presently 7 approaching lanes reduce to 3 lanes right after the tolls on the entrance of bridge. This leads congestions to occur right before the feet of bridge. By merging lanes couple of km before foots will indisputably make the traffic flow faster and smoothly.

4) Education is the fundamental part of early warning system applications on traffic management. Without proper knowledge, it is almost impossible for drivers to act fast

within a limited time. Dedicated radio channels can surely be used for this purpose. Moreover evacuation drills for test purposes and simulations will help managers to act smartly in emergencies.

6) Real-time earthquake information has to be conveyed through panel boards. This might be done by different color schemes. Bridge currently has night-time lighting system all over for the purpose of scenery. This lighting might be used to convey the messages. A red light would indicate a threat and warn drivers not to enter the bridge. There might also be another option to pass this information to the drivers via loud speakers.

7) Evacuation plan is another part of the precaution measures. The alert system need to be designed by also considering testing and education. While testing is for health monitoring of the whole system, education mode is for simulation and educational purposes to which all media might involve increasing the awareness of the system.

V. CONCLUSION

Istanbul, the biggest metropolitan city of Turkey, is expecting one of the most devastating earthquakes of its history with a huge number of buildings to be collapsed and damaged. The expected earthquake will affect the city from a wide spectrum of daily life, causing many people to die and get wounded. The Bosporus suspended bridge, without any doubt, is one of the most critical structures of the city. This bridge is not just important as being one of the most important connecting elements of the European and Asian sides of the city; it also represents the highest volumes of traffic of the city as a whole. Determination of proper traffic management strategies will have utmost importance in order to minimize the total number of dead and/or injured people using the bridge for their daily travel purposes.

In this study, the Bosporus suspended bridge is investigated and proper traffic management techniques are suggested against the possible upcoming Marmara Earthquake. This research is believed to be one of the pioneer studies in the application of EEWS to bridge traffic management. Although, the assumptions made are quite reasonable to get the broad picture of the problem, consideration of analysis of collapse mode along with the probability of earthquake occurrence in each possible location would make the solution approach more powerful and effective.

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