A Data-Driven Approach for Direct Assessment and Analysis of Traffic Tunnel Resilience

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Abstract. The resilience of tunnels can have a significant impact on the efficiency of the entire transportation network. The ability to accurately assess the resilience of tunnels is important for tunnel owners and stakeholders when they evaluate the cost-benefit of the investment made and the monetary value of future maintenance and upgrade activities. In this paper, a simple and direct measurement of tunnel functionality was proposed with the focus on the usage of the tunnel. An ideal data collection framework for tunnels was proposed to support the calculation of tunnel functionality, as well as additional data-driven analysis that seeks a correlation between tunnel design and operation parameters with its resilience. As an illustrative example, tunnel operational data for large tunnels in Colorado were summarized and compared with the proposed framework to demonstrate the gap between existing data collection status and the ideal condition.

Keywords: Functionality loss · Resilience · Operation · Traffic tunnel

1 Introduction

Road tunnels are an important part of our infrastructure. A functional road tunnel is a boon to society and a non-functional one is a liability. The construction of tunnel infrastructure is relatively expensive and time-consuming as compared to other transportation infrastructure. However, once completed a tunnel is generally the optimum solution to transportation needs spatially and environmentally. In the long term, society and the transportation network become immensely dependent on tunnel infrastructure hence the continuity of its function is essential.

The function of a tunnel can be defined as its through-pass capacity. The goal of engineering for better transportation infrastructure should be targeted at optimizing our design, construction, and operation to maximize the through-pass capacity of the tunnel. As the tunnel operating conditions are seldom constant, its function is dependent on hazardous loading conditions to which the tunnel is subjected. These conditions could be intrinsic (design, construction or maintenance related) or extrinsic (external loading like fire, accidents or natural events).

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The aim of the study is to create a data collection framework for the design and operation parameters. Then to categorize events related to the tunnel into various states intrinsic to the tunnel. Correlate the events and the data from the framework to identify the best possible design and operation parameters. Further using this information to identify the critical events and components. This will improve our comprehension in scheduling corresponding repairs and upgrades and help in improving future tunnel design.

The present paper explains the methodology of the study. Due to the paucity of available data, fire event occurrence data was simulated for the Eisenhower tunnel in Colorado. The paper elaborates on the process, results, and use of this simulated data. The paper also discusses how similar simulation can be extended to other events.

2 Literature Review

2.1 Functionality Loss

According to FHWA data the total length of road tunnels in US is more than 100 miles, approx. 600,000 linear feet—of Interstates, State routes, and local routes [1]. Some tunnels accommodate huge volumes of daily traffic, for example, Lincoln Tunnel between New York and New Jersey carry approx. 120,000 vehicles per day. FHWA estimates that through-pass traffic of the Eisenhower/Johnson Memorial Tunnels, saved approximately 90.7 million miles of travel per year [1].

Major disruptive events have led to long-term functional losses in road tunnels. On July 10, 2006, a suspended ceiling panel collapsed on the roadway in I-90 connector tunnel, leading to a fatality and a tunnel closure of 6 months. The diverted traffic through a longer route led to delays and productivity loss. Similarly, in the Sasago Tunnel in Japan [2] on December 2, 2012, tunnel ceiling collapsed over a continuous road section of approximately 140 m, which caused nine fatalities. The tunnel was completely closed for 27 days.

A major fire event in Mont Blanc tunnel on March 24, 1999, caused 39 fatalities and many more injured [3]. This led to the closure of the tunnel for approximately three years with total economic loss of $800 million [4]. The cost of repairs and refurbishment with safety upgrades were to the order of $481 million [5]. Similarly, a less severe incident happened in Gotthard Road tunnel on October 24, 2001 in Switzerland [6]. There were 11 fatalities and some people were injured. The total repair cost was around $16 million. The tunnel connecting the North to South Switzerland was closed for less than 2 months. The commuters had to travel by the Gotthard Pass, which is susceptible to heavy snowfall and avalanches.

2.2 Tunnel Resilience

Resilience model was first proposed by Bruneau et al. [7] for quantifying seismic resilience of communities. Chang and Shinozuka [8] introduced a probabilistic approach for assessing resilience, measured with loss of performance and length of time needed for recovery. For civil structures, resilience of the structure is its ability to function at a certain service level even after the occurrence of an extreme event and to recover to desired functionality as rapidly as possible [9]. The need for resilient infrastructure has been emphasized in the Presidential Policy Directive (PPD-21, 2013), where a call for, proactive and coordinated efforts, "to strengthen and maintain secure, functioning, and resilient critical infrastructure – including assets, networks, and systems – that are vital to public confidence and the Nation's safety, prosperity, and well-being" [10].

Although there are some studies related to tunnel resilience for specific conditions, their scope is limited. Rinaudo et al. [11] defined resilience of tunnel as "capacity of tunnels to withstand fires with minimum losses and to recuperate a specific tunnel service level as fast as possible." The paper proposes a methodology for optimizing the placement of fire sensors in a tunnel, using Virgolo tunnel in Italy as a case study. The paper however, does not provide any quantification of resilience in tunnels. The tunnel resilience model proposed by Huang et al. [12] considers lining deformation as the metric to quantify tunnel resilience. Where, tunnel resilience is defined as tunnel's ability to absorb the disruption caused by the hazards and then the ability to recover to the acceptable level of the functionality, which is equivalent to lower levels of deformation and repair. This model has been developed for the structural resilience of Shanghai metro tunnel lining, subjected to the extreme surcharge loading. Huang et al. [13] extended the resilience model for designing repair strategies using real-time monitoring data from wireless network sensors. They used the tilt sensor, crack sensor and seepage sensor for data collection. However, this study focuses on the performance of lining components, and not on the tunnel system resilience as proposed in this paper. The Department of Homeland Security (United States) has developed Integrated Rapid Visual Screening of Tunnels (IRVS) [14] for risk assessment and quantification of resilience of tunnels against explosion, fire, and flood. To the authors' knowledge, there has been very few studies that focused on tunnel resilience at a higher level, from end user's perspective, to minimize traffic disruption as well as social and economic losses for commuters and nearby communities.

3 Tunnel Resilience Quantification

3.1 Metric for Tunnel Functionality

The concept of resilience is widely used in engineering studies related to recovery from natural hazards. In general, resilience is the measure of the ability of a system to recover form a disturbance caused by hazardous events. Resilience study for transportation tunnel is an emerging concept. As mentioned earlier the studies are limited to specific components or events like fire and lining. A generalized quantitative assessment of the tunnel functionality loss is absent. To develop such a metric is very complicated as the tunnel is a complex infrastructure with interdependent components. Additionally, the intensity of an event will depend on the attributes of the tunnel. These attributes of the tunnel will be covered in data collection framework. The assessment of tunnel resilience is intricate, if planned by the bottom-up approach, by predict the performance of each tunnel component during a disturbance and combine their impact using a fragility-based framework.

In this study a direct approach is proposed, to avoid any complexities or the simplifications that need to be done to get a result. The functionality loss of a tunnel is defined as the time-history of tunnel functionality, following any disturbance. The functionality Q, for any traffic tunnel can be quantified as the ratio of traffic capacity available to the public to the maximum traffic capacity available in tunnel design. This can be plotted (see Fig. 1) as a series of points along the time axis. Functionality metric, Q can be written as:

$$Q = \left(\frac{\#\ of\ open\ lanes}{Total\ \#\ of\ lanes}\right) \times \left(\frac{Reduced\ speed\ limit}{Normal\ speed\ limit}\right) \tag{1}$$

The advantages of this simple metric are that it can be recorded easily. It defines the state of tunnel operation as it is a ratio of traffic capacity open to public to the maximum traffic capacity. As the data is collected over longer periods of time it can be used to evaluate the design and operation parameters. Thus, a cost benefit evaluation is possible of the investment made and the monetary value of future maintenance and upgrade activities can be estimated.

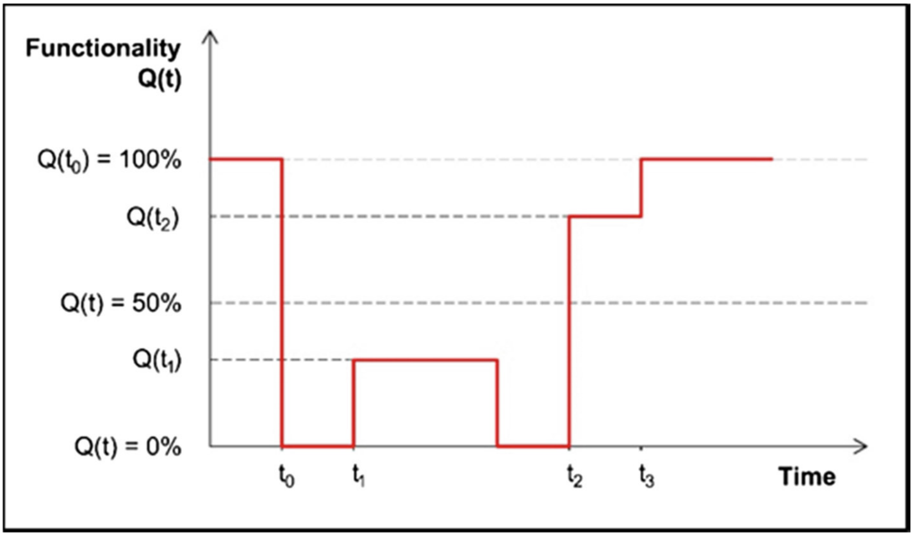

Fig. 1. A typical tunnel functionality plot

3.2 Data Framework for Resilience Assessment

Functionality of the tunnel is determined by the design and operational characteristics of the tunnel, as well as some external factors (e.g. weather, traffic composition, traffic volume, etc.) A data framework was proposed in this study [15] that covers all necessary data of a tunnel, so that its functionality and resilience can be assessed (either through data-driven approach or simulation). The current problem in getting tunnel data is not only the lack of data collection but also the dissimilarities in the way data is collected from one tunnel to another, i.e. lack of uniform practice in tunnel data collection.

The data framework [15] has 3 major components static, dynamic and function data. The static data is associated with design and construction with fixed parameters like the length or shape of the tunnel. The dynamic data is related to operation of components and maintenance of tunnel, and organizational setting of the operator. Function data is the continuous data collected during the tunnel operation. It outlines the maximum through pass traffic capacity, hazardous events and function loss data. This data helps in quantifying the functionality metrics.

The main issue with data collection, at this stage, is the lack of available data and the format in which it is collected. Thus, the researchers first explored a simulation-based approach to assess tunnel functionality as discussed in the following section. Tunnel functionality is affected by many different factors, in this paper, we only presented a simulation scheme to generate realistic functionality loss due to tunnel fire events. Other effects of tunnel functionality loss will be addressed in future studies.

4 Example Functionality Data Simulation for Fire Event

Fire in tunnels is the integral part of the system as it functions. A tunnel has its intrinsic attributes, in other words design and extrinsic attributes or traffic volume, type and human behavior. It is very difficult to consider all these aspects to develop a model for estimating a fire event. So, this study takes a statistical approach to estimate the occurrence of fire in a tunnel and its size. Although the objective of the study is not to generate a fire event accurately. At the same time, it is important to create a realistic scenario for function data generation. In this study we consider the Eisenhower tunnel in Colorado for the design and operation attribute of the tunnel, like length of the tunnel, traffic data and number of lanes, to generate the distribution of probability of fire event in the tunnel over a period.

The probability of fire is generated using the USFA data for vehicle fire [16]. It gives a percentage of the vehicle fire occurrence by day of the week, hour of the day and monthly. Combining this with the traffic volume through the Eisenhower tunnel for a year gives the probability of fire at any hour of the day in the tunnel. The size of fire is considered as maximum heat release rate (HRR), in MW, during the fire. The data considered in calculating the magnitude of the event is given in Table 1. This table, like tunnel attributes, is stored in an excel sheet and the values can be modified as required with time, without changing the MATLAB code, which makes the simulation adaptable to change in tunnel attributes and traffic data.

In this case we assume damage states of tunnel lining. The tunnel lining damage is divided into 5 categories. These damage states are defined based on reports by PIARC [17], NFPA [18] and NCHRP [19]. The damage states are lognormally distributed. The MATLAB code randomly allocates an event over the period when the cumulation of the probability reaches one. Based on the tunnel traffic content, i.e., type of vehicles crossing the tunnel, the probability of type of fire is estimated. Once the type of damage

Table 1. Fire damage parameters

Component name	Damage states					
Lining	Unit	DS1	DS2	DS3	DS4	DS5
Damage type		No lining damage	Negligible lining damage	Minor spalling	Concrete lining spalling	Support lining damaged
Demand parameter	Mean HRR (MW)	4	15	50	100	200
	Lognormal	0.35	0.35	0.35	0.35	0.35
Degree of loss	Level 1 (%)	50	50	100	100	100
	Level 2 (%)	0	0	50	50	50
Response time	(minutes)	5	5	5	5	5
Time of recovery	Mean (minutes)	20	120	2880	43200	129600
	Lognormal	0.48	0.48	0.48	0.48	0.48
	Mean (minutes)	0	300	7200	86400	259200
	Lognormal	0.48	0.48	0.48	0.48	0.48
Repair cost	Mean cost (USD)	10,000	100,000	1,000,000	10,000,000	100,000,000
	Lognormal	0.48	0.48	0.48	0.48	0.48
Remarks		Only vehicle pushout	Tunnel closed for 2 h, one lane closed for 5 h	Tunnel closed for 48 h, one lane closed for 120 h	Tunnel closed for 1 month, repair work 2 months	Tunnel closed for 3 months, repair work for 6 months

state is chosen, the parameters associated with the damage state are chosen from lognormally distributed values. It is very difficult to know the extent of damage in minor fire events. So, the values for smaller events are extrapolated from large fire data. The damage state 4 and 5 are associated in magnitude to the major fire events like the Gotthard, 1997, 2001 and Mont Blanc, 1999 [6, 17, 20].

The simulation is done for 1 year and the code goes through 1000 iterations. The resulting data is given in Table 2. The average of fire events per year is around 1.8. Considering an average 33,000 vehicles crossing EJMT per day, gives the chances of fire to be 5.5 times per 10^8 vehicles km. The result is close to the data published by Nelisse et al. [21], PIARC [22], Norway [23] and China [24]. It has been noted that EJMT has 1 to 2 vehicle fires per year [19]. Further, the EJMT has had 3 fire events in past 18 months. The available information validates the frequency of event occurrence generated by the simulations.

The result shows that the mean functionality loss per year is 0.56%. This is equivalent to an average of 49 functional hours, lost due to fire annually. Every 100 years there are 2 to 3 events with more than 10% functionality loss and 1 event with

Table 2. Fire simulation results

Values per year	# of events	Functionality (%)	Cost (USD)
Minimum	1.0	52.47%	2269.00
Maximum	2.0	100.00%	256075471.00
Mean	1.8	99.44%	851280.70
Median	2.0	99.99%	24110.00
Mode	2.0	100.00%	4842.00
Std. Dev.	0.4	2.98%	9427172.51

15% function loss or more (see Fig. 2). The mean expenditure annually due to fire event is roughly 1 million USD. Consequently, fire will cost the Eisenhower tunnel damage of 85 million USD over 100 years (see Fig. 3). There is a 20% chance of an event costing more than 100 million USD loss occurring in 100-year interval. The simulation also predicts that in every 100 years there might be approximately 2 events with losses of more than 10 million USD due to fire. The simulation generated 2 events with more than 100 million loss over 1000 years and 1 event with loss of over 250 million in the same duration.

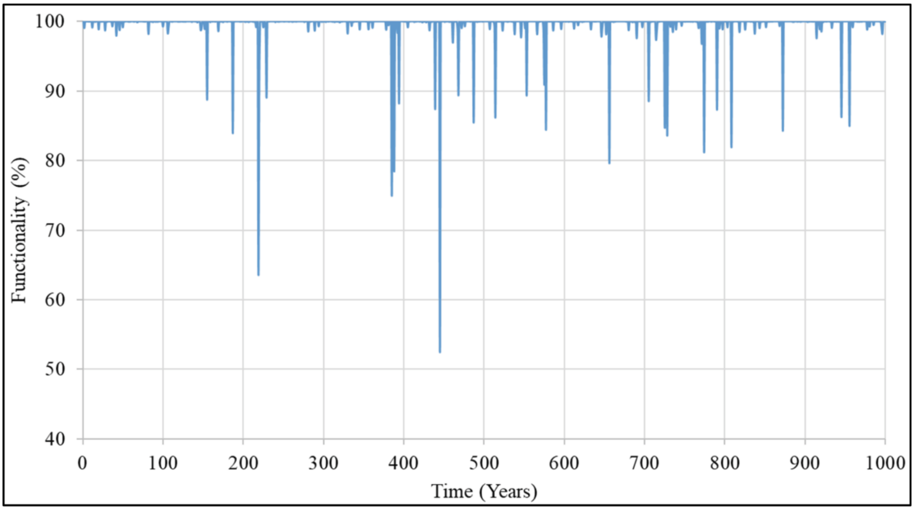

Fig. 2. Annual tunnel functionality (%)

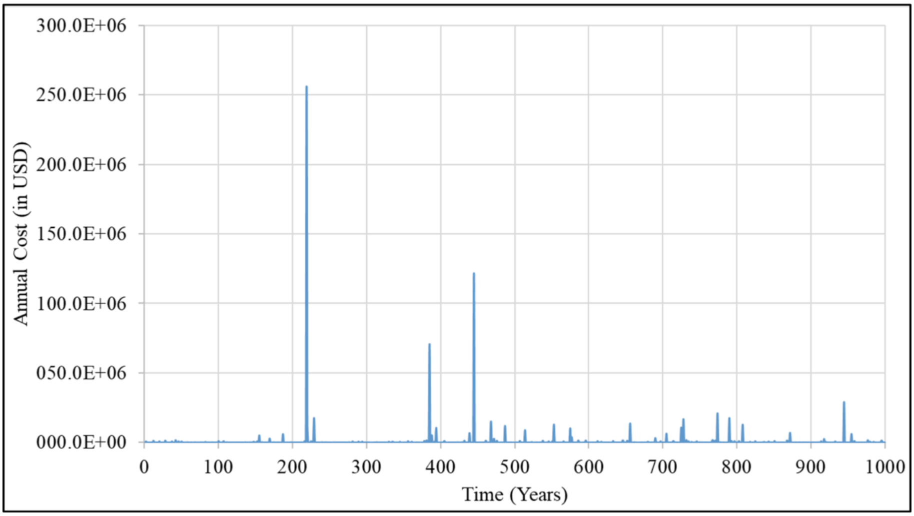

Fig. 3. Annual cost due to fire event (USD)

5 Conclusion and Future Work

5.1 Conclusion

The results from fire event simulation are close to realistic and other literature found. From these results magnitude of consequences due to fire can be accessed. The model can be customized to any tunnel as it takes the parameter of the tunnel and considers its traffic volume at any point of time. More data is needed from more tunnel operators to improve the model. The model has capacity to evolve with time as it considers the increase in traffic by using traffic data. HRR mean values can also be modified in future with the increase in new electrical vehicles and subsequently the damage states.

5.2 Future Work

The simulation is being expanded to other events affecting the tunnel functionality. Some of the events are accidents, tunnel component failure, natural hazards, vehicle breakdown and social events. Some events, like natural hazards, related to the location of the tunnel will be diverse from other tunnels. For example, Eisenhower tunnel is affected by snow a lot, on the other hand tunnels near the coast lose functionality during Tropical storms. So, coast tunnel will have closures due to flooding. The model can for customized to incorporate events based on location.

The model will be used to evaluate critical events, that is the events which effect the tunnel the most. The effect of critical event on the tunnel components can be seen, hence quantified. This will help in identifying the critical components of the tunnel, which will further guide when decisions are made for repair or upgrade of tunnel component.

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