Operational resilience of traffic tunnels: An example case study

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ABSTRACT: Functionality losses in tunnels (i.e. partial or full loss of use due to natural and human-induced disruptive events) can greatly undermine the transportation network efficiency. Severe functionality loss related to fire, earthquake or adverse climate will result in significant economic loss thereby affecting the communities socially and economically. Even short-term functionality loss due to minor events such as vehicular breakdown, weather conditions and tunnel repair can also hamper the traffic flow. Tunnel management and operation also affect functionality recovery from the loss, since the tunnel "down time" is highly dependent on the immediate measures taken after an event. Understanding tunnel operational resilience requires a holistic approach considering various scenarios, tunnel type, its location, design, and management methods. The paper discusses the importance of tunnel operation data collection in helping establish tunnel functionality loss models. Using a one-year of operation log data from the Eisenhower-Johnson Mountain Tunnel (EJMT) in Colorado, USA, this study illustrated, using limited data, the approach to statistically determine the operational resilience of EJMT under various events.

1 INTRODUCTION

Functionality losses in tunnels (i.e. partial or full loss of use due to natural and human-induced disruptive events) can greatly undermine the transportation network efficiency. Functionality losses can be either long term or short term, with one caused by major natural or man-made disruptive events like fire, earthquake, adverse climatic conditions, or major renovation; and the other related to routing operational, maintenance or minor traffic breakdowns/accidents. These function loss events can be very costly and have great negative impacts on the public socially and economically. The impact of such events should be quantified when assessing the resilience of the tunnel, with the ultimate objective of keeping transportation services available under adverse circumstances.

Although a unified approach to assess and analyze tunnel resilience is reasonable, majority of past tunnel functionality loss studies analyzed these events on a case-by-case basis. Typically, only significant functionality loss events due to accidents were recorded carefully. There is currently a lack of systematic data collected or analysis done to look into the overall trend for the occurrence and severity of such events. A systematic analysis of tunnel function-loss cases across different levels of severity can answer some of the most critical questions of interest to tunnel owners. For example, in a given tunnel, what is the best and worst-case scenario function loss one can expect, when a certain hazardous condition occurs? Are there certain tunnel type, design, or management methods that are vulnerable to such functional interruption? Is there a statistically significant difference in the recovery time for the same event under different circumstances? This paper statistically determines the operational resilience of

Eisenhower-Johnson Mountain Tunnel (EJMT) under various events based on 1 year of data provided by Colorado Department of Transport (CDOT).

2 LITERATURE REVIEW

Most of the tunnels in the United States were constructed during two eras 0. First after the Great Depression in 1930's and 1940's. Another phase came during the development of Interstate Highway in 1950's and 1960's. Some of these structures have crossed their design service life. They often do not adhere to the latest design codes. Their operation and maintenance periods have increased leading to disruptions in traffic. Regular inspections are necessary to collect data to continue safe operations and prevent structural, geotechnical and functional failures.

An estimation by FHWA data reviles the total length of road tunnels to be 100 miles, approximately 517,000 linear feet—of Interstates, State routes, and local routes in the US (NTIS, 2015). Tunnels accommodate huge volumes of daily traffic, e.g. Lincoln Tunnel between New York and New Jersey carry approx. 120,000 vehicles per day. Amtrak reported an operational loss of nearly $60 million due to the closures of four of its tunnels due to Hurricane Sandy. FHWA estimates that by traveling through the EJMT, the public saved approximately 90.7 million miles of travel per year (NTIS, 2015).

Some major events have led to long-term functional loss. On July 10, 2006; a suspended ceiling panel collapsed on the roadway in I-90 connector tunnel, leading to a fatality and the tunnel closure for 6 months. The traffic was diverted from a longer route, leading to traffic delays and productivity loss. In the Sasago Tunnel in Japan (Kawahara et al., 2014), on December 2, 2012, tunnel ceiling collapsed over a continuous road section of about 140 m, causing nine fatalities. The tunnel was completely closed for 27 days. The commuters had to take a detour, 50 km longer.

There was a major fire in Mont Blanc tunnel on March 24, 1999, causing 39 fatalities and many injured (Fridolf et al., 2013). The cost of repairs and refurbishment with safety upgrades were to the order of $481 million (Barry, 2010). The detour length was around 80 km. In Gotthard Road tunnel on October 24, 2001 in Switzerland (Bettelini et al., 2003) fire broke out, causing 11 fatalities and some injuries. The total repair cost was around $16 million. The tunnel was closed for approximately 2 months. The travel length increased by 30 km crossing the Gotthard Pass, which is susceptible to heavy snowfall and avalanches.

3 RESILIENCE

Resilience is the measure of the ability of a system to resist an unusual disruption and to recover efficiently form the damage state induced by the disruption. 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 (Bocchini et al., 2014). Bruneau et al. (2003) gives a conceptual framework defining seismic resilience of communities quantitatively. A measure, $Q(t)$, was defined for the quality of the infrastructure of a community. The seismic resilience is conceptualized as the ability of the system to reduce failure probabilities, reduce consequences from failure and reduce time to recovery. The proposed "resilience triangle" has been used frequently afterwards as the fundamental concept of resilience. Chang and Shinozuka (2004) introduced a probabilistic approach for assessing resilience, measured with loss of performance and length of recovery.

Resilience is a less researched topic in tunneling industry as most of the research is focused in design and construction stages of the project and little study has been done on the operations of tunnels. As the tunnel infrastructure is getting old in the USA and due to climate change, transportation tunnels are under stress from degradation by aging, natural hazards and increasing traffic load. 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 –

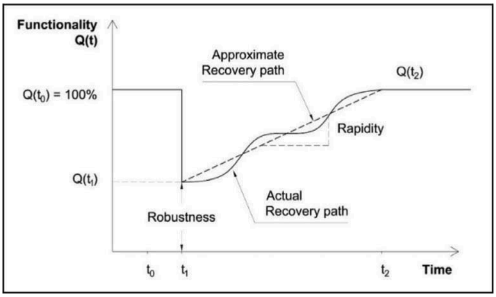

Figure 1. Resilience Triangle.

including assets, networks, and systems – that are vital to public confidence and the Nation's safety, prosperity, and well-being."

There are some studies related to tunnel resilience for specific conditions. Rinaudo et al (2016) 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 however, does not quantify resilience in tunnels. Huang & Zhang (2016) proposes a tunnel resilience model, where lining deformation was considered as the metric to quantify tunnel resilience. This model has been developed for the structural resilience of Shanghai metro tunnel lining that is sometimes been subjected to the extreme surcharge loading. Huang et al. (2017) proposed a resilience model for designing repair strategies using real-time monitoring data from wireless network sensors. However, this study is limited to the performance of lining components. In the United States, the Department of Homeland Security has developed Integrated Rapid Visual Screening of Tunnels (IRVS, 2011) 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 from end user's perspective, to minimize traffic disruption as well as social and economic losses for commuters and nearby communities.

The objective of improving tunnel resilience is to minimize traffic disruption as well as temporal, social and economic losses. A more resilient tunnel will improve the functional reliability of the highway on which it is located. The resilience of the tunnel will depend on its structural characteristics (like geometry, geological setting, construction technique, support system, aging, etc.), contemporary systems (like Ventilation, Lighting, Fire Suppression, Power Supply), tunnel traffic, operation and maintenance works (including emergency responses) of the tunnel. Substantial research has been done in the field of tunnel maintenance by agencies all over the world. Recommendations on tunnel management and maintenance strategies have been proposed to reduce losses. The previously done research works are mostly qualitative and there is no literature as such, which quantifies the current practices and policies that focus on improving the resilience. Moreover, there is a lack of quantifiable data with the operators or the format of the data is not compatible to quantify the tunnel resilience.

4 OPERATION DATA COLLECTION FOR RESILIENCE ASSESSMENT

Transportation tunnels are complex because they contain many inter-dependent components. The proper functioning of all the components will be required to ensure the full functionality of the tunnel. Some of these components are part of the tunnel infrastructure such as the lining structure and ventilation system, while others can be mobile operational components such as on-site firefighting vehicles. Each tunnel is unique in terms of its components and their protocols in handling disruptive events. The nature and intensity of disruptive events depend on the various factors, like tunnel's geographical location, social behavior of localities, the age of infrastructure, the economic condition of the operator and maintenance pattern. Each event will affect the components of the tunnel in a different manner. Modeling of individual response under hazardous events will be very complicated. Tunnel's recovery after a disturbance is affected by availability of funding, bidding process for repair work, contracting schedule, and other human factors. The assessment of tunnel resilience is very complicated if one plans to use a bottom-up approach, which is to predict the performance of each tunnel component during a disturbance and combine their impact using a fragility-based framework (as it was done for seismic resilience of building structures). Many simplifications must be made, and the results will have a high level of dispersion.

To assess tunnel system resilience a direct approach is proposed in this study. The concept is to systematically collect tunnel functionality loss data during the tunnel operation process using simple metrics such as tunnel lane closure and the time needed for tunnel reopening. The functionality loss of a tunnel is defined as the time-history of tunnel functionality following any disturbance. As it is illustrated in Figure 1 earlier, any functionality loss of a tunnel can be characterized as a series of points in the graph as [t_1, $Q(t_1)$], [t_2, $Q(t_2)$],... etc. In this study, 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. One simplified way to quantify this metric is:

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

The advantages of this simple definition are, firstly, Q is solely a state of tunnel operation (i.e. open or close) independent of traffic condition. For example, even when the traffic flow in the tunnel is completely stopped due to traffic jam, if the tunnel is still fully open, its functionality should be 100% (although the efficiency of passengers using this available functionality is very low). Secondly, the simpler the metric is, the easier it is for the tunnel operators to record it accurately every time. The collected data cannot be used directly for resilience prediction, but it can serve as a quantitative measure of existing tunnel resilience against any events that had happened in that tunnel (if such data were collected during that event). Moreover, if one collects a large amount of functionality loss data over the service life of the tunnel, the data set can be combined with other design and operation/management parameters to identify patterns and correlation. This can eventually enable predictive tools supported by large quantity of data.

The challenge with this data-driven approach is that there is currently no uniform data collection strategy or framework. Most of the major tunnels in the U.S. has some level of ad-hoc operation data collection that may or may not contain adequate information for resilience quantification. Hence, the first stage is to establish an ideal data structure for use in everyday tunnel operation management. This framework should be designed to support the assessment of resilience as discussed above, as well as enable further data-driven analysis. A complete tunnel data framework is proposed in this study as shown in Figure 2.

As shown in Figure 2, there are three components in the proposed tunnel data framework. The first being static data, which is defined as the design and construction information which has not changed for a long period unless there is intended changes or upgrades. Static data will include general information, design documents, as built drawings, equipment layout and changes in the layout with time. This information is generally constant over time with minor variations. In cities, the geotechnical setting might change relatively more frequently as the tunnel is close to the surface. Sometimes the condition also changes if an additional bore is constructed close or parallel to the existing tunnel. This data is typically readily available for all U.S. public tunnels through National Tunnel Inventory (SNTI, 2015) and inspection data.

The second component is dynamic data, which is defined as the time-varying condition of the tunnel components and usage conditions. The dynamic data consists of operational and maintenance data of the tunnel components. Collection of this data is a continuous process. Operational data includes traffic volume, status of the equipment, organizational setting, staff and mobile equipment. Maintenance data consist of inspection data on tunnel system and components, which can be used to calculate rate of deterioration, condition states and failure probabilities. The dynamic data can be plotted on a timeline with tags. Some components of

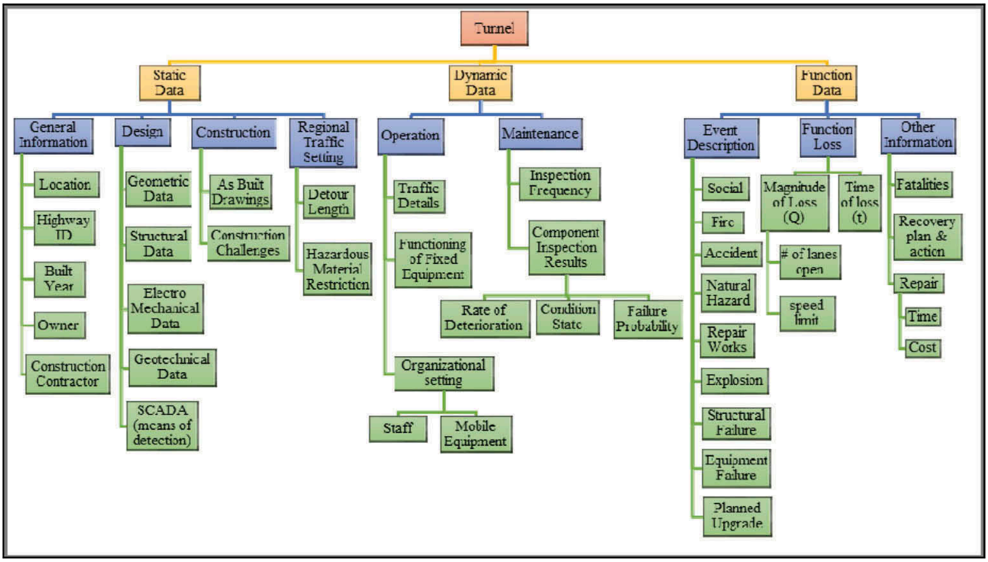

Figure 2. A data collection framework to support tunnel resilience assessment.

the dynamic data are recorded in ad-hoc tunnel management logs kept by individual tunnels, such as traffic volume and operation condition.

The third component is functionality loss data due to an event, which is defined as any information related to reduction and recovery of tunnel functionality (reduced speed, partial closure, full closure). The minimum data collection required is the quantitative measure of available functionality (defined in Equation 1), time stamp (relative to the starting of the event) corresponding to the functionality, and a categorized cause and severity of the external disturbance. The full recovery curve illustrated in Figure 1 can be reconstructed using this minimal information. Additional information that can be included in this category may include fatality, direct financial loss, and cost of restoration. In the analysis later, for EJMT, some of these data were buried partially within ad-hoc logging or traffic management systems not dedicated to record resilience. It is very difficult to extract these data at large scale unless some effort was put towards data collection with this proposed framework in mind.

5 DATA ANALYSIS

An ideal data collection framework is mentioned above, but currently the operators collect data according to their systems developed over time, as per the requirements. At CDOT the tunnel data is collected for EJMT at the tunnel control room. The hourly vehicle count is recorded continuously since the opening of the tunnel, originally by hand and now electronically (still rely on manual inputs). The tunnel does not have an automated system like Supervisory Control and Data Acquisition (SCADA), to record data related to the use of various systems. The operational data is recorded in form of manually generated logs. These logs were initially handwritten on logbooks but are now recorded in excel sheets (still manually). These logs include hourly traffic count, carbon monoxide readings, fan operation status, continuous flow metering and operation activities. These logs are based on visual monitoring via cameras and data collection via sensors. In addition, a recent upgrade in the fire suppression system introduced a new set of sprinklers that are controlled by a separate program. Separate data collection presents a general challenge in older tunnels that went through separate upgrades.

The data related to organization setup of the tunnel is available with CDOT. The tunnel goes through regular inspection checks according to Tunnel Operations, Maintenance,

Table 1. Full Closure events in Eisenhower tunnel from May 2017 to April 2018.

Sr. No.	Direction	Event Type	Event Sub Type	CMV	Fatality	Hazmat	Event Severity	Event Start Date	Event End Date	Full Closure Duration (minutes)
1	East	Planned Event	Road Work	No	No	No	Moderate	Jul 9, 2017	Jul 13, 2017	607
2	East	Incident	Accident	No	No	No	Severe	Apr 21, 2018	Apr 21, 2018	22
3	East	Incident	Mechanical	No	No	No	Severe	Aug 5, 2017	Aug 5, 2017	14
4	East	Incident	Safety Closure	Yes	No	No	Severe	Aug 25, 2017	Aug 25, 2017	73
5	East	Incident	Safety Closure	No	No	No	Severe	Dec 25, 2017	Dec 25, 2017	68
6	East	Incident	Safety Closure	Yes	No	No	Severe	Dec 26, 2017	Dec 26, 2017	14
7	East	Incident	Safety Closure	No	No	No	Severe	Mar 10, 2018	Mar 10, 2018	56
8	East	Incident	Safety Closure	No	No	No	Severe	Apr 24, 2018	Apr 24, 2018	143
9	West	Incident	Accident	No	No	No	Severe	Nov 21, 2017	Nov 21, 2017	14
10	West	Incident	Accident	Yes	No	No	Severe	May 8, 2017	May 8, 2017	9
11	West	Incident	Mechanical	Yes	No	No	Severe	May 26, 2017	May 26, 2017	16
12	West	Incident	Mechanical	No	No	No	Severe	Apr 28, 2018	Apr 28, 2018	3
13	West	Incident	Mechanical	No	No	No	Severe	Apr 28, 2018	Apr 28, 2018	2
14	West	Incident	Outside Agency	No	No	No	Severe	Dec 17, 2017	Dec 17, 2017	3
15	West	Incident	Safety Closure	No	No	No	Severe	May 14, 2017	May 14, 2017	111
16	West	Incident	Safety Closure	Yes	No	No	Severe	Jul 5, 2017	Jul 5, 2017	14
17	West	Incident	Safety Closure	No	No	No	Severe	Oct 1, 2017	Oct 1, 2017	78
18	West	Incident	Safety Closure	No	No	No	Severe	Nov 23, 2017	Nov 23, 2017	18
19	West	Incident	Safety Closure	No	No	No	Severe	Nov 23, 2017	Nov 23, 2017	40
20	West	Incident	Safety Closure	No	No	No	Severe	Dec 7, 2017	Dec 7, 2017	14
21	West	Incident	Safety Closure	Yes	No	No	Severe	Dec 17, 2017	Dec 17, 2017	129
22	West	Incident	Safety Closure	No	No	No	Severe	Mar 4, 2018	Mar 4, 2018	50
23	West	Incident	Safety Closure	No	No	No	Severe	Mar 28, 2018	Mar 28, 2018	36
24	West	Incident	Safety Closure	No	No	No	Severe	Mar 28, 2018	Mar 28, 2018	6
25	West	Incident	Safety Closure	Yes	No	No	Severe	May 18, 2017	May 18, 2017	51
26	West	Incident	Safety Closure	No	No	No	Severe	May 18, 2017	May 18, 2017	50
27	West	Incident	Safety Closure	No	No	No	Severe	May 18, 2017	May 18, 2017	8
28	West	Incident	Safety Closure	Yes	No	No	Severe	Nov 4, 2017	Nov 4, 2017	83
29	West	Incident	Safety Closure	No	No	No	Severe	Dec 21, 2017	Dec 21, 2017	128
30	West	Incident	Safety Closure	No	No	No	Severe	Dec 23, 2017	Dec 23, 2017	11
31	West	Incident	Safety Closure	No	No	No	Severe	Jan 3, 2018	Jan 3, 2018	44
32	West	Incident	Spun Out/Slide Off	Yes	No	No	Severe	Jan 12, 2018	Jan 12, 2018	12
33	West	Planned Event	Avalanche Control	No	No	No	Moderate	Dec 25, 2017	Dec 25, 2017	46
34	West	Planned Event	Avalanche Control	No	No	No	Moderate	Dec 26, 2017	Dec 26, 2017	39
35	West	Planned Event	Road Work	No	No	No	Moderate	Apr 30, 2018	Apr 30, 2018	19
36	West	Planned Event	Road Work	No	No	No	Severe	Jun 10, 2017	Jun 14, 2017	84

Inspection, and Evaluation (TOMIE) manual. CDOT is developing Colorado Tunnel Inventory & Inspection Manual based on TOMIE manual and SNTI to customize it to state specific requirements. Contractors/consultants are hired to do initial, routine and in-depth inspection. Inspection data for structural, geotechnical and electro-mechanical components is recorded in form of inspection logs and reports. These inspection reports can be used to generate most of the maintenance data. However, this process has not been automated.

CDOT is one of the leading DOTs in the US, to modernize data management, initiating statewide management and information system for current and planned deployment of Intelligent Transportation System (ITS, 2008). Moving ahead in the same track, CDOT has developed Colorado Traffic Management system (CTMS) through which the department monitors and records events. The Eisenhower tunnel is part of the system, hence the events happening in the Eisenhower tunnel are also recorded by the CTMS. This might help in corroborating with the data recorded at EJMT. The data structure in CTMS was designed with a focus on traffic accident reporting and resolution instead of focusing on a particular transportation infrastructure component. Thus, it is not dedicated for tunnel traffic alone, but applies to all roadways management by CDOT. Any event that causes disruption of traffic will first be called in either by the monitoring crew or emergency responder. An open call will be generated in CTMS with detailed information about the time, cause, and severity of the event. As the event gets resolved, the parties involved are supposed to report necessary details (time, action taken, resources, etc.) back to CTMS to complete the event data, which gets saved in the CTMS database. CTMS data is a great source for tunnel functionality loss and recovery data.

The data from CTMS was sorted to get the closure information of EJMT. One-year CTMS data was provided by CDOT starting from May 2017 to April 2018. The information recorded in the data made available included partial, full closure or no lanes closed with slowed traffic condition like during continuous flow metering. The direction of traffic which was affected by the event is recorded. The events are divided into type sub-type and sub-class. Information on commercial vehicle (CMV) or hazmat involved in the incident is also recorded. The severity of the event is defined qualitatively as minimal, moderate and severe. The start and end of an event is recorded and hence the duration is calculated. A list of full closure events is given in Table 1.

Table 2. Closure Types at EJMT.

Closure Type	(In minutes)	West Bound	East Bound
Full Closure	Total time	1118	997
	Longest duration	129	607
Partial Closure	Total time	22102	77848
	Longest duration	1768	64364
No Lanes Closed/Slow Traffic	Total time	4796	6269
	Longest duration	2468	538

Table 3. Event Severity in both tunnels at EJMT.

Event Severity	(In minutes)	(West Bound) (Closures)			(East Bound) (Closures)		
		Full	Partial	None	Full	Partial	None
Severe	Number of events	25	8	4	7	4	24
	Total time	1014	1847	349	390	118	4696
	Longest duration	129	983	174	143	46	480
Moderate	Number of events	3	44	6	1	18	6
	Total time	104	20255	1046	607	77730	996
	Longest duration	46	1768	494	607	64364	287
Minimal	Number of events	-	-	5	-	-	3
	Total time	-	-	3401	-	-	577
	Longest duration	-	-	2468	-	-	538

There are 36 full closure events and 74 partial closure events in both bores. The length of closures in the West Bound tunnel more uniformly distributed than the East bound tunnel (Table 2). Although the West bound has 28 full closure events and East bound has just 8 such events. The longer events are generally planned events. There are 74 partial closure events. Again, West bound has more events, 52, as compared to East bound which has 22 of such events. 84% of the partial closure events are planned events, whereas just 14% of the full closure events are planned. 89% of the full closure events are severe whereas 15% of the partial closure events are severe (Table 3). An event type is defined as a planned event or an incident

Table 4. Event Type in both tunnels at EJMT.

Event Type	Event Sub Type	(In minutes)	(West Bound) (Closures)			(East Bound) (Closures)		
			Full	Partial	None	Full	Partial	None
Planned Event	Road Work	Number of events	2	44	5	1	18	-
		Total time	103	21203	946	607	77730	-
		Longest duration	84	1768	494	607	64364	-
	Avalanche Control	Number of events	2	-	-	-	-	-
		Total time	85	-	-	-	-	-
		Longest duration	46	-	-	-	-	-
Incident	Safety Closure	Number of events	17	-	-	5	-	-
		Total time	871	-	-	354	-	-
		Longest duration	129	-	-	143	-	-
	Mechanical	Number of events	3	3	1	1	1	2
		Total time	21	75	6	14	27	121
		Longest duration	16	35	6	14	27	96
	Accident	Number of events	2	1	1	1	2	2
		Total time	23	74	64	22	76	28
		Longest duration	14	74	64	22	46	14
	Outside Agency Activity	Number of events	1	-	-	-	-	-
		Total time	3	-	-	-	-	-
		Longest duration	3	-	-	-	-	-
	Spun Out/Slide Off	Number of events	1	2	-	-	-	-
		Total time	12	108	-	-	-	-
		Longest duration	12	98	-	-	-	-
	Debris	Number of events	-	-	1	-	1	1
		Total time	-	-	105	-	15	8
		Longest duration	-	-	105	-	15	8
	Abandoned Vehicle	Number of events	-	1	-	-	-	-
		Total time	-	49	-	-	-	-
		Longest duration	-	49	-	-	-	-
	Emergency Roadwork	Number of events	-	1	-	-	-	1
		Total time	-	593	-	-	-	24
		Longest duration	-	593	-	-	-	24
	Snow Removal Ops	Number of events	-	-	3	-	-	1
		Total time	-	-	590	-	-	538
		Longest duration	-	-	373	-	-	538
	Continuous Flow Metering	Number of events	-	-	-	-	-	24
		Total time	-	-	-	-	-	5060
		Longest duration	-	-	-	-	-	480
	Safety Metering	Number of events	-	-	-	-	-	1
		Total time	-	-	-	-	-	287
		Longest duration	-	-	-	-	-	287
	Heavy Traffic	Number of events	-	-	1	-	-	1
		Total time	-	-	100	-	-	203
		Longest duration	-	-	100	-	-	203
	Environmental	Number of events	-	-	1	-	-	-
		Total time	-	-	174	-	-	-
		Longest duration	-	-	174	-	-	-
Weather Event	Warning	Number of events	-	-	2	-	-	-
		Total time	-	-	2811	-	-	-
		Longest duration	-	-	2468	-	-	-

or a weather event, Table 4 shows the event type distribution. These types have subtypes which could be road work, accident, safety closure, mechanical, snow removal, continuous flow metering, etc. Out of 72 planned events only 2 planned events are severe whereas 83 % of the incidents are severe.

6 CONCLUSION AND FUTURE WORK

Tunnels are an important part of transportation infrastructure that are very costly to construct, maintain, and upgrade. To provide a rational approach for tunnel performance, a simple functionality loss metrics is proposed in this study together with the needed data structure to enable the calculation of this metrics. The available data was analyzed as it was provided (in its current state), without calculating the resilience metrics. Although it is difficult to calculate or simulate overall resilience of a given tunnel design, it is hoped that through systematic long-term data collection, the resilience of traffic tunnel can be assessed to justify monetary value of improvements and upgrades in term of resilience improvement. The objective of this study is to suggest a way to collect data to quantify the impact of funding decisions on tunnel infrastructure. While feasibility studies and cost-benefit studies can provide a projected outcome of an investment decision, the data collected following the recommended structure will be able to provide more realistic and quantifiable measures of success.

Observations on current data collection practice of tunnel operation of EJMT in Colorado:

i. The events are logged incomprehensively, as distinct observers log the event differently, thus, making it difficult to extract resilience data. Hence, in this paper the logs were not analyzed. However, the data recorded in CTMS is more organized and has clear descriptors.
ii. The proposed resilience metric is simple to quantify functionality and the severity of events. The metric is defined such that it will be sensitive to upgrades over a long period of time, even if these upgrades have a non-integrated data generation system.
iii. For further analysis, the details of events from the CTMS software are needed to the analyzed and compared to the events recorded in data logs at tunnel level.
iv. The CTMS system used by CDOT has very good potential to become an automated and integrated tool for gathering tunnel resilience data. Although it is event-based rather than infrastructure-based, thereby making it hard to automatically assess resilience of a tunnel. CTMS software can also be upgraded according to the proposed framework.

A tangible metric for tunnel resilience that can be validated by realistic data is of great value to effective management of the tunnels. This study provided a simple tunnel-focused data structure that can be referenced to reduce the fragmentation of data. Once a large quantity of structured tunnel resilience data is collected, it can be used as a basis for efficiency evaluation, cost-benefit analysis, and additional data mining to identify influential factors for tunnel resilience.

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