A new methodology for the multi-risk assessment of existing road tunnels

(Article begins on next page)

Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 62 (2024) 1112–1119

Structural Integrity Procedia

www.elsevier.com/locate/procedia

II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24)

A new methodology for the multi-risk assessment of existing road tunnels

Walter Salvatore[a], Francesco Morelli[a], Vittorio Palma[a], Daniele Peila[b], Andrea Carigi[b], Maddalena Marchelli[b], Giovanni Plizzari[c], Giuseppe Tiberti[c], Massimo Di Gangi[d], Antonio Polimeni[d], Pierluigi Coppola[e], Fulvio Silvestri[e], Marco Pasetto[f], Emiliano Pasquini[f], Andrea Baliello[f]

[a] Dipartimento di Ingegneria Civile e Industriale, Università di Pisa. Largo Lucio Lazzarino 1, 56122, Pisa.
[b] Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture, Politecnico di Torino. Corso Duca degli Abruzzi 24, 10129, Torino.
[c] Dipartimento di Ingegneria Civile, Architettura, Territorio, Ambiente e di Matematica, Università degli Studi di Brescia. Via Branze 43, 25121, Brescia.
[d] Dipartimento di Ingegneria, Università degli Studi di Messina. Contrada di Dio Vill. Sant'Agata, 98166, Messina.
[e] Dipartimento di Meccanica, Politecnico di Milano. Via La Masa 1, 20156, Milano.
[f] Dipartimento di Ingegneria Civile, Edile e Ambientale, Università degli Studi di Padova. Via Marzolo 9, 35131, Padova.

Abstract

The optimal management of infrastructural assets is a key aspect to guarantee the adequate competitiveness of a country from the economic point of view and a good level of quality from the social one. In this framework, particular attention shall be paid to the critical elements of the infrastructure network, such as bridges and tunnels, which often strongly influence the resilience of the network itself, as highlighted both by what happened immediately after the collapse of the Morandi bridge in Genoa and by the situation that was created following the several construction sites implemented to reduce the structural risk in the tunnels of the Ligurian territory. Indeed, on one hand these critical elements are often characterized by lower structural safety levels than those required by the regulations for similar newly built structures but, on the other hand, the presence of construction sites determines a reduction in the performance of the infrastructure with a significant increase of the road accident and traffic risk. This paper proposes an operational methodology for assessing the risk associated to existing road tunnels. The research is carried out in collaboration with SINA SpA and ASPI, Autostrade per l'Italia, and has the main objective of providing practical tools that can help the road managers to evaluate the global risk variation when temporary interventions are carried out in tunnels and to give indications regarding the optimal construction site organization.

Keywords: Existing tunnels, geotechnical and structural risk, road accident and traffic risk, interventions optimization.

10.1016/j.prostr.2024.09.147

1. Introduction

Road tunnels, similarly to bridges and viaducts, are critical elements of transportation networks: the interruption of service, even if partial, can lead to significant economic and social losses. These can be both direct, such as costs associated with repair interventions and potential loss of human lives, and indirect, like the one associated with medium/long term effects (increasing of travel time, loss of competitiveness of the surrounding territory, etc.).

In this context, one of the most relevant aspects whose influence is strongly underestimated is the impact of the worksite on the traffic safety. Indeed, if on one hand the execution of repair works on a given infrastructure leads to a reduction of a specific risk (e.g. the reinforcement of a bridge or tunnel structure aims at reducing the structural risk, the road pavement reparation at the transport risk, etc.), on the other hand the influence of the worksite on the traffic conditions can lead to, for the period in which the worksite is present, a very significant increase in the transport risk.

This aspect becomes particularly important in the planning of temporary and permanent interventions in road tunnels. Indeed, the common approach currently adopted foresees the execution of temporary interventions in the case of apparent sources of risk in the concrete tunnel lining as a measure for reducing the geotechnical/structural risk for the time needed to accurately assess the situation and design the final interventions. This approach results in an increasing of the road accident and traffic risk that can be possibly higher than the reduction of the structural/geotechnical one. The main purpose of the paper is to present an operational methodology for the risk assessment of the geotechnical/structural and road accident/traffic risk associated to existing road tunnels. This study is carried out in collaboration with SINA SpA and Autostrade per l'Italia (ASPI). The research seeks to provide practical tools for evaluating the feasibility, in terms of minimization of risk to road users, of carrying out temporary geotechnical/structural risk mitigation interventions in tunnels, and to offer insights into optimal strategies for the organization of the worksites. Only by evaluating both risks it is possible to verify the convenience of performing temporary interventions to reduce geotechnical/structural risk (while necessarily increasing the road accident/traffic risk) or, instead, accept the geotechnical/structural risk for the time necessary to accurately assess the situation and then proceed with the design and execution of permanent solutions. The proposed analysis focuses on assessing the risk associated with existing tunnels, adopting a multi-risk approach that includes "geotechnical/structural risk" for each tunnel, associated to the scenario of material detachment from the tunnel's lining, and the "road accident/traffic risk" of the road section including tunnels, considering various worksite scenarios. Combining these two types of risk allows for a comparison of the main possible intervention scenarios, including the option of non-intervention, and to establish intervention priorities along the infrastructural network to reduce the overall risk. This methodology also enables the definition of a priority order for interventions, whether temporary or definitive, for restoring tunnel linings on a given highway section, identifying critical situations that require special attention, and defining the construction site scenario with the minimum risk.

2. General Methodology

The proposed methodology is schematically shown in Figure 1. This approach considers the assessment of both geotechnical/structural and road accident/traffic risks associated to a selected portion of the transportation network. The former is assessed for each single tunnel included in the selected portion of the transportation network in the current state, providing indications about the magnitude of risk, associated to the scenario of a concrete block detachment from the tunnel lining, for the traffic passing through the specific tunnel. Considered the very low data available on this scenario, the geotechnical/structural risk assessment can provide only the indication about the risk magnitude. The latter is assessed at the level of the whole selected portion of the transportation network in several scenarios, including the absence of worksites or different spatial and temporal configurations of the worksites. The road accident/traffic risk is calibrated, as better described in the specific paragraph, on the basis of numerous real data and its precision is far better than the evaluated geotechnical/structural risk. The first results show that the geotechnical-structural risk is generally some orders of magnitude lower than the road accident and traffic risk, as also supported by available literature statistics (PIARC, 2016). Hence, a numerical comparison might misleadingly suggest that interventions, especially temporary ones for restoring or reinforcing tunnel linings, are inadvisable due to the significantly higher road accident and traffic risk increase caused by worksites. However, this conclusion, while partially accurate, overlooks several quantifiable and non-quantifiable factors.

For this reason, the methodology shown in Figure 1 does not foresee a direct comparison between the two risks but, on the contrary, it envisages first the geotechnical/structural risk assessment. If this evaluation indicates a non-negligible risk level (referred to as "p_{faail}" in Figure 1), it necessitates provisional interventions to mitigate this risk, coupled with further investigations and instrumental monitoring for more detailed information (e.g., actual presence of pressurized water, localized changes in lining geometry, etc.). In such scenarios, road accident and traffic risk must be evaluated considering short-term construction scenarios related to temporary interventions and the geotechnical-structural risk situation in adjacent tunnels, assessing the feasibility of combining construction sites.

If the geotechnical-structural risk level is not high, temporary safety interventions are not advised, as the induced increase in road accident and traffic risk would not be justifiable as compared to the geotechnical-structural risk reduction. Thus, only definitive interventions are recommended, and road accident/traffic risk assessment, aimed at identifying the construction scenario with the lowest risk, considers a medium-term construction timeline.

Furthermore, tunnels with loaded second-phase linings, as indicated by flat jack test readings, are excluded from this methodology; indeed, these tunnels require ongoing monitoring due to potential significant pressures on the tunnel structure, exceeding those estimated using this methodology.

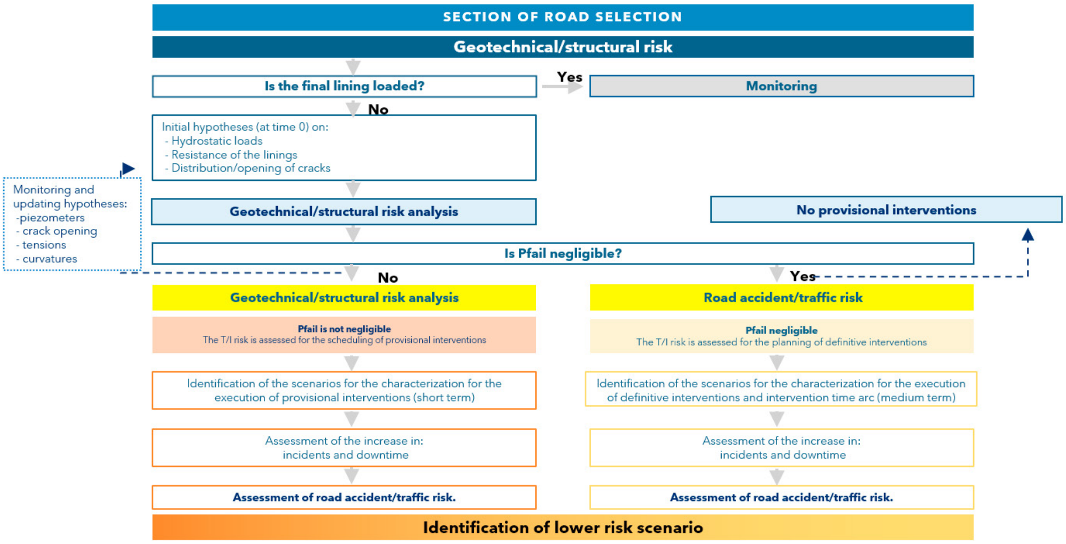

Fig. 1. Flow of general methodology

The detailed risk assessment for geotechnical/structural and road accident/traffic risks is organized in the classical framework of risk assessment that foresees the evaluation of the three main risk factors: hazard, vulnerability, and exposure. In the present research, the hazard is associated to external factors that causes the scenario (e.g. external actions on the concrete lining for the geotechnical/structural risk or construction activities for the road accident/traffic risk). The vulnerability is associated to the resistance of the concrete lining to external actions. Lastly, exposure refers to magnitude of damage associated to the scenario.

3. Geotechnical and structural risk Analysis

The quantity and quality of available data significantly influences the assessment of geotechnical/structural risk in existing tunnels. Indeed, as already highlighted above, the absence of reliable data on past event involving the detachment of a significant portion of concrete (e.g. detachment of a concrete piece with a depth higher than 10 cm) from the tunnel lining makes possible only a rough estimation of the probability of happening of this scenario. The proposed methodology does not include scenarios of superficial detachment and surface alterations, as these issues are generally already addressed through immediate safety interventions and are difficult to predict analytically.

Furthermore, the methodology excludes the analytical estimation of risk for tunnels whose lining is subject to relevant residual stresses, due to the high level of uncertainty associated with the analysis of such situations, particularly regarding the estimation of acting forces. In these cases, the installation of an instrumental monitoring system is essential. Considering these factors, the parameters influencing the factors of hazard, vulnerability, and exposure are described below, and a combination of these leads to the evaluation of geotechnical-structural risk.

3.1 Hazard Definition

The hazard factor is determined by considering the forces acting on the crown of the tunnel's lining, in particular the local pressure transmitted by rocks and water. The evaluation of such actions generally requires the development of a reliable probabilistic model, to estimate both the spatial and temporal distribution of these forces.

However, obtaining detailed information about the spatial and temporal variability of these forces is often not feasible, nor is it always possible to acquire average values for each tunnel. Therefore, this study adopts realistic, conventional values. In situations where specific data is lacking, we assume a local force equivalent to that exerted by a 1.5-meter-high water column above the tunnel lining's crown. The model can be, in any case, updated on the base of eventual further data and information in the next future, like the one derived from monitoring systems.

3.2 Vulnerability definition

The vulnerability is associated to the probability that the resistance of the concrete lining to the external actions is not sufficient to avoid the detachment of a portion of the lining itself. The vulnerability is influenced by several parameters, as the concrete strength, its variability along the lining and over time, the presence of relevant local reduction in the concrete depth, of cracks and their characteristics or any other factor that can reduce the resistance of the lining (e.g. porosity, local variation of curvature, etc.). The exact assessment of the vulnerability would require the knowledge of all these parameters and of their variability over the space and time, knowledge that is usually not available in practical cases. In this context, the existing stress in the tunnel lining, derived on the base of the actions estimated of the hazard, is compared with its ultimate load-bearing capacity, focusing mainly on the punching shear limit state. The value of the shear stresses depends on the area on which the local pressure of the rocks and of the water is applied. The estimation of the loaded area is very difficult to be performed and therefore a conventional circular load area of 1 m^2 has been adopted. Referring to the standard UNI EN 1992-1-1:2015 and considering the standardized load application area, the acting shear-punching stress, v_{ed}, is calculated as follows:

$$v_{ed} = \frac{\beta V_{ed}}{u_1 d} \tag{1}$$

where β is a coefficient that depends on the eccentricity of the load applied to the punching element. Its value can be derived from literature sources (such as UNI EN 1992-1-1:2015 §6.4.3); V_{ed} represents the punching shear stress acting on the investigated portion of the lining; d s the effective depth of the section, and , u_1 is the critical perimeter defined as: $u_1 = 2 \cdot (r + 2 \cdot d) \cdot \pi$. Regarding shear resistance, considering the general case of non-reinforced concrete lining, the possible mechanisms contributing to shear resistance include arch action and interlock action. Considering the low curvature/thickness values of tunnel linings, the only reliable mechanism is the interlock, whose resistance can be evaluated as follows:

$$v_{Rd,c} = 0{,}25 \cdot f_{ctd} \cdot k \tag{2}$$

where f_{ctd} represents the tensile strength of the concrete expressed in MPa, and $k = 1 + \sqrt{\frac{200}{d}} \leq 2{,}0$ with d expressed in mm. Using the mean value of f_{ctd} supplies a mean value of the resistance. The estimation of the p_{fail} is derived from the probability distribution of the concrete resistance.

3.3 Exposure definition

The exposure assessment for the road network considers the probability that a detached concrete block causes a traffic accident. Three main variables mainly influence the exposure: vehicles' speed distribution, vehicles' spacing distribution, and average vehicles length, derived from traffic data systems. The assessment calculates the probability of a vehicle passing when the tunnel lining detaches, considering two scenarios: one where a vehicle is passing during the detachment and another where a vehicle hits debris post-detachment. In the following, only the first scenario is analysed. To evaluate the transit probability in the first scenario, the vehicles' speed distribution f_v and the distribution f_a of the sizes of the lining segment that could detach are considered. From these, the time T is defined, during which a vehicle occupies the space potentially affected by the detachment; this time is calculated as $T = \frac{a}{v}$. In this context, T is considered a random variable characterized by a specific probability density, denoted as f_T. Based on the assumptions of stationarity, lack of memory, and ordinariness of the process, we can define the probability $P_m(\tau)$, of having m arrivals in a time interval τ. This probability follows a Poisson distribution:

$$P_m(\tau) = \frac{(\lambda_p \tau)^m}{m!} e^{-\lambda_p \tau} \quad (3)$$

Where λ_p represents the flow density, i.e., the average number of crossings per unit of time per lane. Considering that v, a and T are random variables, the probability of a vehicle passing in a time $T = T_0$ is given by:

$$P_1(T = T_0) = \lambda_p T_0 \, e^{-\lambda_p T_0} \quad (4)$$

Consequently, the expected value of the probability function of a vehicle passing at the moment of detachment is:

$$P_1 = E[P_1] = \int_{D_T} P_1(t) f_T(t) \, dt \quad (5)$$

where D_T represents the temporal domain over which f_T is defined.

In the second scenario, the probability P_2 of a vehicle colliding with a piece of fallen tunnel lining that has landed on the roadway is evaluated adopting a similar approach. Finally, the total probability of transit at the moment of the lining's detachment, Q_{inc}, is the sum of the probabilities of the two scenarios. To account for the mutual exclusivity of the scenarios, the value of Q_{inc} is capped at 1 (100%).

3.4 Quantification of Geotechnical/Structural Risk

After assessing the hazard and vulnerability parameters, which include the external stress (demand) and the resistance capacity of the examined tunnel lining sections, the probability of a lining's block detachment can be evaluated. This calculation is based on the premise that detachment occurs when the stress (S) exceeds the resistant capacity (R). It's crucial to recognize that both S and R are assessed considering their random characteristics at a specific moment in time (τ). The capacity R is defined as the critical value beyond which the concrete can no longer hold, leading to the lining's detachment. This happens when the demand/capacity ratio reaches 1. In this context, we can determine the probability of the resistance being less than R at the moment of detachment using the resistance probability function, $f(r)$. The critical probability of detachment (P_{cr}) is then calculated as:

$$P_{cr} = \int_0^R f(r) \, dr \quad (6)$$

Having defined P_{cr}, the probability of the lining's detachment over time τ, and the overall probability of transit Q_{inc} (exposure), we can calculate the overall probability of an incident for each tunnel section. This incident probability (P_{inc}) at time τ is expressed as a combination of the probabilities of detachment and transit:

$$P_{inc}(\tau) = Q_{inc} \cdot P_{cr} \quad (7)$$

4. Road accident and traffic risk analysis

As anticipated, the road accident and traffic risk can be estimated by assessing hazard (i.e., road accidents), vulnerability (i.e., road capacity) and exposure (i.e., vehicular flows). The method is developed to evaluate the impact of working sites on road safety and traffic congestion with respect to standard service conditions.

4.1. Hazard definition

The hazard factor is intended as the risk of road accidents during infrastructure service due to specific relevant properties (i.e., traffic volume, cross-section composition, geometric design, pavement state, etc.). To this aim, regressive models in accordance with the Highway Safety Manual (HSM) (AASHTO, 2010) are used to predict number, type (single/multi-vehicle) and severity (fatal and injury/property damage only) of road accidents. These are first calculated in the base conditions for each homogeneous segment composing the selected freeway section (subdivision based on geometric and functional characteristics) using the Safety Performance Function (SPF) described in Equation 8. Then, specific Crash Modification Factors (CMFs) are considered to account the actual roadway characteristics (Equation 9).

$$N_{spf} = L_i \cdot exp[a + b \cdot \ln(c \cdot AADT)] \quad (8)$$

$$N_p = N_{spf} \cdot (CMF_1 \cdot CMF_2 \cdot \ldots \cdot CMF_n \cdot) \quad (9)$$

where N_{spf} is the predicted number of accidents in the base condition, L_i is the segment length, $AADT$ is the annual average daily traffic, a, b and c are regression coefficients, N_p is the predicted number of accidents in the present conditions and CMF_i are the relevant crash modification factors. In particular, the proposed methodology accounts for CMFs referring to curves geometry, lanes and shoulders width, presence and characteristics of barriers, longitudinal and transversal slopes (AASHTO, 2010), as well as pavement evenness, skid resistance, drainage and retroreflectivity of horizonal markings (Cafiso, Montella, D'Agostino, Mauriello, & Galante, 2021), (Sayed & de Leur, 2008), (Smadi, Souleyrette, Ormand, & Hawkins, 2008). Moreover, additional CMFs are suggested for tunnel segments to account for tunnel length, heavy traffic volume and lighting luminance (Schubert, Høj, Köhler, & Faber, 2011).

For a construction work scenario, the above-mentioned prediction should be adjusted considering the cross-section and operational changes due to the presence, timing (i.e., annual period) and layout of the working site. Moreover, the introduction of further specific CMFs is suggested to consider worksite length and duration as well as specific markings and signals (AASHTO, 2010). Based on the described approach, the general framework to evaluate the road accident and traffic risk hazard can be summarized as follow: i) division of freeway section in homogeneous segments; ii) accident prediction for the "basic" scenario (i.e., without working sites); iii) definition of construction site characteristics (layout, period, etc.); iv) accident prediction in the construction site segments; v) accident prediction in the "worksite" scenario. For each freeway carriageway, the main calculation steps are schematized in Figure 2, properly taking into account the worksite annual period, since it influences the traffic input data, and then spreading the construction duration over the annual prediction.

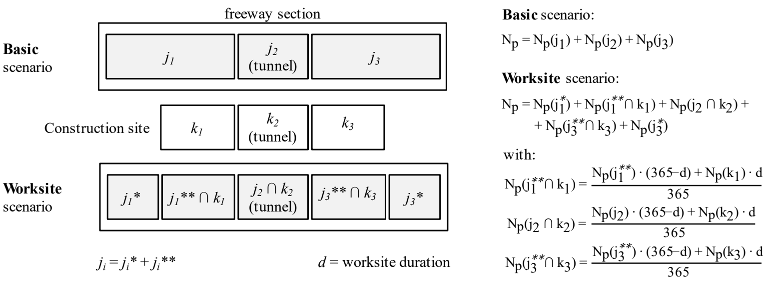

Fig. 2. Schematic framework for the hazard calculation (road accident and traffic risk).

4.2. Vulnerability definition

In the literature, there is no univocal definition of vulnerability, mainly because it has generally been defined in relation to the type of event that occurred (Balijepalli and Oppong, 2014). The definition of road/infrastructural vulnerability followed in this paragraph relies on the resistance of the infrastructures, both material and immaterial, when an external event (able to affect the road/infrastructural system performances) occurs (Russo and Vitetta, 2006; Berdica, 2002). As an example, the collapse (even partial) of a tunnel or a bridge reduces the accessibility of some zones and causes an increase of the travel time in the transport system. Therefore, it appears to be evident that the vulnerability assessment is useful in the planning phase, both for the maintenance of the road network and for the preparation of alternative plans to be implemented to reduce the effects of an event on the system. Furthermore, it must be taken into account that not all links of the network have the same importance in the vulnerability assessment.

Vulnerability can be measured through a series of indices, typically based on the cost or on the distance. An example of indicators usable for vulnerability, based on generalized cost, is as follows:

$$T_l = \sum_r d_r \cdot (c_r - \hat{c}_{rl}) \tag{10}$$

This formulation, where sum is extended to all the origin-destination pairs *r*, considers the demand d_r and the variation in the shortest route cost (c_r) when a link *l* is not available ($\hat{c}_{rl}$).

4.3. Exposure definition

The exposure factor here refers to the vehicular flows affected by a disturbance (such as a construction work site) on the road network. The exposure analysis aims at determining the extent of the impacts of the disturbance for each homogeneous section of the considered network and for each time interval of analysis. These impacts are measured in terms of:

- Modifications in the Level of Service (LoS) of the infrastructure (HCM, 2010)
- Changes in queue generation phenomena (queue length and number of vehicles involved)
- Variations in travel times (duration of delays and idle time).

The variables describing the flow and queue conditions are obtained through a dynamic microsimulation model (Wiedemann, 1974). The assignment of travel demand (vehicles) to transport supply (infrastructure) is primarily based on four sub-models: a path choice model, for modeling decisions regarding which road alternatives to take (if there is more than one); a car-following model, for modeling traffic flow on a single lane and its evolution over time; a lane-changing model, for modeling drivers' decisions on the opportunity to change lanes; a gap-acceptance model, for modeling drivers' decisions regarding the timing of merging into a traffic flow. Therefore, a probabilistic model is used to characterize exposure based on the following random variables: vehicle interarrival times in the network, perceived utilities associated with alternative paths, desired travel speeds.

As regards the interarrival times, it can be assumed that the average time gap between two vehicles is derived from the observed hourly flow (i.e. traffic counts), representing the mean value of a negative exponential distribution. The interarrival times are therefore obtained from this distribution, which corresponds to a Poisson distribution.

For the perceived utility associated with routes, it is assumed that the choice of a route among the possible alternatives is based on the generalized cost of routes (U_j), i.e. the so-called perceived utility of route j in discrete choice theory. Specifically, it depends on systematic utility (V_j), which includes measurable characteristics (X_j) such as travel times, distance traveled, and toll costs, as well as other unobservable factors (including decision-maker-specific ones) represented by random residuals (ε_j) (Cascetta, 2009):

$$U_j = V_j + \varepsilon_j = \sum \beta X_j + \varepsilon_j \tag{11}$$

The most used function to model discrete choice behavior is the Logit function, which estimate the probability that route j is chosen among the alternatives in the choice set I as:

$$Prob(j) = \frac{\exp(\mu V_j)}{\sum \exp(\mu V_i)} \tag{12}$$

With the Logit model, it is assumed that the random residuals are independently and identically distributed according to a Gumbel random variable with zero mean and parameter μ. The sensitivity parameter μ determines the strength of the distribution's reaction to utility differences (Cascetta, 2009).

Finally, desired transit speeds are associated with each vehicle class (e.g. light and heavy vehicles), with a normal distribution function whose parameters are calibrated based on observed traffic data on the network.

Through the probabilistic treatment of exposure, it is possible to estimate the probabilities of changes in the LoS, queue generation and variations in travel times.

4.4. Quantification of road accident and traffic risk

In order to achieve a comprehensive estimation of the road accident and traffic risk, a homogenization of hazard, vulnerability and exposure inputs is necessary. To this aim, a monetary conversion of such findings is proposed in order to quantify the social and economic impacts on the society, arising from the increase in road accidents and traffic risk due to the presence of working sites; specific Italian ministerial guidelines are considered to this purpose

(Ministero delle Infrastrutture e dei Trasporti, 2012), (Ministero delle Infrastrutture e dei Trasporti, 2017). In particular, the former provides the monetary losses associated to fatal, injury or non-injury accidents while the latter is taken into account to estimate the monetary impacts due to the increase in travelling time and traffic congestion.

5. Conclusion

The current approach to tunnel maintenance, particularly in critical situations, foresees the execution of specific, temporary, local measures. Designed as temporary safeguards, these measures stabilize the tunnel while permanent solutions are being planned and executed. However, as they are often conceived in response to emergencies, they lack comprehensive studies and need the installation of significant construction sites in the tunnels, which disrupts traffic flow, inadvertently increasing road accident and traffic risk. To effectively manage these interventions, it is crucial to consider both road accident-traffic and geotechnical-structural risks. The methodology presented in this article offers a comprehensive risk analysis of existing freeway tunnels, considering both factors to devise strategies that minimize the global risk. The proposed approach helps in identifying situations where the geotechnical-structural risk is relevant and temporary safety measures are required. Evaluating the road accident-traffic risk enables:

1. In high geotechnical-structural risk scenarios, short-term planning of temporary measures to limit the increase of road accident and traffic risk.
2. In scenarios with negligible geotechnical-structural risk, long-term planning for definitive interventions that minimize road accident and traffic risk.

Looking ahead, an integrated management approach for existing infrastructure is essential. This approach should encompass general planning for interventions across various assets (e.g., tunnels, bridges, barriers, pavements, etc.). Planning should not be compartmentalized; instead, a holistic view is needed. All significant interventions on a network section should be based on a common road accident/traffic risk assessment and considering specific risks associated with different critical elements (structural, geotechnical, hydraulic, etc.). The goal of this approach should be the minimization of the overall risk for users.

References

AASHTO. (2010). *Highway safety manual.* National Research Council (US). Transportation Research Board.

Balijepalli, C. &. (2014). Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas. *Journal of Transport Geography, 39*, 145-155. doi: https://doi.org/10.1016/j.jtrangeo.2014.06.025

Berdica, K. (2002). An introduction to road vulnerability: what has been done, is done and should be done. *Transport Policy, 9*, 117-127. doi:https://doi.org/10.1016/S0967-070X(02)00011-2

Cafiso, S. D., Montella, A., D'Agostino, C., Mauriello, F., & Galante, F. (2021). Crash modification functions for pavement surface condition and geometric design indicators. *Accident Analysis & Prevention, 149*, 105887.

Cascetta, E. (2009). *Transportation Systems Analysis: Models and Applications* (2nd ed. ed.). Springer US. doi:https://doi.org/10.1007/978-0-387-75857-2

Consiglio Superiore dei Lavori Pubblici, Commissione Permanente per le Gallerie - "Relazione annuale al Parlamento ai sensi dell'art.15, comme 4,Interventi di adeguamento delle gallerie stradali realizzati nell'anno 2011 e previsti per l'anno 2012. (2012, giugno 30). Roma.

Domenichini, L., & Caputo, F. J. (2016). *Sicurezza in Galleria.* Forlì: Egaf Edizioni.

HCM, 2. (2010). *Highway Capacity Manual.* Washington, D.C.: Transportation Research Board.

Lemke, K. (2000). *Road Safety in tunnel.* Brno: Young Researchers Seminar.

Ministero delle Infrastrutture e dei Trasporti. (2012). *Costo sociale medio per incidenti gravi.* Decreto Dirigenziale n. 189 del 24/09/2012.

Ministero delle Infrastrutture e dei Trasporti. (2017). *Linee guida per la valutazione degli investimenti in opere pubbliche nei settori di competenza del Ministero delle infrastrutture e dei trasporti.* Decreto Ministeriale n. 300 del 16/06/2017.

PIARC. (2016). *Comité technique 3.3 Exploitation des tunnels routiers / Technical Committee 3.3 Road Tunnel Operation.*

Russo, F. &. (2006). Risk evaluation in a transportation system. *International Journal of SDP, 1*, 170-191. doi:https://doi.org/10.2495/SDP-V1-N2-170-191

Sayed, T., & de Leur, P. (2008). *Collision modification factors for British Columbia.* Prepared for Engineering Branch BC Ministry of Transportation and Infrastructure.

Schubert, M., Høj, N. P., Köhler, J., & Faber, M. H. (2011). *Development of a best practice methodology for risk assessment in road tunnels.* Norwegian Public Roads Administration.

Smadi, O., Souleyrette, R. R., Ormand, D. J., & Hawkins, N. (2008). An analysis of the safety effectiveness of pavement marking retroreflectivity. *Transportation Research Record*.

Wiedemann, R. (1974). *Simulation des Straßenverkehrsflusses.* Karlsruhe, Germany: Institut für Verkehrswesen der Universität Karlsruhe.