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Road Tunnel Safety Evaluation and Crash Analysis: Experiences from Serbia

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Abstract: Road tunnels represent critical sections of the transport infrastructure where the risk of traffic crashes and fire incidents is significantly increased due to confined space, specific geometry, and limited visibility and ventilation conditions. This paper presents an analysis of traffic crashes that occurred on the motorway network in the Republic of Serbia during the period 2020–2024, with a special focus on the Šarani and Lipak tunnels. Data from the national crash database and the internal records of the public enterprise "Roads of Serbia" were used to identify the most frequent crash types and related risk factors. Although crashes in tunnels account for less than 0.1% of all recorded crashes, they show a notably higher proportion of severe outcomes. The analysis includes factors such as lighting conditions, pavement surface, traffic signalization, and the functionality of safety equipment. Furthermore, the paper outlines the national methodology for conducting Road Safety Inspections (RSI) in tunnels, harmonized with the current PIARC recommendations and the Serbian Rulebook on tunnel safety requirements. The results highlight the need for systematic monitoring of tunnel safety equipment and the implementation of risk-management measures to enhance the safety of road users in closed traffic environments.

Keywords: road tunnels, traffic safety, road safety inspection, Serbia

1. INTRODUCTION

Road tunnels represent some of the most complex and safety-sensitive elements of modern road infrastructure. Their confined geometry, reduced visibility, and restricted space for maneuvering pose particular challenges to drivers and to those responsible for their safe operation. Although accident frequencies in tunnels are typically lower than on open roads, the consequences of incidents that occur are often much more severe due to limited escape routes, potential fire and smoke accumulation, and difficult access for rescue services (Lemke, 2000; Nussbaumer, 2007).

Numerous international studies have addressed various aspects of tunnel safety. Early research by Vashitz, Shinar, and Blum (2008) emphasized the role of in-vehicle information systems in enhancing driver awareness in tunnels. Ma, Shao, and Zhang (2009) analyzed accident data from Chinese freeway tunnels, highlighting distinct risk patterns compared to open-road environments. The impact of vehicle fires has also been the subject of numerical modeling by Caliendo et al. (2012), whose simulations of heavy-goods-vehicle (HGV) fire scenarios underscored the importance of tunnel geometry and ventilation design for user safety. Behavioral studies, such as

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Yeung and Wong (2014), explored car-following behavior in tunnels, revealing longer headways and lower speeds as typical adaptive responses to confined driving conditions.

Other authors have focused on the environmental and operational dimensions of tunnel safety. Li et al. (2015) investigated pollutant dispersion and its interaction with traffic flow, while Lu et al. (2015) identified key risk factors influencing the severity of crashes in Shanghai river-crossing tunnels. Bassan (2016) provided an overview of tunnel design principles and their influence on driver behavior and accident risk. Hou, Tarko, and Meng (2017) advanced this line of research through a correlated random-parameters model to explain crash-frequency variations across tunnel sections. More recent simulation-based studies, such as Król and Król (2021), have examined fire and evacuation dynamics in urban tunnels, confirming the need for integrated safety systems that combine engineering, operational, and behavioral perspectives.

Collectively, the literature shows that tunnel safety depends on the interaction between human behavior, infrastructure design, and traffic management measures. Following the EU Directive 2004/54/EC on minimum safety requirements for the Trans-European Road Network, many European countries have introduced systematic inspections and harmonized technical standards for tunnel safety.

1.1. Tunnel safety in Serbia

In Serbia, the expansion of motorway infrastructure in the past decade has introduced several long and complex tunnels, particularly along Corridors X and XI. Managing safety in these facilities has therefore become a strategic priority. In response, a national methodology for Road Safety Inspections (RSI) in tunnels was developed in 2022 (Lipovac et al., 2023; Smailović et al., 2023), based on PIARC and SEETO guidelines and harmonized with national regulations (Official Gazette RS 51/19, 52/19). The first complete RSI campaign was carried out in 2023, covering ten motorway tunnels on the state road network (Predajane, Manajle, Sarlah, Lipak, Šarani, and others).

Each inspection was conducted by a multidisciplinary team—comprising traffic, civil, mechanical, electrical, and fire-safety engineers—and included both video-based assessments under regular traffic and detailed pedestrian walkthroughs during scheduled closures. The inspection process evaluated over 15 categories, including geometric characteristics, lighting, ventilation, drainage, signage, ITS equipment, and passive safety features. Results were classified according to the risk level (low, medium, high) and accompanied by proposed countermeasures and cost categories (Antić et al., 2021; Smailović et al., 2021).

Parallel to the inspection activities, the Road Traffic Safety Agency of Serbia (ABS) provided data on traffic crashes in tunnels during the period 2020–2024. A total of 197 crashes were recorded, of which 6 were fatal and 81 involved injuries. The majority of crashes were single-vehicle loss-of-control events and rear-end collisions, indicating that driver behavior, inappropriate speed, and limited visibility are the main contributing factors. In more than 80% of cases, human factors were identified as the primary cause, while infrastructure and technical issues accounted for a smaller but still notable share—particularly near tunnel portals, where abrupt changes in luminance and speed adjustments occur.

1.2. Aim and scope of the study

This paper combines international research findings with national inspection and crash data to provide an integrated overview of tunnel safety and to identify practical directions for improvement. Specifically, it aims to:

- Present key insights from recent international studies on tunnel safety and human factors;
- Summarize the main findings from the 2023 RSI campaign in Serbian motorway tunnels;
- Analyze crash data from the ABS database (2020–2024) to identify prevailing accident types and causal factors; and
- Propose a set of targeted measures to enhance safety and operational resilience.

By linking engineering inspections, operational incident analysis, and real-world crash statistics, the study seeks to highlight the importance of a systematic, data-driven approach to tunnel safety. The ultimate goal is to contribute to the development of a comprehensive tunnel-safety framework applicable both to interurban motorways and to future urban underground corridors, in line with the ACUUS 2025 conference theme Safety, Security and Human Factors.

2. METHODOLOGY

2.1. Inspection scope

Inspections covered ten motorway tunnels on Class IA state roads and the corresponding influence zones extending up to 500 m from each portal, in both directions. This range was defined as the upper limit of the area potentially affected by tunnel systems or by changes in driving behavior when entering or exiting a tunnel.

The inspected tunnels included:

- **A1 corridor:** Predajane and Manajle (both tubes) and Železnik (right tube);
- **A2 corridor:** Veliki Kik, Savinac, and Brđani (both tubes);
- **A4 corridor:** Progon, Pržojna Padina, Sopot, and Sarlah (both tubes).

2.2. Field procedure

Inspections were conducted in two stages:

1. Drive-through surveys under regular traffic conditions, carried out during daylight hours with continuous video recording and commentary from the inspection team;
2. Detailed pedestrian walkthroughs, performed during planned closures of single tunnel tubes. These sessions included visual inspection, measurements, testing of installations, and documentation of observed problems.

All fieldwork was coordinated with tunnel operators and maintenance companies responsible for system testing and routine safety checks.

2.3. Elements and structure of assessment

Each tunnel was examined using a structured checklist covering all elements relevant to traffic safety and system operation.

The analysis included both the tunnel tubes and adjacent open sections, divided into thematic chapters corresponding to the standard RSI report format:

- Road function and classification;
- Cross-section and alignment;
- Pavement and drainage condition;
- Intersections and service facilities within the influence area;
- Needs of vulnerable road users (where applicable);
- Traffic signs, markings, and ITS systems;
- Lighting and visibility conditions;
- Roadside environment and passive-safety elements;
- Electrical, telecommunication, and optical-cable installations;
- Ventilation and fire-detection systems;
- Fire-suppression equipment and emergency facilities;
- Response systems for incident detection and notification.
- For each observed issue, inspectors recorded:
- the description of the deficiency;
- potential risk to road users;
- recommended corrective or mitigating measure;
- indicative cost category for implementation.

Risk levels were determined through expert evaluation, considering tunnel geometry, traffic characteristics, previous incident records, and possible accident consequences. Each issue was rated on a three-level scale: low, medium, or high risk. This classification provided a clear overview of priority problems and ensured systematic treatment of interrelated safety issues.

2.4. Incident database

Part of the analysis focused on operational data obtained from PE “Roads of Serbia”, covering extraordinary events and incident situations recorded in tunnel areas between 2016 and 2023. Each event was described by its type, duration, location, and brief circumstances. Two additional variables were added for analysis:

- Risk level, estimated by expert judgment based on event description and context;
- Cause category, defining whether the incident was related to driver behavior, technical malfunction, environmental influence, or maintenance activity.

A total of 5,411 incidents were included, comprising 3,997 traffic events and 1,414 equipment failures. The purpose of the analysis was not to assign responsibility but to identify groups of factors and recurring patterns that could influence safety performance and to provide supporting data for RSI interpretation.

2.5. Crash database

To complement field observations, crash data were collected from the Road Traffic Safety Agency (ABS) for the period 2020–2024. The dataset included all crashes that occurred inside tunnels and within their approach zones. Each record contained information on crash type, contributing factors, number of vehicles involved, injury severity, and location referenced to the national road network.

Crashes were categorized by mechanism (single-vehicle, rear-end, lane-change, pedestrian, and stationary-object collisions) and by primary contributing factor (human, road, technical, or environmental). Spatial coordinates and chainage data were used to align crash locations with RSI findings for subsequent analysis.

2.6. Data organization and integration

All collected information—inspection results, incident records, and crash data—was harmonized within a unified analytical framework. Data from different sources were standardized, coded, and georeferenced to ensure comparability. Descriptive statistics and qualitative coding were applied to prepare datasets for correlation analysis in the next phase of research. The integration of these datasets made it possible to link infrastructure conditions with real-world operational and safety performance, providing the basis for the results presented in the following section.

3. RESULTS

3.1. Overview of inspection findings

Road Safety Inspections conducted in 2023 confirmed that tunnel sections on Class IA state roads generally meet the required technical and safety standards. However, several recurring issues were identified, particularly in the zones of tunnel portals and emergency facilities.

The most common deficiencies included:

1. Insufficient or non-adaptive lighting at portal areas (Figure 1) – pronounced luminance contrast between external daylight and the interior of the tunnel, causing temporary glare and reduced visibility during entry or exit.
2. High curbs and unsafe edges of evacuation paths (Figure 2) – excessive curb height and abrupt transitions between the traffic lane and the pedestrian escape walkway, which can destabilize vehicles and hinder evacuation.
3. Unsafe positioning of electrical and control cabinets within the traffic zone (Figure 3) – cabinets and technical installations placed on tunnel walls inside the dynamic envelope, posing both passive-safety and operational-reliability risks in the event of impact.
4. Inadequate visibility and damaged or faded vertical signage (Figure 4) – reduced retroreflectivity and contrast of signs, combined with uneven lighting at portal areas.
5. Unprotected wall surfaces of emergency-stop niches (Figure 5) – lack of passive-safety elements or energy-absorbing protection, increasing the potential severity of collision impacts.
6. Limited space for emergency stops and lay-bys in longer tunnels (Figure 6) – insufficient width or depth of the stopping area preventing complete vehicle pull-off, especially for heavy goods vehicles.
7. Presence of passively unsafe obstacles (Figure 7) – rigid elements such as concrete edges, steel frames, or unprotected equipment located close to the traffic lane without deformable or shielding protection.

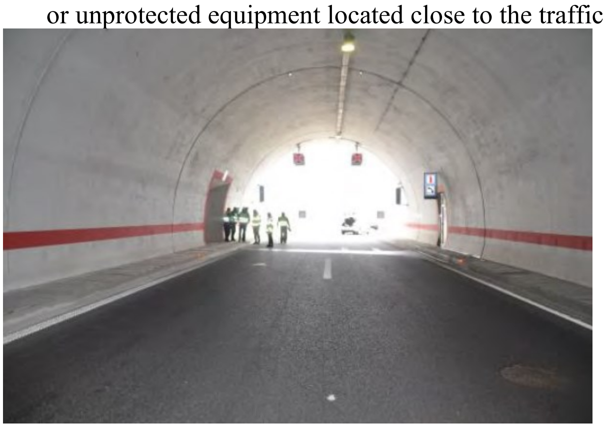

Figure 1. *Insufficient or non-adaptive lighting at portal areas,*

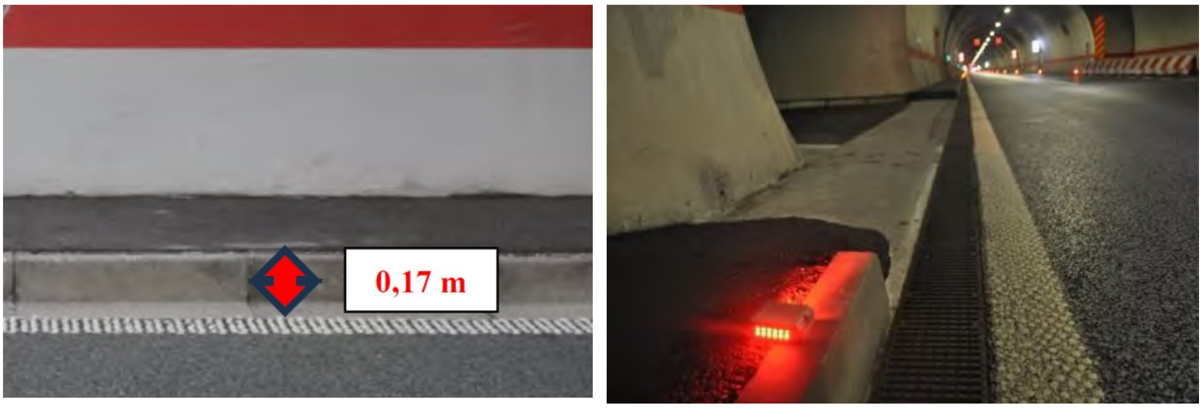

Figure 2. *High curbs and unsafe edge of the evacuation path*

Figure 3. *Unsafe positioning of electrical and control cabinets in the traffic zone*

Figure 4. *inadequate visibility and damaged or faded signage*

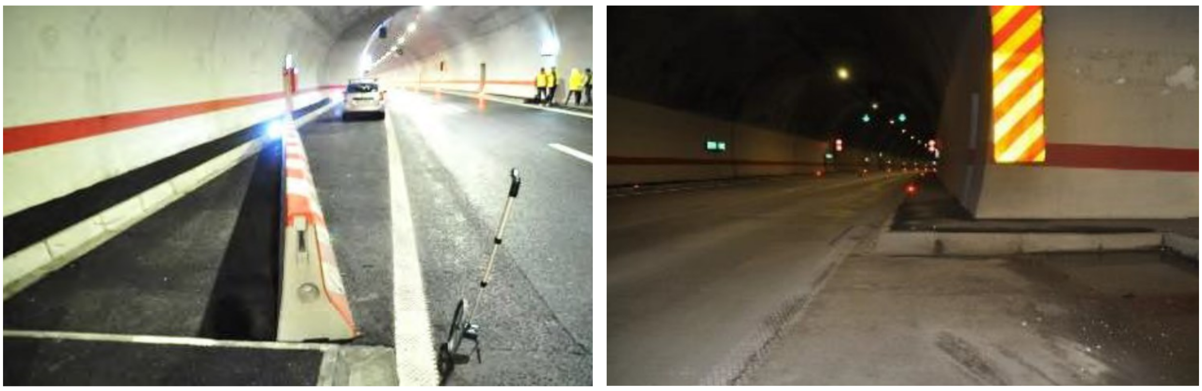

Figure 5. *limited space for emergency stops and lay-bys in longer tunnels*

Figure 6. *Unprotected wall of emergency stop niche*

Figure 7. *Passively unsafe obstacle*

3.2. Incident analysis

The database provided by PE “Roads of Serbia” contained 5,411 incident records for motorway tunnels between 2016 and 2023. Incidents were divided into four main categories: human-related, technical, environmental, and maintenance-related. Table 1 shows their distribution by cause and risk level, following the same format used in the 2024 national study.

Table 1. *Distribution of recorded incidents in motorway tunnels (2016–2023)*

Type of incident	Number of events	Share (%)	Dominant risk level	Typical examples
Driver-related	1,837	34.0	Medium	Stopped vehicles, pedestrians, wrong-way driving
Technical failures	1,414	26.1	High	Power supply interruption, lighting or ventilation failure
Environmental influences	1,051	19.4	Medium	Fog, ice, water leakage, low visibility
Maintenance and planned closures	1,109	20.5	Low	Cleaning, system testing, repair works
Total	5,411	100.0	—	—

About one third were driver-related, most often involving stopped vehicles (46%), pedestrians (18%), cyclists (4%), wrong-way or reverse driving (4%), and traffic crashes (15%). Such events typically occur in confined tunnel spaces where there is no shoulder or safe refuge. Among technical incidents, the most frequent problem was power supply interruption—present in 92% of recorded equipment failures—indicating the importance of reliable and redundant electrical systems.

Incidents caused by maintenance activities represented about one fifth of all cases and were generally low to medium in risk, while environmental influences were linked mainly to snow (43%), fog (32%), and ice (14%), usually in portal zones.Seasonal and daily variations were evident: most incidents occurred in summer (29%) and winter (32%), during morning (39%) and afternoon (28%) hours. Slightly higher frequencies were observed on Tuesdays (16%), Thursdays (14%), and Sundays (12%). About 60% of incidents lasted less than two hours; longer ones—often linked to adverse weather, power loss, or vehicle stoppage—had wider operational effects. Risk assessment showed that 45% of all events were rated as high-risk, mostly those involving pedestrians or wrong-way movements.

Roughly 35% of incidents could be attributed directly to user behavior, while others stemmed from environmental or system-related factors. Overall, the analysis confirms that tunnel safety depends equally on user discipline and system reliability.The clear seasonal and temporal peaks emphasize the need for adaptive management measures such as controlled lighting, variable speed limits, and automated incident detection to ensure stable safety performance year-round.

3.3. Crash analysis

Crash data from the Road Traffic Safety Agency (ABS) covered the period 2020–2024 and included all reported crashes that occurred within tunnel zones. A total of 197 crashes were recorded, of which 6 were fatal, 81 involved injuries, and 110 resulted only in material damage. The annual distribution of crashes is shown in Table 2.

Year	Fatal crashes (F)	Serious injuries (S)	Slight injuries (L)	Property damage only (PDO)	Total
2020	0	3	11	21	35
2021	4	9	13	28	54
2022	0	2	13	18	33
2023	1	4	5	14	24
2024	1	8	12	30	51
Total	**6**	**26**	**54**	**111**	**197**

The data show a fluctuation in annual crash frequency, with a clear peak in 2021 and a gradual stabilization in the following years. Fatal outcomes remain rare, but injury crashes represent more than 40% of all recorded cases, confirming that tunnel environments, although relatively safe in terms of frequency, can lead to severe consequences when crashes occur. When classified by type, single-vehicle crashes were most common (75 cases), followed by rear-end collisions (50), lane-change or overtaking conflicts (17), pedestrian crashes (6), and crashes with stationary vehicles or obstacles (4).

This pattern corresponds to the typical conditions of limited space, reduced visibility, and the absence of safe recovery zones inside tunnels.

4. DISCUSSION

The results of inspections, incident records, and crash analysis show that the safety level in Serbian motorway tunnels is generally satisfactory, but several recurring problems limit operational reliability and user safety. Most identified issues are linked to lighting quality, visibility, passive safety, and user behavior, rather than to major design or structural deficiencies.

Lighting and visibility stand out as a key factor. Non-adaptive lighting near portals creates sharp contrasts between external daylight and the tunnel interior, leading to temporary glare and reduced reaction time. This corresponds with the large share of single-vehicle crashes and driver-related incidents, confirming that visibility management directly affects driver performance.

Passive-safety elements such as high curbs, unprotected walls of stop niches, and rigid obstacles increase the consequences of errors rather than their frequency. Even when crash speeds are moderate, contact with these rigid structures can lead to severe damage. Improving edge profiles, adding protective barriers, and introducing energy-absorbing surfaces in lay-bys would significantly reduce impact severity.

Technical reliability also plays a major role. Nearly all equipment failures were caused by interruptions in power supply, emphasizing the need for redundant systems and better maintenance coordination. Although such failures are relatively rare, they can quickly escalate into safety-critical situations if lighting or ventilation is lost during heavy traffic.

Human behavior and operational control remain decisive. More than one third of all incidents were caused by drivers—mostly stopped vehicles, pedestrians, or wrong-way entries—showing that even well-designed tunnels require constant monitoring and rapid operator response. Automated Incident Detection (AID) and real-time surveillance are essential to shorten reaction times and prevent secondary collisions.

Seasonal and daily patterns of incidents suggest that tunnel safety management should adapt to changing conditions. High frequencies during summer and winter, and during morning and afternoon peaks, indicate that operational regimes—lighting, ventilation, and variable speed limits—should be dynamically adjusted according to traffic intensity and weather.

Comparing these findings with international studies confirms the same trend: tunnels generally record fewer crashes than open-road sections, but the severity of outcomes is higher due to confined space and lack of recovery areas. This pattern highlights the importance of risk mitigation measures, not only through infrastructure upgrades but also through operational management and user awareness.

In summary, the results emphasize three main priorities for improving tunnel safety in Serbia:

- Enhancing visibility and adaptive lighting, especially in transition zones at portals;
- Upgrading passive-safety elements and protecting technical installations within the traffic envelope;

- Strengthening operational reliability through redundant power systems, continuous monitoring, and automated incident detection.

Together, these measures form a practical basis for improving both user protection and the overall resilience of tunnel infrastructure on the national motorway network.

5. CONCLUSION

The conducted inspections and analyses show that the general technical condition of Serbian motorway tunnels is satisfactory, yet several recurring deficiencies continue to affect operational safety. Most of these problems are not structural but functional and behavioral, arising from limited visibility, insufficient passive protection, or inadequate user response in critical situations.

The findings highlight that tunnel safety cannot rely solely on design compliance—it depends equally on real-time monitoring, adaptive control, and user behavior management. Power-supply interruptions, non-adaptive lighting, and driver-related incidents remain the dominant risk factors, each requiring a tailored technical response.

In this context, smart technologies can play a decisive role. Automated Incident Detection (AID), variable speed management, adaptive lighting control, and integrated traffic supervision platforms represent key tools for timely response and prevention. These systems directly address the main causes identified in this study—human error, visibility changes, and delayed operator intervention—by providing early warnings and automatic countermeasures.

Future improvements should therefore focus on:

- Integrating AID and tunnel management systems to ensure rapid detection of stopped vehicles, pedestrians, or wrong-way movements;
- Introducing adaptive lighting and variable message signs that respond to external light, traffic density, and weather conditions;
- Enhancing redundancy of power and communication networks to maintain functionality during failures;
- Applying data-driven safety management, combining inspection reports, incident logs, and crash databases for continuous risk monitoring.

By linking traditional engineering measures with intelligent systems, tunnel safety management can evolve from reactive maintenance toward proactive, resilience-based operation.

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