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Challenges in electrical and mechanical asset renewal in established road tunnels

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ABSTRACT: This paper examines challenges in electrical and mechanical asset renewal in established road tunnels to address evolving risk profiles. As infrastructure ages, both technological advancements and changes in the operating context necessitate updating systems to maintain operational efficiency and mitigate emerging hazards. Changes in traffic patterns, vehicle emissions, and safety regulations have altered the risk landscape are explored, as well as their impact on existing systems, flagging where aging assets may no longer meet modern standards or operational demands. Additionally, integration of new technologies, products and materials, to enhance system reliability and ensure a safe and efficient tunnel environment are discussed. Stakeholder and client engagement is also discussed as a key to ensure technical requirements are updated for asset renewal. Proactive asset renewal and revision of original provisions are essential to manage system failure risk, improve resilience to changing conditions, and to ensure regulatory compliance.

1 INTRODUCTION

Technical specifications for the different engineering systems that make up a road tunnel are numerous, requiring a mechanism to clearly articulate what is expected from each of them. Most of these technical specifications are formulated in terms of an explicitly stated performance requirement (e.g. the tunnel drainage system shall withstand a rain event of a specified severity) or outright prescribed (e.g. the tunnel must be equipped with a linear heat detection system). These technical specifications are drafted on a case-by-case basis and reflect the available technology and current industry practice for design and construction, as reflected in publications such as AusRoads and PIARC [1-2].

Although of a technical nature, these specifications are embedded in contractual documents drafted as part of tenders for the tunnel design and construction, some of which in Australia have taken the form of Public Private Partnerships (PPP) [3]. As described by Bjelland et. al. [4] these documents constitute a Scope of Works and Technical Contract (SWTC) or PSTR (Project Scope and Technical Criteria) which are then delivered by a design and construction entity, typically a joint venture, at a significant cost. Using as reference, six established tunnels in Australia, this cost can range between 33 and 730 million dollars per km [3]. Such variability can be related to the design and construction complexities due to the scale of such projects, which in Norway (a country known for its technical proficiency and its catalogue of impressive tunnel projects) has led to a significant increase in legal disputes, the top reasons being 1. Understanding of the tender specification and contract, 2. Payment related and 3. Changes in projects [5].

The SWTC provisions, as well as any related operating license, are meant to be fulfilled by the time the tunnel is operating and few include mechanisms to update or modify the established requirements, as this could negatively impact the tunnel risk profile. As such, mechanisms for modifying the SWTC provisions rely on an entity -typically the operator- putting forward a request for modification to the asset owner.

Despite the lack of a mechanism to review and update the technical specifications, the reality of any operating infrastructure is that it will age, deteriorate and be exposed to changes in regulation, technology advancements, and changes in operational demands. As such, Mechanical and Electrical (M&E) systems should be renewed (restored to its original condition) or modernised to ensure continued functionality and safety as these changes materialise. These drivers for renewal or modernisation of M&E assets often clash with the lack of effective mechanisms to review and update the original technical specifications, creating a risk to the end user of the roads.

This paper explores the main challenges faced in renewing M&E assets in established road tunnels and analyses the impact of aging infrastructure on operational efficiency and safety. It also outlines various influencing factors contributing to the evolving risk profile of road tunnels and addresses the complexities associated with modernising these assets in accordance with SWTC provisions and constraints. Finally, this paper considers the role of stakeholder engagement in updating technical specifications is examined, along with the need for a proactive approach to mitigate future risks.

2 CHANGES TO VEHICLE FLEET

Stricter environmental regulations have led to a decline in vehicle emissions as shown by the distribution of emissions intensity of vehicles sold between 1991 and January 2024. This indicates a drop in the national average emissions (CO_2) intensity from close to 350 to just shy of 150 g/km, constituting a change close to -60% in three decades [6]. This downward trend in vehicle emissions will continue, given the national and international commitments to lower carbon footprints and the larger proportion of electric vehicles within the total vehicle fleet. With regards to regulation, it was only in 2024 when Australia imposed CO_2 emission standards which will see a decrease from 141 g/km in 2025 to 58 g/km in 2029, targeting net zero emissions by 2050 [7]. Other vehicle emissions such as CO and NO_x have been decreasing by the combined effect of regulations, vehicle engine developments and fuel improvements.

2.1 *Impact on tunnel ventilation systems*

For a road tunnel built in the late 1990s, this means its ventilation system would be overdesigned by at least 20% once the vehicle fleet in the 2020s was in operation. If said road tunnel was to be equipped with five axial fans for pollution management, this change in the operating context could translate into one of these fans going from duty to stand-by. The impact of such change would provide additional margin in the Minimum Operating Requirements and could lead to a change in the asset lifecycle model, potentially freeing up a capital expenditure allocation to enhance the ventilation system or to cover requirements from other systems.

This is a simplification where only emission rates are considered, though many other variables such as specific tunnel layout and traffic volume would also need to be considered to make an informed decision to drive a modification to the original ventilation system. Traffic volume in Australia has seen a constant growth ranging from +9% (Hobart) to +41% (Perth) and a national increase of 30% measured in vehicle-kilometre travelled (VKT) in the period of 2002 to 2020 [8]. This increase could offset the emissions reduction to date, however further decrease in emissions and the potential for a net zero future could lead to a scenario where current ventilation systems will be oversized.

As the trends above continue to develop, it is possible to contemplate changes to the original ventilation requirements, if not to reduce its capacity, to at least operate them in a more optimised fashion as demonstrated by industry case studies [9]. As most of the tunnels were designed and built in the early 2000s, the ventilation requirements were driven by CO/CO_2 emissions and visibility, with the fleet change described above shifting this towards a drive from NO_x emissions.

2.2 *Changing fire risk*

As the emission profile improves with the advent of electric vehicles and alternative energy carriers, new risks also emerge which can impact the risk profile of the tunnel and both the demand and effectiveness of fire safety provisions. The increased presence of battery electric vehicles (BEVs) with lithium-ion batteries introduces different fire hazards to the tunnel environment compared to conventional internal combustion engines. This change should trigger a risk assessment process to understand the new hazard and associated scenarios under the constraints of available information and then identify the need for new or enhanced controls.

Both accidents and research campaigns have shown that BEV fires do not behave as their internal combustion engine (ICE) counterparts and can present a particularly challenging set of conditions in an enclosed space [10]. A list of non-exhaustive relevant facts about electric battery fires are presented below and their impact to the risk profile of the tunnel:

- BEV fires do not require external oxidisers to sustain a combustion reaction as its electrolyte produces them once this is broken down by excessive heating, which fundamentally alters the way in which ICE fires can be tackled such as by means of smothering the fire by applying a fire blanket over the vehicle until the oxygen is depleted.
- BEV fires occur due to a runaway exothermal chemical reaction in which the affected battery cells heat up their neighbouring cells and break down their electrolyte, anode and cathode, producing both fuel and oxidiser, which can accumulate and pressurise. Upon finding relief, the gases are expelled and can lead to jet fires or vapour cloud explosions, scenarios that are not contemplated within a tunnel design for fire safety.
- BEV fires detection is hindered due to battery location and encasing, which can limit the ability to detect such fires through existing detection technology such as CCTV cameras, automatic video detection and linear heat detection.
- BEV fires produce about 10x the amount of hydrofluoric acid (HF) than its ICE counterparts [11], posing a threat to first responders and requiring the tunnel operation to use the available ventilation system to dilute and displace such concentrations where possible.

Based on statistics from five countries with a high uptake of BEVs, the likelihood of a fire event involving the battery seems to be ~10 times less likely compared to that of ICE vehicles [12]. Although positive, such observation does not account for the aging of batteries, which as yet is not an influencing factor due to the recent uptake of the technology. Over the next five to ten years, an increase in EV fire incidents is anticipated, particularly if unauthorised repairs and batteries are utilised, as has been the case for personal mobility vehicles.

3 EMERGENCE OF NEW AND BETTER PERFORMING TECHNOLOGIES

Despite best efforts to look ahead, SWTC and designs are constrained by available technology, effectively becoming a snapshot in time of current engineering practice for ventilation, lighting, power supply and all other systems making up the M&E assets. As time goes by, research and development leads to the emergence of new technologies, while some problems are better understood and reformulated. Reassessing original designs in light of newly available pathways to address a particular tunnel need present a challenge, exemplified by the examples put forward below.

- LED lights have improved over the years and are now widely used in road and tunnel projects. These would likely replace the existing fluorescent and High Pressure Sodium lights. However, changing from florescent to LED lights would require lighting design revision as LED lights would not be linearly installed as florescent lights. This change is likely not covered in the technical specifications.
- Fire detection in tunnel mainline and ramps is quite a challenge due to the varying air flow, the presence of soot and both the relative humidity and temperature variability. This has led to the adoption in Australia of Linear Head Detection (LHD) as the go-to solution for automatic fire detection, emphasized by limitations on systems relying on field of view such as CCTV and Automatic Video Incident Detection (AVID), including their high rate of false alarms [13]. However, the issues with LHD are the significant delays due to heat transfer and airflow affecting location accuracy. Nowadays video detection technology has evolved to the point that

industry underwriters such as FM have produced standards for such products used in automatic fire alarm signalling [15]. The improvement in video software and technology makes the use of video fire and smoke detection much more reliable than the traditional LHD cable systems used in tunnels, with the acknowledgement that no instances of legitimate fire detections by LHD have been recorded in Australia [16]. The replacement of the linear heat detection system by video-based systems have the potential to improve automatic fire detection capabilities but do challenge the original provisions in SWTCs and existing Australian Standards for fire detection systems (AS1670.1).
- In fire suppression systems, almost all Australian road tunnels have fixed firefighting systems (FFFS), most of which employ deluge (water spray) and have been growing in their application across the world after their uptake in Asia and Australia [17]. Amidst this uptake, concerns about water usage (found within the range of 1-4 kL/min per suppression zone, typically of about 30 m length) and the limitations of water spray (deluge) to address concealed fires (such as in EV fire scenarios) and flammable spill fires (such as in tanker accident scenarios), have led to the introduction of water mist suppression systems. These have been widely available in other industries, through technology development had to wait several decades for readily available commercial solutions such as the one installed in the Heysen tunnel in Adelaide, South Australia [21]. Water mist systems can reduce the water usage demand compared to that from deluge systems (up to around half), with its fire suppression mechanism not relying on wetting the fuel but in effectively removing large amounts of heat generated by the fire and displacing oxygen. Although the specification of the mist parameters remains a challenge and some risks might be introduced (such as flame fanning at the initial application) [13], the technology represents a potential alternative for large, water-intensive, and expensive to maintain deluge systems.
- In tunnel ventilation, the substantial reduction in vehicle emissions presented in section 2.1 of this paper has driven air pollution control to become less of a determining parameter in ventilation system design and selection. Air flow volumes in normal operation would reduce substantially, with the system performance being driven by smoke control and fire safety. In practice, this can lead to less onerous minimum operating requirements and the potential for axial fan removal as a means to optimise long-term maintenance expenditure. Finally, reduced vehicle emissions may offer the opportunity of allowing tunnel air to be exhausted via the portals without significantly affecting ambient air quality, while providing a sustainability benefit of reduced energy use. However, would necessitate an amendment to the project specifications, as portal emissions are currently not permitted in most Australian tunnels.

4 ACCELERATED OBSOLESCENCE AND DEGRADATION

As tunnels age, plant and equipment deteriorate over time. Tunnels are usually rated as a harsh service environment for E&M equipment, especially road tunnels in the coastal states, where air salinity can lead to additional external corrosion. SWTC and O&M manuals typically prescribe the maintenance regimes, which are also based on current practice, known failure modes and on applicable maintenance standards. The provisions are tightly associated to compliance obligations within the SWTC, as well as with each technical authority such as the Electrical Safety Office associated to WorkSafe Australia, the stat based requirements such as those of the Queensland Building and Construction Commission (QBCC), as well as requirements from applicable acts and regulations. Given these compliance requirements, modifying maintenance regimes based on varying risk factors such as the external corrosion and changes in legislation can be challenging. This situation is exemplified by the following examples:
- Fire mains are typically based on galvanised steel, which can be susceptible to external corrosion, particularly if caused by ground water leaks. The normal and typically unpredictable occurrence of ground water in tunnels is not explicitly accounted for in the design of fire mains, nor in the AS1851:2012 requirements for inspection of the pipes. Based on Transurban operational experience, fire mains require condition assessments beyond the standard requirements, increasing operator costs to effectively manage the accelerated corrosion rates.
- Initially used as the go-to gas suppression agent, Halon was used between the 1970s and 1992 when it was phased out after the Montreal Protocol identified it as an ozone-depleting chemical

[18]. Similarly, the gas suppression agent FM-200 (also known as HFC-227ea) is currently undergoing phase-down despite being the main replacement for Halon. Existing gas suppression systems covering high voltage rooms in electrical substations as well as other sensitive equipment such as data rooms are then required to be upgraded, some potentially ahead of their original design life.

Though environmental and health risks associated with per- and polyfluoroalkyl substances (PFAS) was identified since the 1970s, aqueous film-forming foam (AFFF) for fire suppression has been a key fire protection element for hazardous industry as well as for road tunnel sumps, where the potential for hydrocarbon spill exists. In the 2010s, jurisdictions worldwide began efforts to replace 'long-chain' PFAS with 'short-chain' (also known as C8 and C6, respectively), with Queensland doing so through their Operational Policy for the Environmental Management of Firefighting Foam [19]. More recently, a total ban on PFAS with effect from 1 July 2025 was introduced into federal legislation in Australia by adopting the Industrial Chemicals Environmental Management Standard (IChEMS) [20]; this directly impacted all existing AFFF systems and required operators to retrospectively assess the original design requirements of their fire systems and identify viable alternatives as well as their impacts on the firefighting performance and long-term financial aspects.

5 CONCLUSIONS

This paper has presented a series of practical examples on how M&E asset renewal are driven beyond the original provisions of the applicable SWTCs. These renewals are essential to meet the performance requirements of the different mechanical, electrical and fire systems that ensure the road tunnels maintain or improve their risk profile over the decades of their expected service life. Changes in traffic patterns, vehicle emissions, and safety and environmental standards necessitate the updating of outdated systems. By integrating emerging technologies, adopting sustainable materials, and employing a proactive approach, tunnel operators can enhance safety, reliability, and efficiency.

The challenges presented in this paper have a significant impact on renewal projects and the overall asset lifecycle allocations, which in turn can inhibit or enable the adequate operation of critical life safety systems over the many decades of the tunnel design life. In this manner, this paper calls for all relevant stakeholders involved in the development of SWTC provisions to better accommodate the changing landscape and influencing factors for asset renewal.

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