DESIGNING TUNNEL SYSTEMS TO ACCOMMODATE ZERO-EMISSION VEHICLES

A holistic approach to decarbonization and safety considering battery-electric hydrogen-powered vehicles

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Introduction

The drive to decarbonize toward net zero is increasingly guiding decision-making across sectors. How does this imperative affect the design of tunnels and their subsystems in the transition away from fossil-fuel vehicles to battery-electric and hydrogen-powered vehicles? Several WSP tunnel structures and systems experts discuss key considerations and challenges involved.

Electric Vehicle Overview

Silas Li: The drive to achieve net zero emissions has significant implications for the design of road tunnels and their subsystems to ensure safe and reliable operations. It requires careful planning, considerations of battery fire risks, emergency ventilation, fire protection for tunnel structures, emergency response and a holistic approach to decarbonization and safety.

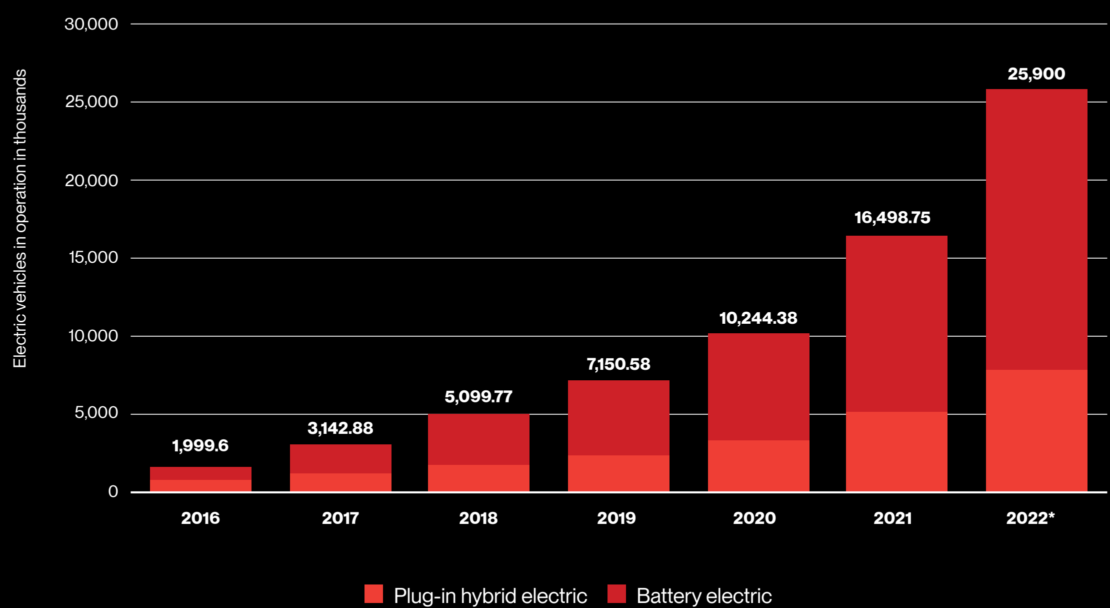
The main alternative fuels at present are hydrogen and battery, with greater adoption of battery. The year 2021 witnessed a remarkable surge in the presence of battery electric vehicles on the road, with over 16.5 million in operation—a threefold increase in just three years.

Similarly, the United States observed a 66 percent growth in the number of zero-emission buses in 2021.[1]

This upward trajectory is anticipated to persist, with electric vehicles projected to become the dominant choice in the US automotive market. By 2030, they are expected to constitute 50 percent of all passenger car sales in the United States.[2]

Xavier Guigas: The rate of replacement is difficult to assess precisely and depends on the country concerned. Mixed fleets will be roaming our tunnels for decades to come as communities around the world continue the transition away from fossil-fuel vehicles to electric vehicles (EVs) and hydrogen vehicles (HVs). We must think now about the consequences of this transition for the design of infrastructure.

Estimated number of electric vehicles in use worldwide between 2016 and 2022, by type (in 1,000s)



Source
IEA
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Additional Information:
Worldwide 2016 to 2022

Diagram source: statista - The International Energy Agency (IEA) Global EV Outlook 2023 includes information on hydrogen-powered vehicles, noting that in 2022 the stock of fuel cell electric vehicles (FCEVs) increased 40 percent compared to 2021, reaching over 72 000 vehicles globally. The IEA report also states that projected demand for electric cars in major car markets will have profound implications on energy markets and climate goals in the current policy environment.

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1 Michelle Lewis, "US zero-emission transit buses saw a 66% increase in 2022 – here's why," electrek, February 4, 2023.
2 Javier Colato and Lindsey Ice, "Charging into the future: the transition to electric vehicles," U.S. Bureau of Labor Statistics, accessed October 2, 2023.

Road Tunnels

Life safety systems and considerations

EVs

Xavier Guigas: The design of road tunnels will have to take new types of risk into account, whether for new structures or for the rehabilitation of existing structures. The main systems affected are ventilation/smoke control, fire and gas detection and fire-fighting. Real-time monitoring of the tunnel's contents (in terms of number of vehicles per engine type) may be necessary to adapt the response in the event of fire. ATEX (explosive atmosphere)[3] characteristics might be required for some tunnel equipment.

Silas Li: Battery fires pose unique safety concerns and present distinct challenges. They can release hazardous chemicals and gases, requiring specialized firefighting techniques and equipment. Addressing these unique concerns is crucial to ensuring the overall safety of electric vehicles in tunnels.

The primary risk associated with battery fires is the occurrence of thermal runaway within a battery cell. This phenomenon involves the rapid, self-sustaining heating of a battery cell due to an exothermic reaction. Thermal runaway typically results from electrical failures, mechanical damage or prolonged exposure to excessive heat. Such events can lead to the release of flammable gases, potentially resulting in combustion and explosion. These incidents raise significant safety concerns, including the release of intense heat, the possibility of explosion, the emission of toxic and irritant gases, structural damage, the potential for fire to spread rapidly, challenges in fire suppression, increased water demand and the risk of reignition.

Xavier Guigas: Because of the high energy density EVs contain, which is increasing, and their confinement, the batteries of these vehicles are difficult to extinguish in the event of fire. The heat release rate and the nature/quantity of toxic gases emitted during an EV fire is not yet fully documented and may evolve with the technology of the batteries.

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3 Equipment for Potentially Explosive Atmospheres," European Commission, accessed September 20, 2023.

Silas Li: Battery fires can reach higher temperatures and last longer compared to conventional fires. As a result, it is imperative to implement fire protection measures, including passive fireproofing or active fixed fire suppression system, for tunnel structures. These measures serve multiple critical purposes, including ensuring the safe evacuation of tunnel users, facilitating firefighter access, minimizing economic repercussions and mitigating structural damage. Presently, the cutting-edge approach to assessing structural impacts and designing mitigation measures involves the integration of computational fluid dynamics analysis and finite element analysis.

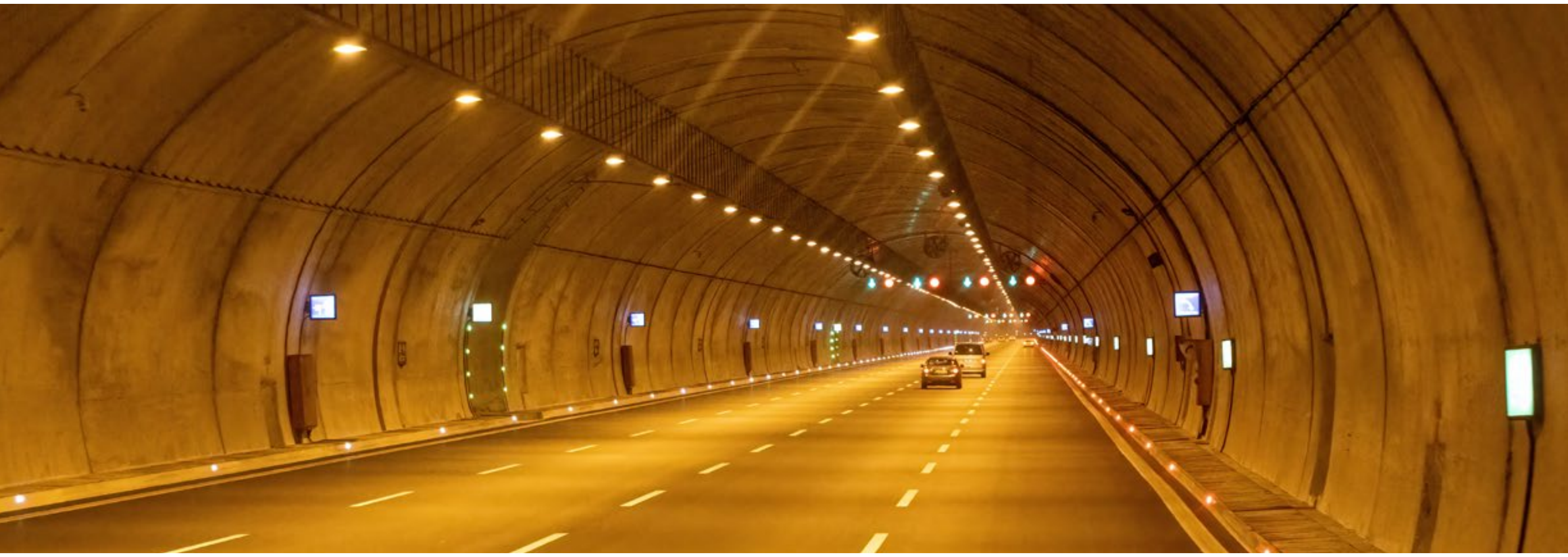
Emergency scenarios involving EVs, such as battery fires or thermal runaway, require specialized ventilation strategies to ensure the safety of tunnel users and emergency responders. The design and operation of ventilation systems must ensure adequate ventilation to reduce the risk of toxic gas inhalation and improve visibility for egress and post-incident recovery.

Mark Gilbey: Building on the point about difficult extinguishing made by Xavier and Silas, a risk arises on the performance of fixed firefighting and suppression systems. They have a strong potential either to manage or reduce the size of a fire. However, the performance of these systems is affected by the nature of the fuels involved. Fires in vehicle battery compartments can be difficult for the water to reach and penetrate to suppress or control the fire. In some cases, water may not be the best fire-suppression or fire-fighting medium. This may not affect the ability of suppression systems to reduce the magnitude of the large fires from heavy goods vehicle loads, but it could increase the frequency and duration of smaller sustained fires associated with cars and their battery cells. This means the incident durations for smaller fires could be longer and critical assets could be out of service for longer.

Silas Li: In the event of an EV-related fire, it's essential for firefighters to employ a substantial amount of water to effectively suppress and cool both the fire and the battery. For instance, during a recent EV fire on a California freeway, firefighters required 6,000 gallons (about 23,000 litres) of water to extinguish the blaze successfully. Consequently, first responders should undergo specialized training to effectively manage accidents involving battery-electric vehicles, which includes addressing potential high-voltage electrical hazards.

Mark Gilbey: The issues around the ability to effectively fight fires means tunnel systems designers will need to work closely with the emergency services to better understand how their approaches to firefighting are evolving to meet this challenge. We may need to build into the design features to help the fire services very quickly remove affected vehicles from the tunnels and locate them in areas where they can be made safer in terms of fire risk, electrocution risk and environmental risk before they are taken to a place of ultimate disposal.

A further issue related to battery vehicles relates to what happens if they break down. For long tunnels, high elevation tunnels (where cars have had to climb to reach the tunnel) and tunnels in cold climates, the battery capacity might become severely limited before the car enters the tunnel. If a battery-powered car breaks down in a tunnel, it can create a collision and resulting fire hazard for other road users. Road tunnel operators may need to provide warnings or limitations about what state of charge is required before entering the tunnel.



HVs

Xavier Guigas: Hydrogen vehicles (HVs) can be of several types: internal combustion engines burning hydrogen, fuel cells producing electricity from hydrogen (dihydrogen oxidation) and hybrid systems. In all cases, the quantity of hydrogen transported by vehicles is considerable, and it is currently stored under very high pressure. Hydrogen is a highly flammable gas with high energy density, so fire and explosion risks must be considered.

It should be noted that hydrogen distribution to service stations could also generate transport of hydrogen through tunnels, the danger of which needs to be assessed.

Silas Li: Running hydrogen-powered vehicles in road tunnels poses substantial life safety challenges due to hydrogen's high flammability, making it susceptible to leaks and fires during collisions or malfunctions. Ensuring safety requires the implementation of strong hydrogen detection systems, efficient ventilation and emergency response protocols to manage hydrogen-related incidents. Moreover, essential aspects of a comprehensive safety strategy encompass proper hydrogen storage and handling, rigorous maintenance practices and thorough risk assessments. Additionally, continual development and enforcement of safety standards are imperative to address these distinctive challenges effectively.

Regulatory Compliance

Silas Li: Many safety standards and regulations have yet to update their requirements to adequately address the risks associated with battery fires in the context of decarbonization and safety. In the United States, the relevant standard is NFPA (National Fire Protection Association) 502, titled Standard for Road Tunnels, Bridges, and Other Limited Access Highways. This standard includes an Annex G that specifically addresses alternative fuel vehicles. Each common alternative fuel is discussed in terms of its associated hazards or risks, potential fire mitigation options, and any pertinent codes. The NFPA 502 technical committee has a dedicated working group focused on this subject matter, tasked with addressing any necessary updates during upcoming standard revision meetings.

By carefully considering these factors and proactively managing associated risks, road tunnels can contribute to the goal of safe and reliable decarbonized transportation infrastructure.

Rail Tunnels

Life safety systems and considerations

Xavier Guigas: For tunnels on electrified rail networks, the impact on the design should be minimal. Electric traction (no need for diesel or H2 traction), effective segregation of freight and passenger trains, and compliance with the current safety standards already ensure an adequate level of safety in these structures.

Operators of electrified rail tunnels where passenger cars and trucks can be transported (e.g.the Channel Tunnel between England and France and the Loetschberg Tunnel in Switzerland) will likely have to review their safety systems and procedures in order to adequately manage the new risks involved by EVs and HVs.

For tunnels on non-electrified networks (still representing a large portion of the rail network), hydrogen traction could make its appearance for both freight and passenger transport. In the latter case, the presence on the same train of an important quantity of pressurized hydrogen and a large number of passengers can be problematic from a safety point of view. A holistic approach of risk analysis will need to be put in place for these cases.

This last point is also applicable to non-electrified light rail systems.

Mark Gilbey: Rail predominantly uses non-fossil fuels, which has a high occupant density per vehicle, making it an important means of reducing transit-related carbon[4] impacts. This may mean that existing and new railways and metros will seek to maximize the passenger capacity of their infrastructure, to move cars away from roads and city centres. Modern electronic signalling systems can be used to help this and increase the number of trains that can run on the network as well dynamically manage the driving profiles for optimum energy usage. This, however, has very important impacts on tunnel ventilation and fire systems, which may need to be upgraded or amended to provide resilience to these changes.

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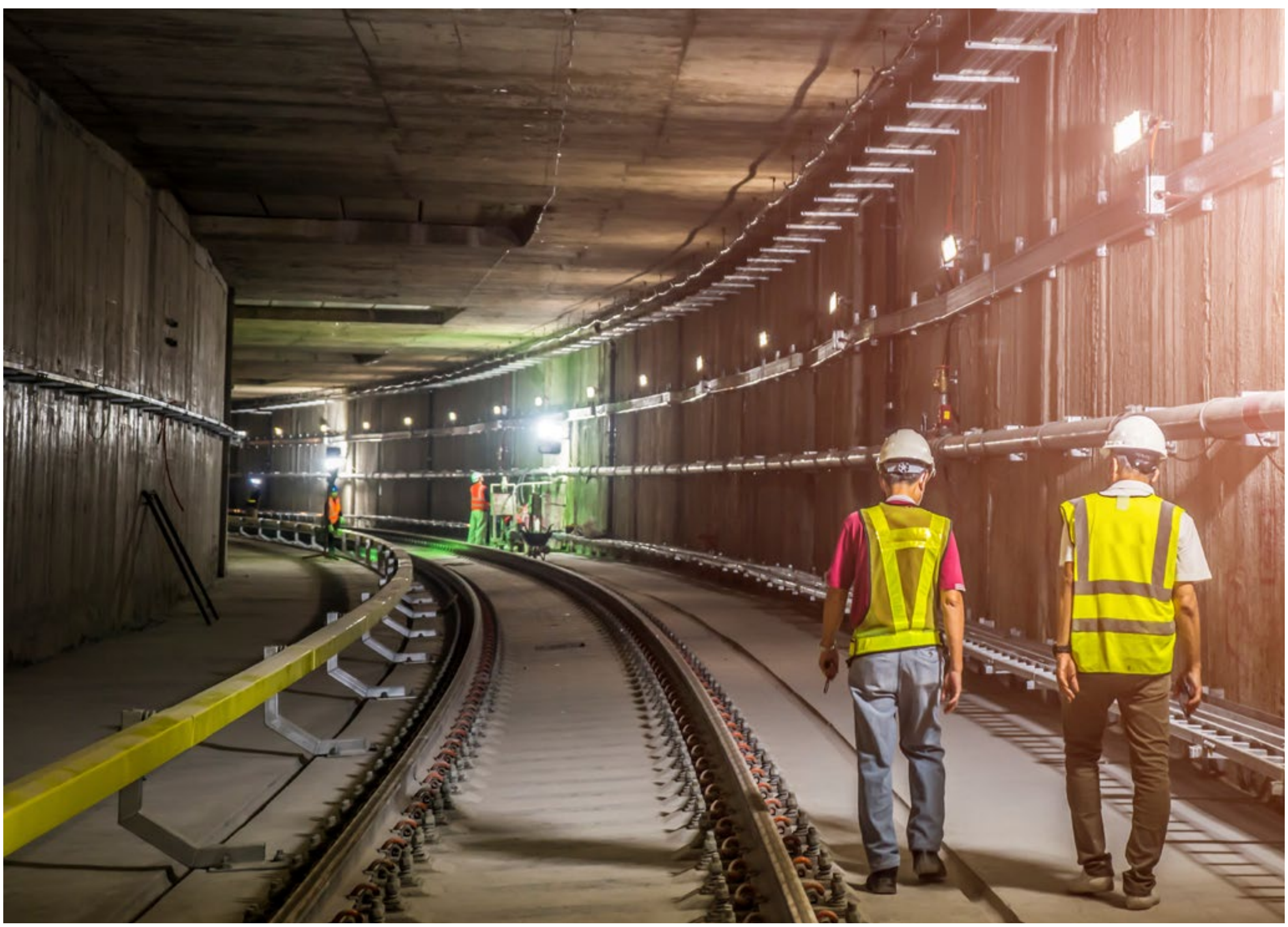
4 The word “carbon” is used to indicate a broader range of emissions, including not just carbon dioxide but also other greenhouse gases.

A first impact relates to heat—more trains invariably mean more heat. When coupled with a warmer climate, major challenges emerge in how to manage this heat, particularly for older railways and metros that may be spatially constrained and have had major cities and developments grow up around them, thus preventing the provision of new ventilation shafts. Cost to effectively deliver practicable railway ventilation and cooling systems that are in themselves energy efficient can be very difficult and a risk.

A second impact relates to fire safety. If the railway allows multiple trains in the tunnel between stations, then if a train becomes stuck in the tunnel on fire, many more passengers can be affected in other trains. This can generate the need for more costly ventilation system designs with intermediate ventilation shafts, and a combination of more complex signalling and traction systems that can give confidence that non-affected trains can quickly be removed from any tunnel section even if it is blocked by a train on fire. All these factors need to be considered carefully as part of a systems approach to railway design that looks at timetable planning, signalling, traction power, station passenger capacity, fire safety and smoke control and thermal comfort and temperature control. The systems approach is critical when building capacity for more electric trains on existing railways.

Silas Li: To enhance ambient and tunnel air quality by eliminating diesel emissions in situations where catenary power is unavailable, railway owners are exploring the use of battery-powered locomotives and trainsets as a viable alternative to their diesel counterparts. Battery power presents several advantages compared to diesel power, including the absence of combustion emissions, reduced noise levels and lower heat generation. However, it is crucial to proactively address any potential fire risks associated with the use of large quantities of batteries in locomotives and trainsets. Identifying and implementing effective fire mitigation techniques will be a valuable aspect of this consideration. Likewise, it is essential to assess and address the potential effects of hydrogen-powered trainsets on life safety and tunnel structures.



Decarbonization and Safety

Silas Li: Balancing the decarbonization of a tunnel ventilation system with the safety for tunnel users presents a critical challenge. This equilibrium is achieved through a comprehensive risk assessment that evaluates the potential impacts of decarbonization measures on safety. The assessment identifies and quantifies the risks associated with reducing fan capacity to address smaller design fires. The decarbonization strategy is aligned with evolving safety best practices and incorporates modern technologies. Furthermore, safety considerations are integrated into the planning, design and implementation of decarbonization measures.

Mark Gilbey: Following on from Silas's point, tunnel ventilation systems consume space, which means a tangible amount of carbon becomes embodied within the civil engineering design, along with the embodied carbon in the ventilation and fire systems themselves. It is responsible to question whether the benefits provided by these systems justify the associated carbon impacts, especially given that fires within rail tunnels are relatively infrequent. To investigate this point, probabilistic risk analyses can be employed to look at how many people on average per year might be affected by tunnel or station fire events and quantify any resulting injuries along with the quantification of the carbon impacts. It might be possible to use such an approach to support the elimination of certain safety systems that have become common on railways, and then also save costs on the construction and maintenance for railways along with carbon impacts. This must of course then be balanced against the risk of what happens if there is an emergency and attendant major loss of life (in any country or railway given the information age) and how would this play out in terms loss of confidence in the public to travel on sustainable transport modes. Decisions need to be made on how to maintain or even improve upon the existing high levels of safety and still use lower embodied carbon.

The embodied carbon question also plays out in a significant way in the design and construction of such structures, particularly in rail. As engineers, we are increasingly calculating the embodied carbon content within our designs, but it can be a lagging indicator (i.e. done when the design is finished). Whilst each discipline can account for embodied carbon in isolation, bigger or the most cost-effective embodied carbon savings can be made when this issue is co-ordinated between disciplines. Common considerations for tunnel and station systems include the amount of steelwork of tunnel brackets versus cast-in ducts and troughs; the impact of tunnel diameter on embodied carbon versus energy usage from train drag and any associated tunnel cooling measures; and surface space and volume to allow transformers and other major heat emitting equipment to be naturally ventilated versus below-ground space and forced ventilation or mechanical cooling.

This means that designers are going to need to be better at quickly estimating embodied carbon content as the design progresses and work as an integrated design team to manage embodied carbon in the same way that we have become accustomed optimizing the space, cost and other environmental impacts of our designs. Such a change can also impact how projects are delivered. Some embodied-carbon-saving initiatives may constrain later freedoms for contractors or may rely on lean manufacturing techniques that need to be accounted for in the early stages of design. This can result in a need for a higher level of client-engineer design and integration prior to going to tender for the final design and installation works. Very close scrutiny as to how packages are split between contracts is also needed to be confident that embodied-carbon-saving opportunities are not frustrated or thwarted by contractual interfaces or fragmentation of the supply chain. A complete systems approach is needed to account for the safety challenges and carbon impacts of alternative fuels, or increasing use of electrical fuels, in both road and rail tunnels.

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