Road tunnel design in the context of the climate action imperative

B. L. Tuckwell & *C. H. B. Stacey*

Stacey Agnew Pty Ltd, Darra QLD. Email: ben@staceyagnew.com

ABSTRACT

The context of global warming is clear, following the knowledge on the geophysics of carbon not only in the biosphere (atmosphere, but also the oceans and tectonically). In this paper, aspects of the carbon budget of a typical Australian road tunnel are discussed, demonstrating that in the global context, 'sustainability' of road tunnel projects is much more than a box ticking exercise.

The quantitative guidance will be most relevant to the concept phase of tunnel projects, where the carbon costs are largely determined. Design decisions significantly impact a project's carbon cost (or benefit) and the ability of governments to address their own carbon reduction targets and the UN Sustainable Development Goals 11 to 13. Design decisions with substantial weight in determining the overall carbon cost through a project's design life include: tunnel depth, tunnel form and materials, philosophy and policy of ventilation operation and the consequent plant size and selection.

INTRODUCTION

It is well-established that we, the global community, need to take action to combat climate change. Clearly our actions should not be limited to acts in our personal lives. Professionally, as businesses and individually, we must pursue sustainable development and operation of our infrastructure.

Road tunnels provide social and economic benefits to the community but have significant carbon footprints. Industry clearly understands that the bulk of the lifetime carbon budget for road tunnels is set during the concept and design stages (Dix, 2022; O'Connor *et al*, 2022; PIARC, 2017). Despite this, the focus of many papers and articles is only on the operational aspects, for example; tunnel lighting and ventilation optimisation. What is lacking is clear identification and ranking the importance of design decisions that substantially influence the lifetime carbon cost of a project.

This paper aims to present the influential design decisions and provide quantitative guidance that can inform and strengthen arguments for more sustainable design and practices.

The Greenhouse Gas Protocol Initiative (2004) set out three 'scopes' to distinguish emission sources: Scope 1, direct emissions; Scope 2, electricity indirect emissions; and Scope 3, other indirect emissions. This paper considers the overall impact of a tunnel project, encompassing all three scopes without distinction, as is important for the Earth.

Climate Change and Infrastructure

Stacey and Hodgkinson (2013) made the summary:

> "The Earth's surface temperature is maintained by a combination of CO_2 and water vapour, but this greenhouse control is not instantaneous. Although increasing CO_2 causes increasing temperature, thermal inertia of the oceans slows the response and, even if emissions stopped now, the full impact of industrial era CO_2 emissions would not be felt for at least a century."

Almost half (42%) of the 2,400 Gt CO_2e emitted from human activities between 1850 and 2019 was emitted after 1990 (IPCC, 2023). In Australia, an increase of about 1.47°C since 1910 has already been observed (CSIRO and The Bureau of Meteorology, 2022).

The delayed environmental response of the biosphere leads to mistrust and general apathy for the topic by some. However, the environmental changes brought about by our present CO_2 emissions will last for millions of years (Stacey and Hodgkinson, 2013). We don't really know the short-term trajectory, but we do know that it is far more rapid than we have seen in geological time. It is our responsibility to actively improve and seek out low carbon approaches to our infrastructure and for our global community. Inaction is unethical.

IMPACTS FROM DESIGN

Repeatedly the impact of design is listed as 60 – 80% of the complete life carbon cost of a project (O'Connor *et al*, 2022; PIARC, 2017).

Literature on the topic of tunnel sustainability is dominated by reviews of the impacts of lighting and concrete type. Information on other design aspects is relatively sparse. This paper looks at the significance of the carbon saving possible within some less considered design aspects.

Tunnel Depth

Tunnel alignments are typically driven by the space available, and the difficulty or cost of tunnelling given the geology of the area. Consideration of how the alignment directly impacts the project carbon cost has not been given the same weight.

Smith (2022) identified that the Fehmarnbelt Tunnel between Germany and Denmark reduced the project carbon footprint through proceeding with a shallow tunnel design, reducing land requirements for approaches and the project gradients. Clearly, shorter, shallower tunnels use fewer materials but there are also benefits to be realised through the reduction in the emissions generated by the traffic.

A simplified analysis of a 5 km long road tunnel, with entry and exit portals at the same level, is presented for different maximum tunnel depths. Table 1 lists the mass of CO_2 equivalent emitted by combustion of fossil fuel (DCCEEW, 2023) for different vehicles.

Type	Emission Factor (kg CO_2e / GJ)
Cars and light commercial vehicles – Petrol	84.82
Cars and light commercial vehicles – Diesel	87.71
Heavy duty vehicles – Diesel	87.67

TABLE 1 – Emission factors for fossil fuel used in transport (evaluated from DCCEEW, 2023).

The analysis assumed that the tunnel services 30,000 vehicles a day, travelling at a constant velocity for the full tunnel length. The simplified fleet composition considered is given in Table 2. Yearly fleet emissions evaluated from the elevation climb from different tunnel depths are presented in Figure 1.

Vehicle type	Fleet composition	Average vehicle mass (kg)	Fleet diesel composition	Adopted average engine thermal efficiency
Passenger Car (PC)	72%	2,000	15%	20%
Light Duty Vehicle (LDV)	14%	4,000	70%	30%
Heavy Goods Vehicle (HGV)	14%	21,000	100%	30%

TABLE 2 – Simplified fleet composition assumed. Diesel composition values evaluated from vehicle data source from the Australian Bureau of Statistics (2021).

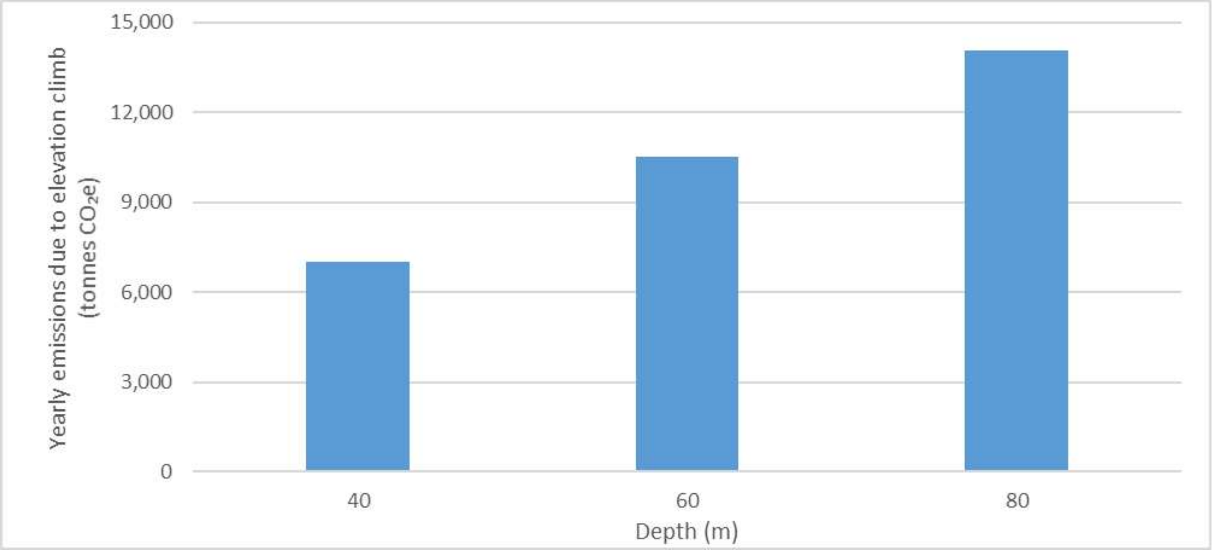

FIGURE 1 – Yearly fleet emissions due to the elevation climb from different tunnel depths.

Gravitational potential energy was converted to vehicle emissions using the assumed engine efficiencies for each case. This simplified analysis generalises the fleet and does not consider speed changes with respect to braking or, accelerating, or travelling around curves. It demonstrates that significant carbon savings can be realised through pragmatic decisions regarding the final tunnel alignment.

As electric vehicles (EV) become more prominent within the fleet, their influence on the tunnel emissions become more significant. Though EVs do not generate emissions within the tunnel, energy required to power the vehicles may generate emissions elsewhere. Presently, the average emission factor for grid power nationally in Australia is 202 kg CO_2e / GJ (DCCEEW, 2023). Note that this varies significantly with power source and location. Emission factors for South Australian power are more than 2.5 times lower than for Queensland power (DCCEEW, 2023). Values should diminish nationally as renewables become more prevalent within the power grid. With the high efficiency of EVs at 77%, the total carbon cost of EV operation is not so different from internal combustion engine vehicle operation (Office of Energy Efficiency and Renewable Energy, n.d.).

For the purpose of this paper, EV emissions are considered comparable to those of conventional vehicles and are not considered separately.

Tunnel Form and Materials

Minimising the required material quantities for construction clearly directly decreases the total carbon cost of the project. Ridley and Stacey (2009) concluded that the CO_2 emissions during construction are dominated by those associated with the manufacture of the concrete used. This is largely accepted by the industry (Smith, 2022).

There is significant effort in the industry to investigate greener concrete options, but the quantity used is clearly pivotal, and a dominating factor that determines the volumes needed for a project is the tunnel form. Tunnel form dictates the required excavation area which itself carries a significant carbon cost, as well as the required tunnel lining and invert infill. Table 3 summarises the values derived by Ridley and Stacey (2009) to give an overall carbon cost per tunnel kilometre constructed, excavated by either a road header (RH) or tunnel boring machine (TBM).

Lanes	Method	Excavation Area	Excavation Energy Cost		Embodied Energy: Concrete		Spoil Removal Energy Cost		Total		
		m²	TJ/km	tonnes CO_2e /km	TJ/km	tonnes CO_2e /km	TJ/km	tonnes CO_2e /km	TJ/km	tonnes CO_2e /km	tonnes CO_2e /lane.km
2	RH	100	7.6	1,356	65.2	11,594	1.9	333	74.7	13,283	6,642
2	TBM	113	4.5	804	90.2	16,039	2.1	374	96.8	17,217	8,609
3	RH	109	8.3	1,474	117.3	20,854	2.0	359	127.6	22,688	7,563
3	TBM	202	8.1	1,437	220.4	39,190	3.8	670	232.3	41,298	13,766

TABLE 3 – Embodied energy and carbon for different tunnel types (Ridley and Stacey, 2009). Converted to per tunnel kilometre and per lane.km values for the purpose of this paper.

These values demonstrate how sensitive the total construction carbon cost is to the tunnel form and construction method. While a two-lane tunnel sees benefit in the excavation cost of a TBM, when accounting for the additional concrete required in a TBM lining, a road header construction becomes more sustainable. Of course, that choice may not be a choice when ground conditions and safety are considered. For a three-lane tunnel, the total carbon cost of a TBM tunnel becomes almost twice that of a road header construction, due to the concrete volume requirements.

Tunnel Length

If a roadway is to be built by some means (either on the surface or underground), then tunnel carbon cost might also be judged against the carbon cost of the surface lane capacity that is not then required. Surface road construction may result in emissions of 1,600 t CO_2e / lane-km (Greening Australia, 2019). This does not include the carbon cost of replacing structures that had to make way for a road (if that were required). Comparing that figure to the last column of Table 3, reduction of the overall required tunnel length clearly reduces the overall carbon cost of the project.

Fixed Fire Fighting Systems

Road tunnels have recently started using a new type of fixed fire fighting system (FFFS); so-called misting systems. There has been discussion within the industry of the performance of misting compared with more traditional deluge systems and some commentary on their smaller carbon footprint. As an indicative review of this claim, an assessment of the carbon cost of only the piping for both types of FFFS is presented here. The benefits in reduced storage, drainage and sump sizing were not considered.

Misting systems typically use stainless steel pipes of a smaller diameter than the galvanised piping used for deluge. Stainless steel is a heavily recycled product (ISSF, 2022). Galvanised steel typically uses more virgin product during manufacture than stainless steel (ISSF, 2022). A comparison of the embodied carbon for both stainless steel and galvanised steel is presented in Table 4.

Metal	Recycled content	Embodied carbon (kg CO_2e/kg)	Source
Stainless steel	60%	2.99	ISSF, 2022
Stainless steel	90%	1.95	ISSF, 2022
Galvanised steel	0% (virgin)	2.84	Hammond and Jones, 2011
Galvanised steel	59%	1.45	Hammond and Jones, 2011

TABLE 4 – Embodied carbon equivalents for stainless steel and galvanised steel.

Tables 5 and 6 list the estimated embodied carbon of the misting or deluge pipes for a typical kilometre of tunnel.

Outer Diameter (mm)	Pipe mass per tunnel length (kg/km)	Embodied carbon per tunnel length (tonnes CO_2e / km)	
		60% Recycled	90% Recycled
200	6,660	19.9	13.0
88.9	7,126	21.3	13.9
54	3,962	11.8	7.7
35	2,531	7.6	4.9
Total for all pipes	20,279	61	40

TABLE 5 – Stainless steel pipe misting system embodied carbon estimate.

Nominal Bore (mm)	Pipe mass per tunnel length (kg/km)	Embodied carbon per tunnel length (tonnes CO_2e / km)	
		0% Recycled	59% Recycled
200	40,300	114.5	58.4
150	25,600	72.7	37.1
100	7,850	22.3	11.4
65	25,080	71.2	36.4
Total for all pipes	98,830	281	143

TABLE 6 – Galvanised steel pipe deluge system embodied carbon estimate.

Figure 2 shows the obvious trends where the embodied carbon decreases with recycled content and generally increases with pipe size. Discrepancy in the proportionality of pipe size with overall embodied carbon estimate can be attributed to both changes in pipe thickness and the type of installation. Stainless steel pipe misting installations are clearly less carbon intensive than galvanised steel pipe deluge systems for tunnels. This assessment is compelling despite considering only the pipework involved. Omitted aspects that would only further support this conclusion include:

- Installation energy. As galvanised pipe installations are substantially heavier, transporting and manoeuvring the components consumes more energy.
- Maintenance and replacement requirements. Over the life of the tunnel, repairs and replacements will add to the lifetime carbon cost of the system. With shorter life and greater mass, galvanised steel pipes would require more frequent maintenance and the additional embodied carbon for replacement would be greater.
- Water storage and runoff capture is much larger for deluge, as discussed below.

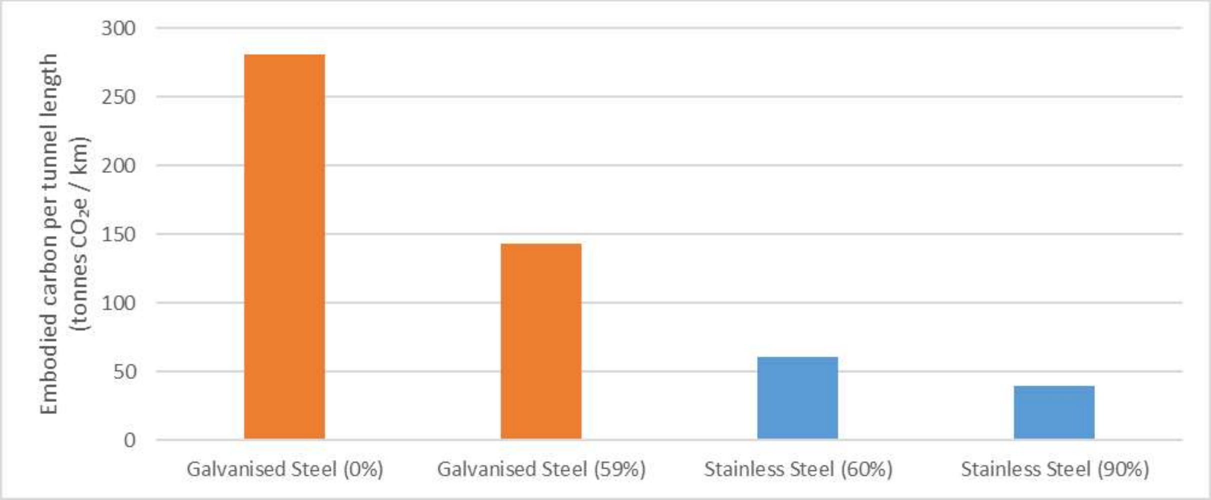

FIGURE 2 – Embodied carbon per tunnel kilometre of different pipe installations considering 60% and 90% recycled stainless steel and 0% and 59% recycled galvanised steel.

FFFS also carry significant spatial requirements for their reservoirs and sumps. Table 7 lists reservoir requirements for comparable systems. Misting systems require around one third of the reservoir required for a comparable deluge system. For a tunnel requiring a low point sump mined as a concrete lined cavern, carbon costs with that construction are significant. Smaller reservoirs also allow for tighter project footprints, possibly reducing the required carbon cost even further.

Parameter	Unit	Deluge	Misting
Discharge density	(mm/minute)	10	3
Flow for 3 x 25 m 3-lane zones	(L/minute)	7500	2300
4-hour reservoir size	(m^3)	450	138

TABLE 7 – Reservoir requirements for deluge and misting systems (Gingell and Stacey, 2023).

Ventilation Design

When designing tunnel ventilations systems (TVS), except for very long tunnels, capacity is now driven by fire scenarios rather than emission dilution requirements. The design fire scenarios are formed from a collection of assumptions such as future traffic profiles and possible fire sizes. Design conservatism is often an outcome of seeking easy approval paths when the governance of the issue is perhaps not fully developed. This was explored by Tabarra *et al* (2022), who wrote: “design conservatism can go too far and lead to larger, more costly and carbon intensive systems.”

Critical Velocity

Critical velocity refers to the minimum tunnel air velocity upstream of a fire that results in no backlayering of smoke. Australian tunnels are typically required to achieve critical velocity under design fire conditions. Critical velocity is typically of the order of 2.7 to 3.2 m/s for road tunnels. The required jet fan thrust to achieve this velocity is dependent on tunnel geometry and fire size.

Tunnel geometry is typically constrained by many other factors (primarily cost), and adjustment of the geometry to suit the TVS fire response is practically limited. The design fire spectrum is derived from review of the expected traffic and potential fuel loads, and are sometimes conservative due to:

- poor understanding of the expected traffic, and
- a focus only on worst possible cases, while maintaining performance criteria expected for more moderate fires.

Tabarra et al (2022) found that embodied carbon reductions of 12% in the TVS and 21% in the supporting infrastructure, could be achieved by more rational selection of the design fire size.

Portal Emissions

Most recent Australian road tunnels are required to have no emissions from the tunnel exit portals, requiring sizable TVS capacities to manage predicted busy times. It is important to note that the design for any new tunnel is based on predictions. We have seen oversizing of vent plant simply due to the need to harmonize traffic predictions for ventilation design with traffic predictions for project financing, with the financing sums taking a different perception of reality. Even without financing involved, a rosy view of the traffic merits of a tunnel may inadvertently add conservatism to the plant sizing. We have not yet found a way for projects to document different traffic estimates for different purposes, in spite of increased numbers being conservative for one aspect, but optimistic for another.

Net portal inflow policies consume energy to relocate traffic emissions up ventilation stacks and away from the public. Using rational traffic expectations and reconsidering the need for complete capture of portal emissions would clearly reduce the design TVS capacities and the required plant.

Changing traffic fleets will progressively include more alternative fuel vehicles, lowering in-tunnel emissions and perhaps reducing the demand for high TVS capacities to manage portal outflows. Designing for future fleets with provisional modes and requirements, or conducting periodic technical reviews of system modes, could result in significant reductions in initial plant sizes, as well as energy consumption.

Plant Selection

With design requirements identified, plant selection can further influence both the embodied carbon for manufacture and construction, and the ongoing energy consumption of the plant. Holistic plant selection should use the existing and future technologies that improve the efficiency of fans (Dix, 2022). Some examples include:

- Aerodynamic design of vent building flow paths.
- Selecting appropriate duty points, without undue conservatism on pressure calculations, to allow efficient operation.
- Jet fans positioned further from tunnel linings and adapting tunnel geometry to benefit ventilation efficiency (Dix, 2022).

Operational policy

Though operational policies are subject to change over the life for a road tunnel, the initial operation assumed during design sets the capability of a system. Optimising the operational policy during design can lead to minimising plant requirements and establishing efficient methods early.

Lighting

Optimising the running costs and subsequent carbon emissions from tunnel lighting systems is the topic of a plethora of papers and articles (e.g. Bracale, 2019; Peña-García and Nguyen, 2018). Ridley (2019) notes that tunnel lighting typically accounts for about one third of the total power usage. For the purposes of this paper, it is sufficient to simply mention that minimising the lighting requirements is a method for reducing the carbon footprint for both new and existing tunnels.

Ventilation Policy

As mentioned earlier, policies such as meeting portal emissions requirements can have a significant influence on the operational carbon cost of a road tunnel.

Biotto *et al* (2023) studied the impact of implementing machine learning algorithms to optimise tunnel ventilation operations over fixed or predictive methodologies. They found that savings of between 3% and 15 % of the yearly power consumption could be achieved for the tunnel reviewed (Domain tunnel on CityLink in Melbourne).

Table 8 details the total operating energy consumption for some Australian tunnels (after Ridley, 2019). Each tunnel is unique in geometry, ventilation systems and operational policy, leading to a significant variation in energy consumption.

For these tunnels, a reduction of 3% to 15% would result in a carbon saving of between 12 t CO_2e to 750 t CO_2e per tunnel kilometre each year.

City	Tunnel	Length	Tubes	Energy (p.a.)		CO_2	
		km		MWh	GJ	tonnes CO_2e pa	tonnes CO_2e pa / tunnel km
Sydney	Sydney Harbour	2.8	2	14,519	52,267	6,775	1,210
	Eastern Distributor	1.7	2	7,058	25,410	3,080	906
	M5 East	3.8	2	81,000	291,600	37,800	4,974
	Cross City	2.1	2	12,249	44,095	5,716	1,361
	Lane Cove	3.5	2	21,678	78,041	10,780	1,540
Brisbane	Clem7	4.8	2	12,745	45,883	5,948	620
	Airport Link	5.7	2	36,471	131,295	17,020	1,493
	Legacy Way	4.6	2	13,061	47,021	6,095	663
Melbourne	Citylink (Burnley & Domain)	5	1	23,415	84,295	15,050	3,010
	Eastlink	1.6	2	2,918	1,054	1,362	426

TABLE 8 – Energy consumption for some Australian tunnels (Ridley, 2019). Values converted to a per tunnel kilometre basis for the purpose of this paper.

Dix (2022) discusses changing energy consumption perspectives to those of reduced peak energy demand and decreased overall energy usage through means of better control systems for tunnel ventilation. Simply put, it is better to use TVS only when it is needed.

Renewable Energy

Energy requirements for an operational tunnel can be sourced sustainably. Under current infrastructure, it may be difficult or impossible to procure a grid connection that is entirely drawn from renewable energy. Though design for complete grid independence using reliable renewable energy technology is often impractical, alternative options of buying green power, procuring carbon credits or renewable energy investment are also viable options.

The World Road Association, PIARC (2019) initiated the Positive Energy Roads project and in summary recommended that road infrastructure should aim to cover as much of the energy requirements as possible through independent, on-site renewable energy production. Road tunnels are often required due to the lack of available surface space for a road, or to reclaim previously occupied road space, so a local renewable source is unlikely.

Though complete independence may not be practical, renewable energy installations could reduce the energy requirements from the grid. Tunnels systems can have greater energy demands during the day, due to greater traffic flows and required illuminance levels, providing an ideal scenario for photovoltaic systems to assist (List, 2020).

Sydney Metro installed 3,287 solar panels onto the roof of their maintenance building to power some of the city's railway stations with approximately 1.5 GWh of electricity per year (Sydney Metro, 2017). This demonstrates that renewable energy investment can be practical even when not directly connected to the relevant underground infrastructure.

REQUIREMENTS, REGULATIONS AND ACCREDITATIONS

For tunnelling projects, Janssen *et al* (2018) believe that "limitations imposed on the project during the initial planning and architectural design and the administrative consultation are not focused enough on energy reduction." Navigating successful project requirements around sustainability concepts is inherently difficult. Stipulating targets to meet, and reductions to be achieved, is likely to miss the mark entirely without a comprehensive understanding of the design at the time of writing the project requirements. This is difficult when the tendering method allows the freedom to change even the basic configuration of the tunnel. This difficultly is amplified when considering new regulations and law.

Though difficult, it is not impossible, and significant effort should be spent to constrain or incentivise new projects to actively seek more sustainable options.

There are already methods for assessing the sustainability of new infrastructure projects. For Australia and New Zealand, the Infrastructure Sustainability Council (ISC) provides an IS rating scheme for evaluating projects across the planning, design, construction and operational phases. This evaluation considers a 'business as usual' base case to which project decisions are compared and credits are awarded where appropriate. Weighting of the credits is agreed between stakeholders to enable comparison of social, economic and environmental decisions.

Both Australian and New Zealand governments have committed to net zero emissions by 2050. To achieve this, industries need to place great value on emissions reduction and reform how projects are specified and developed.

United Nation Sustainable Development Goals

Tunnel projects influence achievement of several of the United Nations (UN) Sustainable Development Goals (SDGs). By approaching tunnel design more sustainably, we can create a clear positive influence towards SDGs 9, 11, 12, and 13 (Dix, 2022; O'Connor, 2022). These goals are:

- Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation.
- Goal 11: Make cities inclusive, safe, resilient and sustainable.
- Goal 12: Ensure sustainable consumption and production patterns.
- Goal 13: Take urgent action to combat climate change and its impacts.

Goal 13 is the most important of these, as, in the medium term, its achievement is a necessary precursor to achieving the others. It is for that reason that carbon reduction is the focus of this paper.

CONCLUSION

Table 9 below nominates the scale of the embodied carbon for a typical three-lane 5 km road tunnel, related to the design decisions discussed quantitatively in this paper. The 20-year emissions savings estimate does not consider maintenance of the tunnel or it's systems, nor does it consider the changing fleet and renewable energy profile.

Design aspect	Carbon emission savings	Maximum total emissions saving for initial 20 years (tonnes CO_2e)
Tunnel length	A surface road with a construction impact of 24,000 t CO_2e could save 89,000 t CO_2e to 183,000 t CO_2e	183,000
Tunnel form	Varies from 113,000 t CO_2e to 207,000 t CO_2e, a difference of 94,000 t CO_2e.	94,000
Tunnel depth	3,500 t CO_2e/annum for every 20 m of extra depth.	70,000
Operational policies	Saving of 20 t CO_2e/annum to 750 t CO_2e/annum	15,000
FFFS type	400 t CO_2e to 1,200 t CO_2e saving, plus sump and supply storage changes.	1,200

TABLE 9 – Scale of the carbon impact involved in various design decisions, based on the initial 20 years of a typical 5 km three lane road tunnel.

The considerations presented are by no means a comprehensive list of areas to reduce the carbon footprint for a tunnel project. In developing a complete carbon assessment of a project, at least induced traffic demand, congestion reduction, and portal and above ground developments should be included.

We can all agree that the whole of life carbon cost of tunnels must be considered seriously. However, confusion of efforts with regards to sustainability can occur without an appropriate (numerical) basis for action. Management of wastewater runoff, collection of roof water from site offices, recycling of site products during construction, and other such actions have their place and typically link with project sustainability, but may have small impacts to the overall carbon cost of a project. We suggest that the weighting for carbon cost should be orders of magnitude greater than for some of the more social measures. After all, we have a climate emergency, not a dog-off-leash area emergency. The hard assessment of the carbon management of a project should happen right from the first suggested concept, and not be limited to low hanging fruit after the major design and construction elements are locked in.

Hopefully this paper stimulates thought on the big picture, suggests opportunities and reminds the industry that action towards reducing tunnel-related carbon emissions is an obligation at all stages of a project. The most sustainable option may not be obvious, so all aspects of design should be questioned. Even whether a road tunnel is truly the best use of carbon.

ACKNOWLEDGEMENTS

We would like to thank the following people for their contribution to this paper.

- Paul Gingell from LPG Fire Australia Pty Ltd for contributing material quantities for misting and deluge systems.
- Scott Losee from Losee Consulting Pty Ltd for review of the paper and explaining, from a practitioner's point of view, the approach taken within the infrastructure sustainability discipline.

REFERENCES

Australian Bureau of Statistics, 2021. *Motor Vehicle Census, Australia*, Australian Bureau of Statistics, Available: https://www.abs.gov.au/statistics/industry/tourism-and-transport/motor-vehicle-census-australia/latest-release [20 September 2023].

Biotto, C, Belbasis, A, Campbell, A, and Ly, H, 2023. *Making tunnels think*.

Bracale, A, Caramia, P, Varilone, P and Verde, P, 2019. *Probabilistic estimation of the energy consumption and performance of the lighting systems of road tunnels for investment decision making*. Energies, 12(8), p.1488.

CSIRO and The Bureau of Meteorology, 2022. *State of the Climate*.

DCCEEW, 2023. *Australian National Greenhouse Accounts Factors.* Australian Government Department of Climate Change, Energy, the Environment and Water

Dix, A, 2022. *Tunnel Ventilation and UN 2030 Sustainability Development Goals we have a story to tell*, in the 11th International Conference Proceedings 'Tunnel Safety and Ventilation' in Graz, Austria

Gingell, P and Stacey, C 2023. *Water mist suppression for road tunnels* [Webinar]. Australian Tunnelling Society – Tunnel Systems Sub-Group. Available: https://www.australiantunnellingsociety.org/ [8 August 2023]

Greenhouse Gas Protocol Initiative, 2004. *A corporate accounting and reporting standard.* World Resources Institute and World Business Council for Sustainable Development.

Greening Australia, 2019. *Investment in Natural Infrastructure to Offset the Environmental Impact of Future Development of Built Infrastructure*. Infrastructure Australia.

Hammond, G and Jones, C, 2011. *Embodied Carbon: The Inventory of Carbon and Energy*. University of Bath, UK

IPCC, 2023. *Summary for Policymakers. In: Climate Change 2023*: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

ISSF, 2022. *Stainless Steels and CO_2; Industry Emissions and Related Data*. International Stainless Steel Forum

Janssen, P, Naber, J, Haas, K, and Lantinga, C, 2018. *Working Towards a Zero-Energy Tunnel: Technical, Contractual and Process Solutions*

List, R, 2020. *The Path To Highly Available, Sustainable And Efficient Operation Of Road Tunnels – Use Of Energy Generation And Storage Opportunities In The Future*, in the 10th International Conference on 'Tunnel Safety and Ventilation' 2020 in Graz, Austria

O'Connor, G, Louis, L, Peglas, T, Xue, S, Tziotis, M and Yeo, R, 2022. *Sustainability in road tunnels: updating the Guide to Road Tunnels* (No. AP-T364-22)

Office of Energy Efficiency and Renewable Energy, n.d. *All-Electric Vehicles.* US Government Department of Energy, https://www.fueleconomy.gov/feg/evtech.shtml. Accessed 22 September 2023.

Peña-García, A and Nguyen, T, 2018. *A global perspective for sustainable highway tunnel lighting regulations: Greater road safety with a lower environmental impact.* International Journal of Environmental Research and Public Health,

PIARC World Road Association, 2019. *Positive Energy Roads*. World Road Association (PIARC)

Ridley, P and Stacey, C, 2009. *Greenhouse cost-benefit analysis for urban road tunnels*. In SSEE 2009: Solutions for a Sustainable Planet (pp. 547-556). Barton, ACT: Engineers Australia.

Ridley, P, 2019. *Overview of Australian Urban Road Tunnels*, The University of Sydney.

Smith, K, 2022. *Counting The Carbon On Fehmarnbelt*. Tunnelling Journal

Stacey, F and Hodgkinson, J, 2013. *Earth As A Cradle For Life, The: The Origin, Evolution And Future Of The Environment*. World Scientific.

Sydney Metro, 2017. *Solar system the size of a football field helping deliver a sustainable Sydney Metro*. Transport for New South Wales. https://www.sydneymetro.info/article/solar-system-size-football-field-helping-deliver-sustainable-sydney-metro. Accessed 22 September 2023

Tabarra, M, Dawda, N, Altura, E, and Abi-Zadeh, D, 2022. *A New Rationale for Sustainable Tunnel Ventilation System Design of Metros*. In the 19th International Symposium on Aerodynamics, Ventilation & Fire in Tunnels Proceedings – Brighton, UK