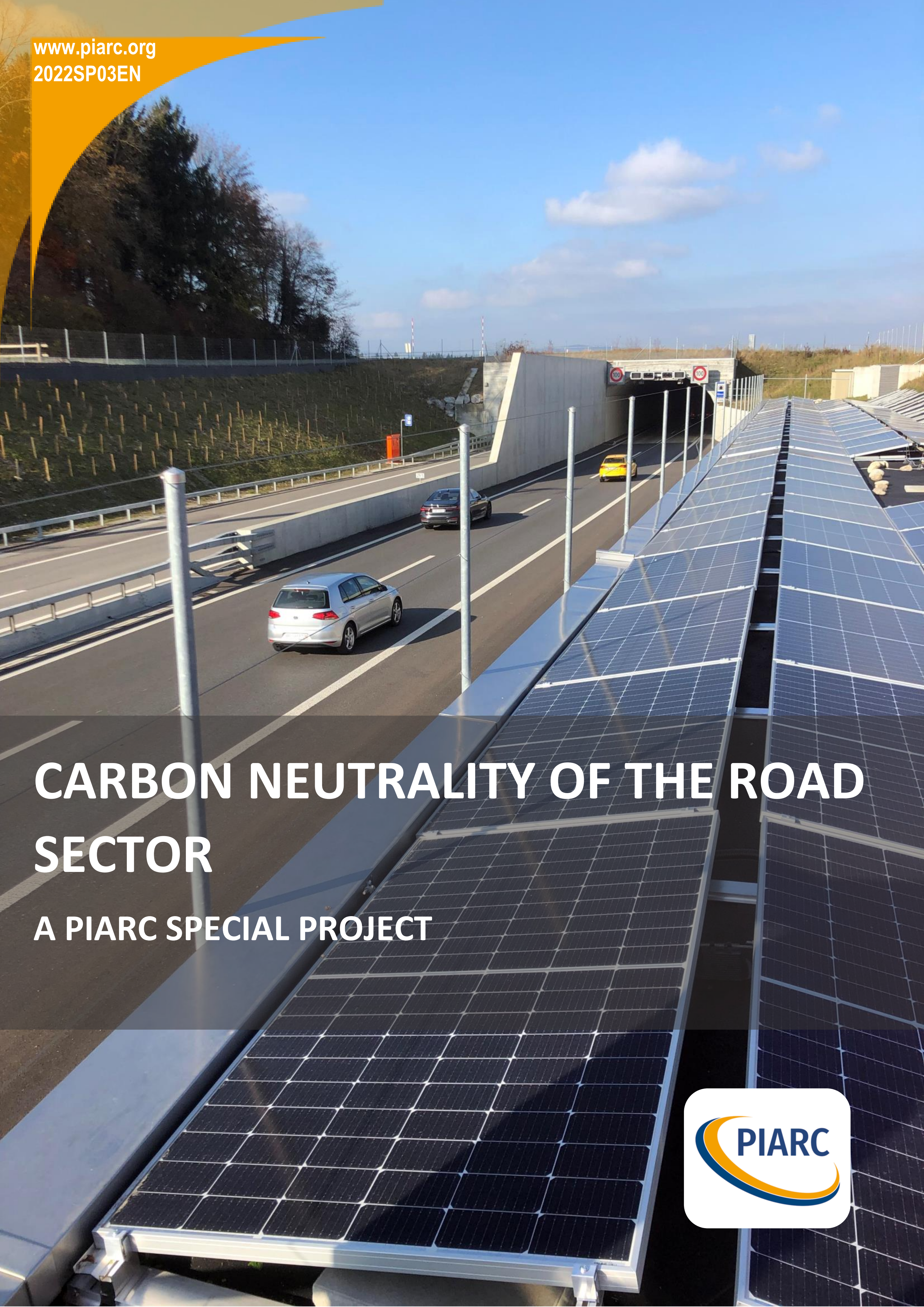

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CARBON NEUTRALITY OF THE ROAD SECTOR

A PIARC SPECIAL PROJECT

PIARC

STATEMENTS

The World Road Association (PIARC) is a non-profit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

This report has been produced by the International Transport Experts Network (ITEN) and Research Driven Solutions (RDS), under a contract with PIARC, awarded to Maple Consulting Ltd, an ITEN member. Any views expressed in this report are not necessarily those of PIARC.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2020–2023 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committees participating on the Project Oversight Team were appointed by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organisations or agencies.

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Front cover: Courtesy of Office fédéral des routes OFROU, Switzerland

CARBON NEUTRALITY OF THE ROAD SECTOR

A PIARC SPECIAL PROJECT

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EXECUTIVE SUMMARY

CARBON NEUTRALITY OF THE ROAD SECTOR

A PIARC SPECIAL PROJECT

Road transport is vital for society to function and, for the foreseeable future, is expected to remain the dominant mode of transport for people and goods. However, the construction, operation, maintenance and use of the highway infrastructure are responsible for large quantities of carbon emissions. Knowledge of the non-reversible, damaging consequences of climate change has resulted in global acceptance of the need to reduce carbon emissions in all sectors of human activity, including the highways sector. However, as efficient transport is vital to national economic growth, actions to reduce carbon emissions must not negatively impact the development and maintenance of high-quality road infrastructure, particularly for LMICs.

This project aims to identify actions being undertaken as well as potential new options to progress towards **carbon neutrality**. Net zero carbon and carbon neutrality represent two different approaches to combat climate change. There has been a certain amount of ambiguity in the understanding of what the two approaches represent and there are examples in literature of the two terms being used interchangeably. However, there is a general consensus on the definitions for the two approaches, as follows:

- **Net Zero carbon***:* is *reducing carbon emissions to as close to zero as possibl*e. Any small amounts of remaining emissions are then offset by absorption in natural carbon sinks like forests or using new technologies like carbon capture
- **Carbon Neutrality***:* is *balancing carbon emissions by 'offsetting',* i.e., separately removing carbon in the atmosphere to balance that which is emitted

The above definitions have been adopted by PIARC and form the basis of their use throughout this report.

In practice, many highway authorities making progress on decarbonisation are adopting a combination of these approaches, having established target dates for achieving Net Zero carbon (generally aligning with the policies set by national governments) and also, in the short term where it is not yet possible to decarbonise, purchasing carbon offsets to mitigate the impact of emissions. This approach has been followed for some major construction schemes with potential for high emissions.

Part A of this report examines the policies and strategies being adopted by National Road Administrations (NRAs). 83% of questionnaire respondents reported that their country had Net Zero targets in place. Irrespective of whether targets are in place, a range of strategies are being adopted for reducing carbon emissions. The report summarises the major themes, which appear to have a high degree of commonality across the world and are being adopted in both LMICs and HICs. Three case studies are highlighted: the Net Zero strategy adopted by National Highways in the UK, which has the most well-developed policy identified, and two road improvement projects where a range of actions were taken to reduce emissions. The levers available to road authorities through their procurement practices and relevant practice from the rail sector are reviewed. Finally, the need to achieve a ‘fair transition’ is discussed, in which carbon emissions are reduced without impeding economic growth in developing countries and regions.

Part B of this report examines the technical solutions that are available for decarbonisation and, for specific technologies, the potential carbon savings were estimated. The technologies considered are summarised below.

EXECUTIVE SUMMARY

Technical solutions

Construction and maintenance of road infrastructure

A hierarchy of options exists, beginning with challenging the need for new construction, plus effective maintenance of existing assets. Further opportunities exist through planning works to reduce emissions, adopting low carbon materials and decarbonising construction plant. Roads can also be designed to reduce rolling resistance for road users.

Decarbonisation of road user vehicles

Road user carbon is the largest component of road emissions. Options will depend on national policy and can be supported by NRAs. Biofuel is already in use and electrification appears a promising option for cars and light vans. For heavy vehicles various options under development include battery electric, electric road systems and hydrogen.

Operations on the road network

Lighting (including road signs and signals) provides a critical role in road safety and forms a high proportion of corporate emissions for many NRAs. Lighting energy can be reduced considerably by LEDs. NRAs also have a role to reduce the impact of their sizeable vehicle fleets and find solutions for specialised use cases such as recovery vehicles, gritters and snow ploughs.

Road user choices

Well-designed networks for non-motorised travel can give road users a healthy alternative to short car journeys. Likewise, passenger-centred public transport can provide an alternative to low-occupancy private vehicle use. Various incentives and penalty schemes have been adopted to encourage modal shift.

Carbon offsetting

There are various approaches to removing atmospheric carbon or avoiding its release. The scale of road carbon emissions is too large to be substantially balanced by these methods, although they offer a means of mitigating emissions that are currently unavoidable. There are several certified schemes but there are also concerns whether the claimed benefits are realised.

In Part C, a more in-depth investigation was carried out into specific solutions in two areas, namely, lighting and road construction/maintenance. For this, additional interviews were undertaken to supplement the literature reviews and findings of the questionnaire.

For the review on LED lighting, current guidelines and targets were explored, followed by various examples of cities or road networks who had rolled out LED lighting schemes, and success factors. Finally, a review of factors that road administrations should consider if planning an LED scheme is presented. Whilst LED lighting is a mature technology, which has been successfully deployed worldwide, the key factors to be considered are as follows:

- Technology: Current system in place, lighting intensity required, smart systems and dimmability
- Economic: Finance, payback and maintenance
- Location: Standalone systems or solar/ wind powered systems
- Environmental: Carbon savings, recyclability and biological impacts
- Other: Political factors and skillset

The second area of more detailed investigation was around the much broader category of road construction and maintenance. Here, the review considered the importance of baseline levels and strategies to drive carbon reduction and consideration of how construction can be designed to be more resource efficient based on local conditions. Case studies and findings on the use of low carbon concrete and reclaimed and recycled asphalt are presented, as the main constituents of highways, along with other secondary materials, such as recycled tyre, steel slag waste and coal combustion by-products. The key conclusions in the area are as follows:

- Existing carbon emissions need to be baselined the major sources of emissions identified so that an appropriate reduction strategy can be developed
- Scenarios evaluated should take account of local conditions (e.g., transport distances and the efficiency of local plant) and all phases of the lifecycle should be evaluated. The system boundaries should also be studied carefully, in case an apparent reduction in emissions in one area results in displacing the burden to a different part of the process
- Existing design strategies can be challenged to allow for greater resource efficiency

- Early engagement with industry stakeholders in the project development stage can allow ways to reduce carbon to be investigated, and drive motivation for further innovation
- Suppliers should be required to produce information on the carbon (and other) impacts of their products to drive a focus on reduction

Estimates of carbon savings for the technologies identified in section B are presented. These estimates are extrapolated from the data available, however they indicate there is significant potential to reduce carbon at all stages of the highway lifecycle. Specific areas identified are as follows:

- Review the need for road construction to allow other options, such as active travel and public transport to be considered
- A well maintained and smooth pavement will lead to lower emissions from vehicles using it. With various assumptions made on worldwide road length and maintenance intervals, potential savings of between 25-28 million tonnes of CO_2 annually could be achieved by choosing maintenance practices such as chip seal and crack seal over thin overlays
- Low carbon construction can offer carbon savings across three main areas of carriageway construction; materials reduction and reuse, energy reduction and transportation efficiencies
- Low carbon concrete: the production of cement is very carbon intensive. Carbon reduction can be achieved using biothermal and renewable energy to produce cement and by reducing clinker or using clinker substitutes. Subject to development and implementation, an ongoing increased reduction of about 7.5 million tonnes of CO_2 could be achieved annually by 2030, based on an assumption that 10% of cement is used in the road construction sector
- Construction of smooth and stiff pavements can reduce transport emissions, by improving fuel efficiency of the vehicles driving on them. When compared to conventional pavement construction, the CO_2 savings associated with low rolling resistance pavements could be between 6,000 and 12,000 tonnes, per 1 km of high traffic, 4-lane carriageway during a 15-year life
- The use of circular economy approaches has the potential to make a significant contribution to completing the decarbonisation of the transport sector, although the savings are currently site specific, as these approaches remain in trial stages generally
- Low carbon materials are available that offer significant carbon savings over conventional materials, for example, the use of warm mix or cold mix asphalt in place of hot mix asphalt could save around 8 to 16 tonnes per 1 km of 4 lane carriageway
- Many smaller items of construction plant, such as mini diggers, are now offered in battery electric variants, whilst trials are underway of direct burn of hydrogen trialled and hydrogen fuel cell operation for large plant. Road maintenance activities alone may emit 8 million tonnes of CO_2 per year. There is the potential to save a significant proportion (potentially up to 50% for some sites and operations) through job site optimisation, machine optimisation and machine control. There is the potential for the remainder to be powered by electricity or hydrogen
- The use of solar powered lighting solutions for construction sites is increasingly replacing diesel generators. Some claim to be able to operate year-round, even when there are 16 hours of darkness, whilst others are solar hybrid with a diesel back up. It could be possible to save 5 tonnes of CO_2 per year, per unit by switching to either solar power, or green hydrogen. Estimating the potential savings achievable by replacing diesel generators with

solar power or green hydrogen is far more difficult due to the large variations in the size and applications, however, savings could be in the order of millions of tonnes per year

- Emissions generated from vehicles using the road represent the largest source of carbon at 5.6 billion tonnes, but the one with which national road administrations have the least control. Theoretically, all this could be provided by carbon neutral means, through electric vehicles being charged with electricity produced by renewables, or green hydrogen produced by electrolysis of water, powered by renewable energy. Better use of existing roads through higher vehicle occupancy, public transport or infrastructure designed for walking and cycling could decrease carbon emissions in the short to medium term
- LED lighting as a replacement for traditional lights can offer savings. In some countries solar lighting solutions can reduce electricity consumption from the grid to zero. Whilst the carbon savings from switching to LED lighting depends greatly on type of system being replaced, globally, the world has approximately 363 million streetlights. It is estimated that by replacing an additional 10% with LED technology, global annual reductions of between 2.5 – 16.5 million tonnes of CO_2 could be achieved
- As with highways, the rail sector also has targets for decarbonisation and there is good practice that can be shared, including examples of measuring and managing carbon, production of renewable energy on estates, certification of electricity being of green origin and power purchase agreements to fund for zero carbon power solutions
- Non-Motorised Transport (NMT) can offer significant carbon savings and offer economic, social and health benefits. However, it is crucial that the schemes are designed with NMT as a priority from inception rather than an add on to motorised schemes. In England, it is expected that there will be between 1-6 million tonnes of CO_2 reduction between 2022 and 2030 due to a reduction in car emissions by promoting public transport, cycling or walking as the natural first choice for those capable. If these figures for England were extrapolated globally, an estimated additional reduction between 2-13 million tonnes of CO_2 could potentially be achieved annually
- Transfer to public transport offers the potential for carbon savings, whilst making better use of the existing infrastructure. Figures from the UK indicate that a modal shift from private car to bus transport for 10% of the public would result in a reduction in the range of 5.8 million tonnes of CO_2 annually. Extrapolation of the figures to a global scale would lead to a reduction of potentially up to 190 million tonnes of CO_2 annually

Part D of the report presents our conclusions and recommendations. Whilst there is the potential to reduce carbon across various areas of road construction, maintenance and operation, the extent to which road administrations have control over the sources of emissions differs. For example, choosing to install LED lighting or purchase green electricity is entirely within the remit of road administrations. Whilst not in their direct control, road owners can request and facilitate the use of lower carbon materials on their network. Finally, for decarbonisation of the vehicles using the network, the road owners have the least influence, but can support wider governmental targets by providing, e.g. EV charging stations. A table of technology options, potential carbon savings, road owner control and suitability for LMIC or HIC is presented.

Much progress has been made, in LMICs and HICs, on establishing policies and pledges to decarbonise road transport, with large numbers of examples demonstrating progress in reducing carbon emissions by NRAs. However, it is also clear that long-term strategies for delivering the transformation needed to become carbon-neutral or reach net-zero across all their networks are either in the early stages of development or yet to start. During this research the following themes have emerged as important enablers:

- Strategy - it is necessary to develop a long-term-strategy, setting out a roadmap with intermediate target dates for reducing carbon emissions. With published target dates for net-zero for most countries within a 30-year horizon, this process must begin urgently. Establishing a baseline of the sources of current emissions is an essential early step to identify the areas for focus and to measure progress in achieving reductions
- The knowledge, skills, mindsets and behaviours of the entire workforce (e.g. policy makers, delivery teams, supply chain), all play a significant role in achieving decarbonisation as they are collectively responsible for identifying and evaluating options, managing procurement and delivering the solutions identified. Road administrations should invest in the skills and knowledge of their personnel and ensure that their supply chains do likewise
- Some initiatives for decarbonisation will be outside the influence of individual NRAs, e.g. incentivising uptake of EVs. NRAs should adopt a proactive role in engaging with other agencies and leading cooperation throughout the supply chain to facilitate change
- The approach adopted by NRAs in procurement greatly influences the response of the supply chain. To achieve decarbonisation, standards (e.g. construction, maintenance, materials, safety etc), must actively encourage innovation and enable the development and adoption of new materials, ways of working etc that have lower carbon impacts. Road administrations should review their standards and tender evaluation criteria so that appropriate weight is given to decarbonisation
- For road construction and maintenance, whole life analysis (WLA) of carbon impacts is critical to understanding the most carbon efficient solution for specific situations. Road administrations should develop the assessment of carbon impacts within WLA and make this a routine part of options appraisal
- A striking finding from the gap analysis is the limited rigour of the evidence presented on the actual or potential reductions in carbon emissions due to adopting particular strategies when implementing projects. This makes it difficult for road administrations to learn from the experience of others and assess how best to pursue their own goals of carbon neutrality. Road administrations should support evidence gathering, data collection, identifying success factors and sharing knowledge of lessons learned

Finally, road administrations have significant opportunity to play an important role in reducing carbon emissions, whilst maintaining mobility for road users. Many of the solutions identified in this report can assist them in doing so.

CONTENTS

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1 INTRODUCTION

Road transport is vital for society to function, enabling work, leisure and other essential travel for people, and the transport of goods between source and destination. Roads will continue to be the dominant mode of transport for people and goods in the foreseeable future. At the same time, the construction, operation, maintenance and use of the highway infrastructure are responsible for large quantities of carbon emissions. Of these emissions, the largest proportion result from vehicles using the infrastructure.

Knowledge of the non-reversible, damaging consequences of climate change has resulted in global acceptance of the need to reduce carbon emissions in all sectors of human activity, including the highways sector. However, as efficient transport is vital to national economic growth, actions to reduce carbon emissions from the sector must not negatively impact the development and maintenance of high-quality road infrastructure, particularly for LMICs (Low and Middle Income Countries).

This project funded by PIARC aims to identify actions being undertaken by the sector as well as potential new options to progress towards carbon neutrality. Net zero carbon and carbon neutrality represent two different approaches to combat climate change. There has been a certain amount of ambiguity in the understanding of these two approaches and there are examples in literature of the terms being used interchangeably[1]. However, there is a general consensus on the definitions for the two approaches, as follows:

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- **Carbon Neutrality***:* is *balancing carbon emissions by 'offsetting',* i.e., separately removing carbon in the atmosphere to balance that which is emitted

The above definitions have been adopted by PIARC and form the basis of their use throughout this report. Whilst the stated aim of the project is to identify best practice and recommendations to support PIARC members achieve carbon neutrality, on a global scale this will only be achievable in the necessary timeframe with a significant reduction in carbon emissions. This report therefore presents an overview of current and potential future practice and technologies that could help the roads sector to contribute significantly to a low or zero carbon transport future.

1. TRANSPORT CONTRIBUTION TO GLOBAL CARBON EMISSIONS

Total global CO_2 emissions increased between 2010 to 2019 and following a temporary reduction on 2020 due to the Covid-19 pandemic, rebounded in 2021 to reach a total of 36.3Gt

[1] https://webflow.plana.earth/academy/what-is-difference-between-carbon-neutral-net-zero-climate-positive#:~:text=When%20carbon%2Dneutral%20refers%20to,energy%20as%20%E2%80%9Czero%20carbon.%E2%80%9D

[2] (36.3 billion metric tonnes). The transport sector share of the total emissions ranges between 20 to 25% [3] and within the transport sector, the roads sector accounts for around 71% of fuel combustion as outlined in Figure 1[4], below. Note that the chart shows the figure for CO_2 from fuel combustion. When using this measure, transport's share of CO_2 emissions is 31%; rather than the 20 – 25% share of overall emissions listed above. This reflects the fact that most of the CO_2 emissions from transport (apart from some electrically powered rail) comes from fuel burnt for propulsion, whereas in other sectors there might be a higher proportion of CO_2 emissions resulting from other sources, such as materials extraction.

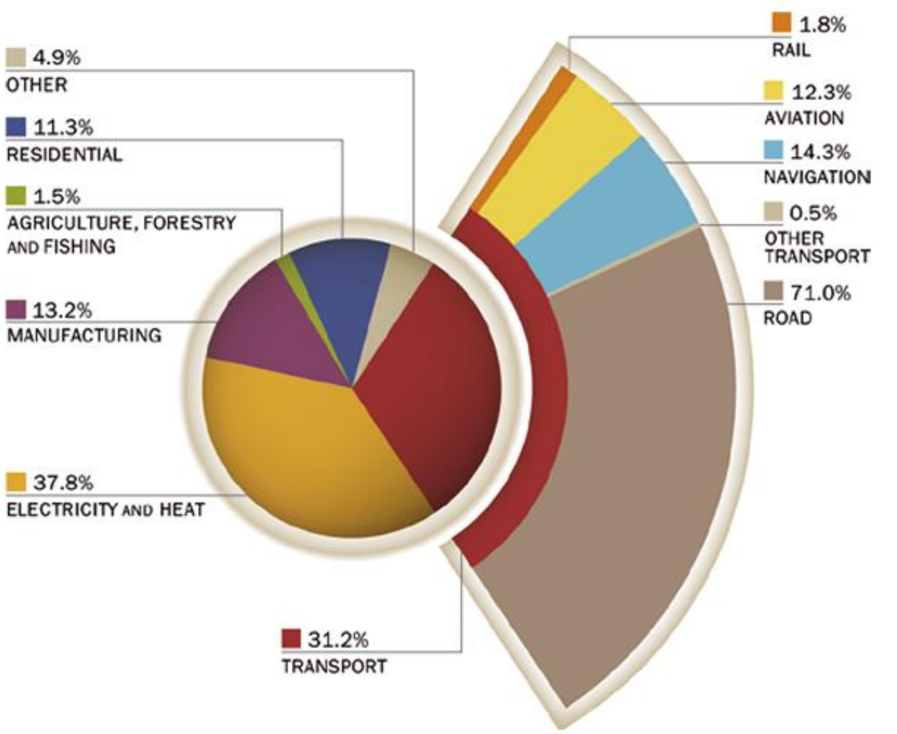

Figure 1. CO_2 emissions from fuel combustion by sector

(Source: IEA/UIC (2012) Energy consumption and CO_2 Emissions of World Railway Sector. All rights reserved)[4]

Specific worldwide examples of this are as follows:

- **China**[5]: in 2020 the total emissions, at 11,680 $MtCO_2e$ (11,680 million metric tonnes), was the highest in the world with the transport sector accounting for around 70%. China is also one of the leading spenders on transitioning to clean energy and has announced a focus on "fossil fuel ban" as the main driving force to achieve net-zero emissions by 2050
- **USA**[6]: In 2020, the transport sector contributed 27% of the total emissions of 5,981 $MtCO_2e$. As with the EU and UK, the transport sector has the largest share of the total emissions, primarily from fossil fuels used by motorised vehicles

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[2] Global Energy Review: CO2 Emissions in 2021 – Analysis - IEA
[3] Cars, planes, trains: where do CO2 emissions from transport come from? - Our World in Data
[4] International Energy Agency and the International Union of Railways, Energy consumption and CO2 Emissions of World Railway Sector, 2012, iea-uic_2012final-lr.pdf.
[5] Toward Net Zero Emissions in the Road Transport Sector in China | WRI China
[6] Sources of Greenhouse Gas Emissions | US EPA

- **EU**[7]: The EU's greenhouse gas emissions totalled approximately 4,375 MtCO_2 e in 2017[8], with transport responsible for a quarter. In contrast to other sectors, GHG emissions from the transport sector have continued to increase in the last 3 decades. Road transport, in general accounts for the largest share and in 2019 accounted for 71.7% of the EU-27 transport sector emissions. Looking ahead, transport sector emissions are predicted to decrease, and the road sector is expected to contribute the largest share of the reduction (most of it coming from reduction in emissions from passenger cars)
- **UK**[8]: In 2019, the transport sector was responsible for 27% of total emissions of 455 MtCO_2e. Within the transport sector, cars and taxis were responsible for 61% (68 MtCO_2e) of the emissions, Heavy Goods Vehicles 18% (19.5 MtCO_2 e) and vans 17% (19 MtCO_2e)
- **India**[9]: In 2020, emissions from the transport sector were reported to be 277 MtCO_2e. Transport is the 3rd most CO_2 emitting sector and, as with other countries, the roads sector bears the largest share (90%). As a developing country with a growing economy, India is in the early stages of building its highway infrastructure and has a rapidly expanding car ownership profile. But the country has declared a Net Zero target to be achieved by 2070 and the highway sector is committed to the target
- **Canada**[10]: transport is Canada's second highest carbon emitting sector, contributing 186 Mt CO_2 e per year (25% of all emissions), behind the oil and gas industry which emits 191 Mt CO_2. In such a large and diverse country, there are significant differences between the provinces; for example, the transportation sector accounted for approximately 12% of Alberta's[11] annual GHG emissions, which is the third largest sector after oil/gas and electricity
- **Australia**: transport in Australia in 2021[12] represents 17.5% of emissions, however, there are significant differences between the States. For example, in South Australia, transport's GHG emissions share was 25%[13] due to the decarbonised grid in the State compared to Australia as a whole, lowering the relative shares of emissions of other sectors. As such, there is great potential for EVs to lower overall emissions in the state

It is notable that the LMIC examples above show transport as having a much higher share of total emissions, 70% and above, compared to HIC (high income countries) share being around 20-25%. This is presumably due to HICs having higher overall emissions from, for example, higher residential energy use through electricals and white goods, such as fridges and washing machines.

Whilst there was a fall in global CO_2 emissions in 2020 due to reduced industrial activity and restrictions on mobility caused by the COVID pandemic[14], energy related emissions grew to 36.3 GtCO_2, in 2021, a record high[15]. Oil use for transport in 2021 remained below pre-

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[7] Transport and environment report 2021 Decarbonising road transport — the role of vehicles, fuels and transport demand. https://www.eea.europa.eu/publications/transport-and-environment-report-2021

[8] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/984685/transport-and-environment-statistics-2021.pdf

[9] CAT_2020-12-09_Report_DecarbonisingIndianTransportSector_Dec2020.pdf (climateactiontracker.org)

[10] https://www.canada.ca/content/dam/eccc/documents/pdf/cesindicators/ghg-emissions/2021/greenhouse-gas-emissions-en.pdf

[11] Climate change and transportation, Government of Alberta, Canada, Climate change and transportation | Alberta.ca

[12] https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-gas-inventory-quarterly-update-march-2021

[13] https://www.environment.sa.gov.au/topics/climate-change/south-australias-greenhouse-gas-emissions

[14] https://www.iea.org/reports/global-energy-review-2021/co2-emissions#abstract

[15] https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

pandemic levels, with demand reduced by 6 million barrels per day below 2019 levels and emissions 600Mt lower.

Even with the reduction in demand in 2020, global CO_2 emissions in 2020 from transport amounted to over 7 Gt, of which road transport emissions (two and three wheelers, light duty vehicles, bus and minibus and heavy trucks) accounted for 5.6 Gt[16], as shown in Figure 2., below. To reach the Net Zero Emissions by 2050 Scenario, requires a 20% reduction in total transport emissions to 5.6 Gt by 2030.

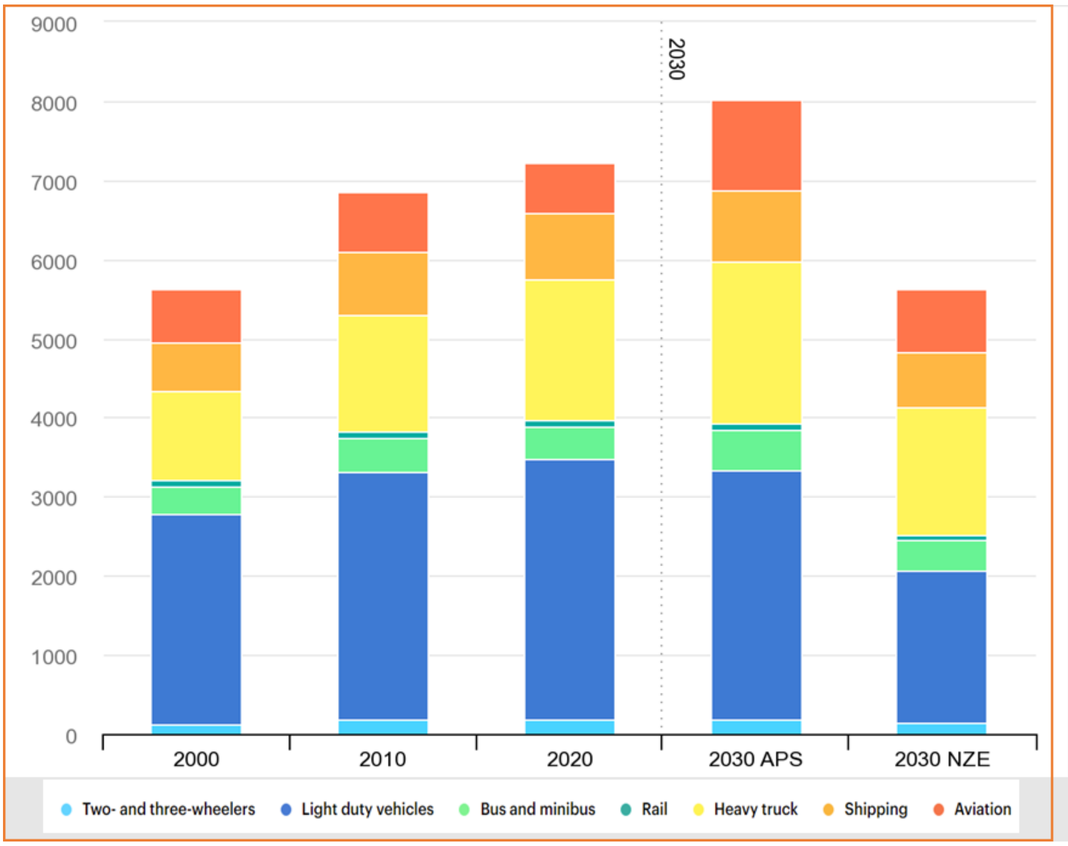


Figure 2. Global transport emissions by subsector 2000 – 2030 (reproduced from IEA)

In reporting national GHG inventories, the 'transport sector' includes vehicle emissions only, which are the largest but, by no means, the only source of emission in the road transport sector. Emissions surrounding e.g. concrete for road construction, or steel for lighting columns would be recorded elsewhere and these need to be considered by transport agencies when planning the path to zero emissions. More information is provided in Figure 4.

2. CLASSIFICATION OF SOURCES OF EMISSIONS

[16] IEA (2021), Tracking Transport 2021, IEA, Paris https://www.iea.org/reports/tracking-transport-2021

There are three classifications defined within the Greenhouse Gas Protocol (GHG Protocol)[17] that are used internationally to describe and understand sources of emissions[18]. As applied to NRAs, they represent:

Scope 1 – This covers emissions from sources directly controlled by the NRA and are the direct result of their activities, for example, the fuel used in their fleet vehicles (non-EVs).

Scope 2 – This covers indirect emissions associated with the activities of the NRA based on emissions from purchased energy, e.g. the electricity purchased by the NRA and used to power EVs. The emissions physically occur at the location where the energy is produced.

Scope 3 – Indirect emissions associated with the NRA and not covered within Scope 2. These are indirect emissions associated with activities up and down the NRA's supply chain, i.e. the emissions are linked to NRA operations but not controlled directly. For example, the use of goods purchased from a supplier or from the company's own products when customers use them.

Scope 1 and Scope 2 emissions are mostly within the control of the NRA. Emissions from Scope 3 are the more difficult to quantify and are also the most difficult to reduce[19]. Figure 3[20] illustrates the key emissions as outlined in the Greenhouse Gas Protocol standards.

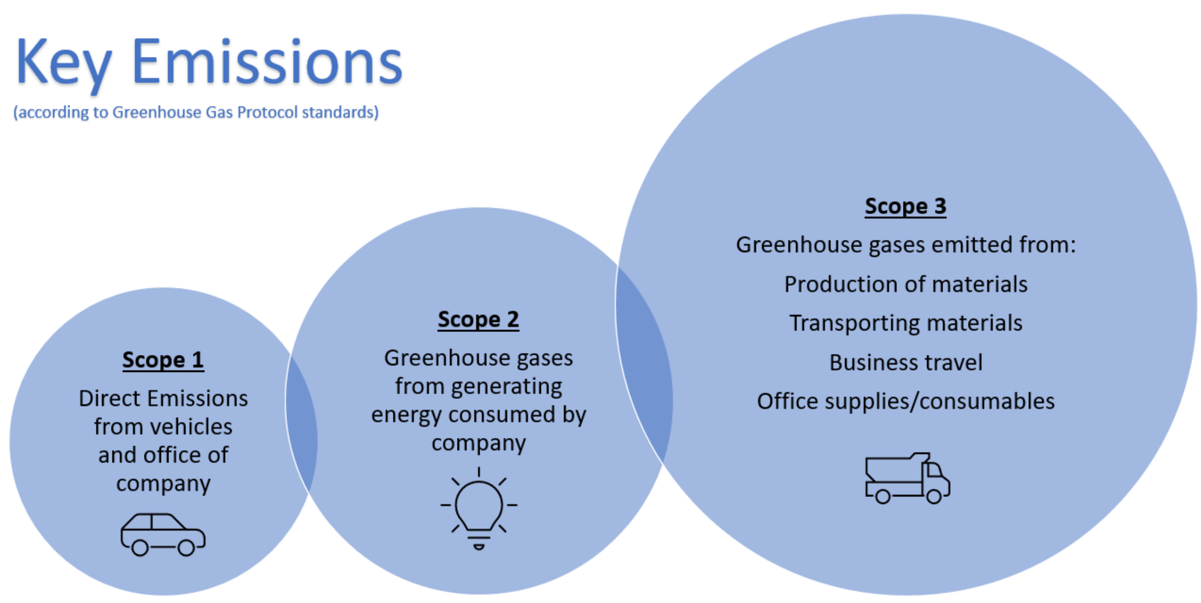


Figure 3. Key Emissions

(Reproduced from National Highways Net Zero Highways plan)

While the GHG Protocol identifies, explains, and provides options for GHG inventory best practices, ISO 14064 "International Standard for GHG Emissions Inventories and Verification"

[17] FAQ.pdf (ghgprotocol.org)
[18] What are scope 1, 2 and 3 carbon emissions? | National Grid Group
[19] What are scope 1, 2 and 3 emissions? | Deloitte UK
[20] net-zero-highways-our-2030-2040-2050-plan.pdf (nationalhighways.co.uk)

is an international standard that acts as a guide to the public and private sector in quantifying and reporting GHG emissions[21]. ISO 14064 is climate policy neutral but can be used as a basis to develop GHG inventories and develop policies in relation to climate change.

National Highways in the UK has taken the approach to identify and categorise sources of emissions within the road network and has set specific targets within each category to reach Net Zero between 2030 and 2050. The distinction between groups is different to the Greenhouse Gas Protocol definition and forms a logical approach against which detailed plans can be developed for reduction. The following three categories are identified[22]:

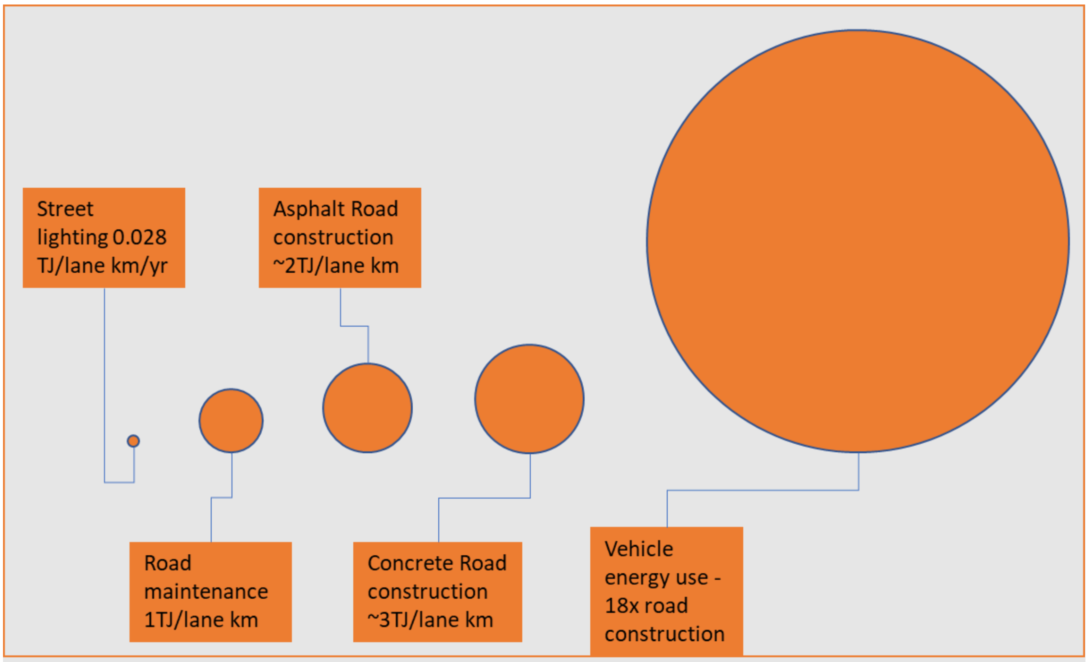
Corporate Emissions – This covers energy used and travel by National Highways. For example, this includes energy purchased and fuel used by fleet vehicles

Maintenance & Construction Emissions – This includes all emissions associated with the production and transport of materials required to construct and maintain roads within the network

Road User Emissions – These cover emissions from users of the road network

3. Sources of Road Transport Emissions

While the largest source of emissions are the vehicles using the road networks, as shown in Figure 4, the construction (e.g. new build), operations (e.g. street lighting, tunnel lighting and ventilation) and maintenance of the highway network also represent large sources of carbon emissions.



[21] ISO 14064 International Standard for GHG Emissions Inventories and Verification (epa.gov)
[22] https://nationalhighways.co.uk/netzerohighways/

Figure 4. Relative energy use per activity

Whilst the 4 circles in Figure 4, covering lighting, maintenance and construction are dwarfed by the magnitude of vehicle energy use, they are not insignificant either proportionately or in terms of total CO_2 emissions. In addition, these are the areas where road administrations have a greater ability to take actions to reduce emissions, acting independently or working in collaboration with its supply chain. Road administrations do have some influence on vehicle energy use by, for example, having well maintained and free flowing roads that promote vehicle fuel efficiency, supporting transition to low emission driving, such as providing efficient infrastructure for electric vehicles (EV), enabling a more friendly infrastructure for public transport vehicles, non-motorised vehicles, pedestrians etc.

4. STRUCTURE OF THIS DOCUMENT

This document details practices and technologies to reduce carbon emissions and achieve carbon neutrality in the highways sector. It is divided into three sections plus conclusions and recommendations, as shown in Figure 5 below.

Part A contains a review of existing policies and strategies adopted by state and national Governments and road administrations, highlighting good practice and opportunities for the future.

In Part B, the technical solutions and opportunities for the future are explored.

Part C, takes a deeper dive into two specific solutions, namely, LED lighting and road construction.

Part D of the report presents our conclusions and recommendations.

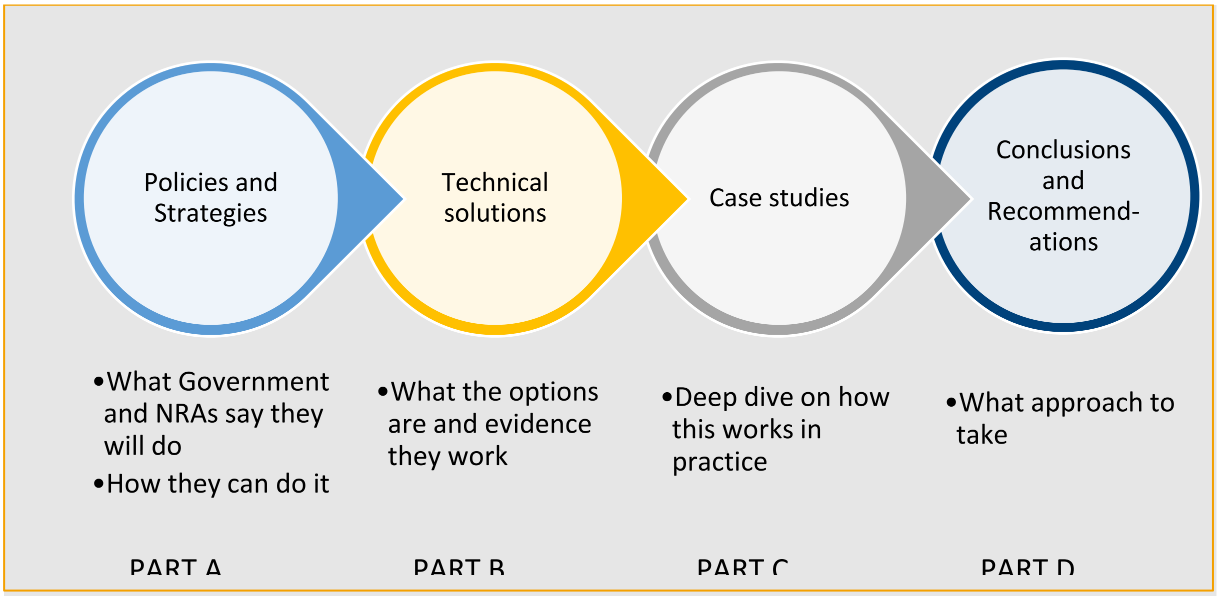


Figure 5. Document structure

Much of the literature reviewed pertains to national highway networks or road networks operated by National Road Authorities (NRAs). Local and regional roads operated by local authorities are not addressed specifically, despite many countries having extensive local road networks, that may carry significant freight traffic contributing to a relatively significant proportion of carbon emissions. It is also acknowledged that in many LMICs, the road network is operated in a fashion more similar to management of local and regional road networks in HICs. This should be given due consideration when reviewing the data contained within this report and in particular, the recommendations. However, many of the approaches and recommendations drawn are applicable to all networks, and governments must always consider the full picture of road transport emissions within any strategy for net-zero and carbon neutrality, and utilise measures which are shown to be effective for the type of road network being addressed.

PART A – Policies, Strategies and Procurement

2 POLICIES AND STRATEGIES

The need to address the consequences of steadily intensifying climate change has gained momentum globally in the last decade and national governments have responded by making strong commitments to reduce their GHG emissions.

2.1 NATIONAL TARGETS FOR DECARBONISATION

On global as well as national scales, significant reduction in carbon emissions is key to mitigating climate change impacts. Over the last few years, globally there has been increasing momentum towards achieving Net Zero[23]. A significant number of national governments have therefore defined their policies based on setting or starting the process for setting the direction to achieve Net Zero.

Table 1 shows the 2022 position with respect to stated Net-Zero policy for 130 countries. Two countries, Bhutan and Suriname have already achieved 'carbon negative' status and their challenge is to maintain this status in the face of expanding road infrastructure and growing numbers of vehicles (currently mainly fossil fuel based). The other 128 countries (78 LMICs and 50 HICs) have set or are in the process of setting target dates spanning the period 2030 to 2070. It is interesting to note that, since 2019 when the UK became the first major economy to enshrine 'Net Zero by 2050' in law, to date only 15 HICs (which includes the EU bloc) and one LMIC have followed suit.

The stated aim of the project is to identify options for carbon neutral roads. While countries do not appear to have adopted carbon neutrality as a target, there is recognition that achieving net-zero nationally will not mean that every sector or area of the country will also reach absolute zero emissions by the same date. The reality is that some sectors or aspects within a sector could still be 'net sources' of GHG by the planned target date and in that case, the emissions would need to be offset by other sectors or aspects of sectors that are 'net sinks'. So, in effect, strategies to achieve net zero include development of options to absorb emissions from the atmosphere, i.e. offsetting.

[23] https://www.un.org/en/climatechange/net-zero-coalition

Table 1. Net Zero Tracker – Global (2022)

Net Zero Policy / Target Years					
Already Carbon Negative (takes more GHG from atmosphere than emitted)					
		Suriname	Bhutan		
In law	**In policy document**		**Declaration/Pledge**	**Proposed/in discussion**	
2045 - 2060	**2030-2060**		**2050-2070**	**2030-2050**	
2045	**2030**	**2053**	**2050**	**2030**	**2045**
Germany	Maldives	Turkey	UAE	Bangladesh	Nepal
Sweden	**2035**	**2060**	Israel	Mauritania	
Portugal	Finland	China	Estonia	Guinea-Bissau	
2050	**2040**	Ukraine	Andorra	**2050**	
Japan	Iceland	Sri Lanka	Brazil	Switzerland	The Bahamas
France	Antigua & Barbuda		Thailand	Slovakia	Nauru
UK	**2050**		Argentina	Cyprus	Seychelles
S Korea	USA		Malysia	Trinidad and Tobago	Niue
Canada	Italy		Vietnam	Mexico	Mauritius
Spain	Belgium		Colombia	Pakistan	Namibia
Ireland	Austria		S Africa	Peru	Togo
Denmark	Chile		Kazakhstan	Ethiopia	Somalia
Hungary	Greece		Malawi	Myenmar	Sierra-Leone
New Zealand	Panama		Cape Verde	Dominican Republic	Burundi
Luxemburg	Croatia		**2060**	Sudan	The Zambia
EU	Uruguay		Saudi Arabia	Bulgaria	Lesotho
Australia	Latvia		Bahrain	Tanzania	Central African Reublic
Fiji	Malta		Nigeria	Lebanon	Tomor-Leste
2060	Slovenia		**2070**	Afghanistan	Solomon Islands
Russian Federation	St Kitts & Nevis		India	Zambia	Granada
	Monaco			Senegal	Comoros
	Singapore			Burkina-Faso	Samoa
	Lithuania			Mozambique	Sao Tome and Principe
	Costa Rica			Papua New Guinea	Vanuatu
	Marshall Islands			Guinea	Tonga
	Belize			Nicaragua	Micronesia
	Romania			Haiti	Palau
	Laos			Niger	Kiribati
	Ecuador			Rwanda	Tuvalu
	Lliberia			Jamaica	Eritrea
				Chad	Yemen
				Saint Vincent & The Grenadines	
HIC				**2060**	
LMIC				Indonesia	

2.2 NRA STRATEGIES TO ACHIEVE NET ZERO/CARBON NEUTRALITY

Road administrations' policies are in general linked to national net zero commitments and strategies are therefore focussed on reducing emissions from their activities, while continuing to deliver on the fundamental role of roads in maintaining the economic well-being of society. There are some common themes in the strategic options being considered by NRAs to reduce emissions. These include:

Transition to EVs: This is seen, by almost all national governments and road administrations as one of the most important actions in the decarbonisation of transport sector. Progress has been made and although there are barriers, in particular for LMICs, there is growing recognition of the critical importance of this transition. For example, EV promotion has been included in the Indian Government's[24] National Electric Mobility Mission Plan (NEMMP) 2020, which set out a roadmap to accelerate the adoption and manufacture of electric and hybrid vehicles in the country, with the aim, among others of achieving national fuel security.

The transition to EVs[25] and the gradual withdrawal of diesel and petrol cars is becoming an integral part of the Net zero strategy through setting timeframes for a ban on sale of new fossil fuel powered cars: Norway 2025, UK 2030, Canada, EU and California 2035[26]. In India, the move away from petrol cars has been extremely slow but the expectation is that lighter vehicles (2 and 3 wheelers) will lead the transition, as happened in China [27].

EV (car) sales have grown dramatically in recent years, mainly in HICs but highest growth has been recorded in China. Growth is, however, lagging in most other LMIC countries, with for example, EVs forming only 0.5% of new cars in Brazil, India, Indonesia with the main barrier to uptake being upfront costs, range, speed, battery life and battery technology. At the same time, reducing reliance on it is also perceived as a means of improving fuel security.

For LMICs in particular upfront cost continues to be a major barrier. For example, Bhutan, an LMIC, is facing a rapid increase in the number of cars (from 25,000 in 2000, to 89,300 in 2017 and 116,926 in 2021)[28] which is a threat to its current 'carbon negative' status. While the drive to EVs began in 2014, the number of EVs in the country currently stands at just 161. In addition to other barriers, cost is a serious challenge, both for the provision of the infrastructure and the purchase of EVs[29].

Investment in building appropriate charging infrastructure has increased nationally (public and private sectors) as well as by global agencies but there are significant barriers too. For example, barriers in the UK[30] include lack of an overarching strategy to enable provision of sufficient charging infrastructure, restricted network (transmission and distribution) capacity and supply of vehicles (particularly vans). A more detailed discussion on EVs is included later in the Report.

- **Non-motorised transport (NMT) infrastructure**: This includes mainly walking and cycling and is seen in both HICs and LMICs as providing significant contribution to decarbonising the road networks (particularly in urban locations) and increasing social cohesion.
- Road infrastructure solutions such as dedicated cycleways and safer junction designs are being used to encourage active transport. Transport for London (UK)[31] have an overarching goal of achieving 80% of journeys in London to be made by walking, cycling or public transport.

[24]https://policy.asiapacificenergy.org/node/2663#:~:text=The%20National%20Electric%20Mobility%20Mission,on%20year%20from%2020 20%20onwards.
[25] International Energy Agency (IEA). Global EV Outlook 2020. Entering the decade of electric drive?
[26] Factbox – fossil fuel-based vehicle bans across the world. Thomson Reuters Foundation. November 2020.
[27] KPMG (2020), Shifting gears: the evolving electric vehicle (EV) landscape in India, Shifting gears: the evolving electric vehicle (EV) land - KPMG India (home.kpmg)
[28] Chow Ping (2022). Electric vehicles are Bhutan's answer to air pollution.
[29] Zhu D, Patella DP, Steinmetz R, Peamsilpakulchorn P (2016). The Bhutan electric vehicle initiative. The World Bank Group.
[30] Terri Wills (2020). The UK's transition to electric vehicles. Climate Change Committee.
[31] Mayor's Transport Strategy, 2018. Mayor of London. Mayor's Transport Strategy (london.gov.uk)

- Netherlands is a leader in the provision of dedicated road infrastructure for cycles and is working on 30 new projects across the country. The terrain (mainly flat), cultural and political factors as well as central government help with financing have contributed to this success.

Germany built its first cycle highway in 2015 and has since moved to a more ambitious project, a 3.65m wide, fully lit 100 km long bicycle autobahn connecting 10 cities in the Ruhr region. The distance between cities in this region is less than 10 miles, making it ideal for commuting by bicycles. In addition to health benefits, this project is predicted to remove 50,000 cars every day from the road network, equivalent to 16,000 tonnes of carbon emissions. Norwegian government has also recently unveiled its plan to invest £700m in bicycle highways.

The actual share of non-motorised transport in cities in LMICs is most often higher than that of similar sized cities globally. For example, in India, Surat has the greatest share of walking and cycling (55% for a population of 2.4 million), while Bangalore has the lowest (25% for a population of 8.6 million) in comparison to London (14% with a population of 6.6 million)[32]. However, another major barrier in LMICs is that as motorisation has increased, safety of pedestrians and cyclists has been impacted, particularly the urban poor who are dependent on these modes. Around 12% of reported road fatalities are reported to be pedestrians and cyclists but the WHO in fact estimates this number to be much higher[33].

While growth of NMT in LMICs is being held back by cultural factors (car ownership is new and growing, and is a status symbol) as well as the quality of the infrastructure (e.g. poor road surfaces and connectivity) and the environment (e.g. pollution), safety and risk, there are also examples of good practice as illustrated with two examples from India and Kenya:

India: NMT is the preferred transport mode for much of the population in India due to its affordability, although in recent decades cities have been experiencing a decline in the use of NMT. There are several underlying causes including a growth in and greater focus on infrastructure for motorised transport and increasing accident rates for pedestrians and cyclists. At the same time there has also been a growing recognition that while per capita emissions in India are low, emissions from the transport sector are on an upward trajectory leading to increasing pollution and health impacts from the higher consumption of energy from non-renewable sources. This has led to efforts by the Government of India to coordinate policies at the national level to achieve a sustainable transport system and build the capacities of cities to improve mobility with lower CO_2 emissions[34].

The Institution for Transportation and Development Policy (ITDP) in India has been working with cities to design and implement sustainable transport policies, e.g. helping the City of Chennai to develop India's first NMT policy[35]. The Chennai Corporation adopted the policy in

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[32] Pai, M. (2007), Transport in cities - India indicators, India-Integrated-Transport-Indicators-EMBARQ.pdf (wrirosscities.org)
[33] WHO (2018) Global safety report on road safety. Global status report on road safety 2018 (who.int)
[34] Tiwari G and Jain D (2013). Promoting low carbon transport in India. NMT Infrastructure in India: Investment, policy and Design. UNEP. ISBN 978-87-92706-19
[35] 2-Training-manual-MAQ3-NMT.pdf (sdabnca.org)

2014 and this resulted in the Corporation mandating 60% of the city's transport budget for the construction and maintenance of NMT. In addition, they have worked to change attitudes to car-free Sundays, tactical urbanism and education programmes for policy makers. By 2018, 120km of pavements and public bike-sharing schemes (to improve last mile connectivity) had been built, and work is on-going to transform 1,000 km of streets to be safe and accessible to pedestrians and cyclists by 2030[36].

Kenya: NMT is the primary form of transport for a significant proportion of the population in many African cities, mainly because motorised (and in general, safer) modes of transport are unaffordable. Despite this, only 10% of countries in Africa have policies to promote walking and cycling, compared with 64% in Europe. In Nairobi, for example, walking and/or cycling is the primary mode of transport for around 50% of the population and despite being clean, healthy and efficient, has been in decline[37].

Working in collaboration with the UNEP-led global programme, 'Share the Road', the Kenyan Government developed and introduced its NMT policy in 2011. The policy was not only about improving the NMT network but also ensuring that NMT facilities and areas were prioritised for investment, and that walking and cycling facilities were integrated within all new urban road projects in Kenya. The Nairobi City County Government launched its NMT policy for Nairobi in 2015. The policy proposed a range of measures including lower road speeds, new infrastructure and traffic calming measures, awareness raising activity, enforcement and financial commitment to address the high numbers of pedestrian fatalities (70% of the 723 road traffic fatalities in Nairobi in 2014) and also committed 20% of existing and future transport budget to walking, cycling and public transport infrastructure and services[38].

Another major barrier to mass take-up can be the high cost of construction of dedicated NMT infrastructure, ~ €2m/km (based on the German experience of cycle highways). This compounds the difficulty of justifying the investments using standard methodologies. For example, BCR for new highways are often driven by the benefits of journey time savings for large numbers of road users, including passenger cars and freight. Enablers of NMT infrastructure include Government investment (e.g. German Government has kick started the process with an initial investment of 1.5 billion Euros) as well as incentives to encourage transfer from cars to bikes ensuring safety on the cycle networks.

To advance the development of NMT in LMICs, UNEP (United Nations Environment Programme) has supported the development of a project appraisal tool to evaluate the costs and benefits of NMT, designed specifically for cities in developing countries[39]. The aim is to

[36] Chennai Non-Motorised Transport Policy (itdp.in)
[37] Share the road – prioritizing walking and cycling in Nairobi - PPMC TRANSPORT (ppmc-transport.org)
[38] Fact sheet: Non-motorised transport (NMT). www.fiafoundation.org
[39] Cost benefit analysis of NMT projects. UNEP. https://www.unep.org/resources/report/cost-benefit-analysis-non-motorized-transport-infrastructure-projects

raise the profile for investment in NMT which is currently perceived as less important than other transport solutions. Four case studies using scenarios in Nairobi, Kenya and training workshops have demonstrated the capability of the tool to accurately and equitably appraise investments in NMT in the African context.

- **Construction and maintenance of roads:** The decarbonisation targets and the more recent move to adopting a circular economy approach to road infrastructure design, construction and maintenance has resulted in an impetus to achieve significant reductions in carbon in highway projects. Globally there are many examples of new materials with reduced embodied carbon and innovative methods to reduce use of virgin materials, etc. More details are provided in Section 3.

Some high-level common threads running through the strategies being adopted by NRAs to reduce emissions during the construction and maintenance of roads include:

- Moving towards use of renewable energy as much as possible
- Building in requirements for emissions reduction targets (including Scope 3 emissions) into the contracts
- Developing, publicising and making available carbon reporting tools to contractors covering
- Tree planting programmes
-

New Zealand

The Ministry of Environment[40] has proposed an Emissions Reduction Plan that will mandate the reporting of energy use and embodied carbon on all new construction and maintenance projects and include aspects such as, using materials and processes that are net zero, resilient to climate change, resource efficient (at use and in the future) and suitable for recycling, reuse and repurposing at end of life.

Sweden

Large transport infrastructure projects (roads, rail, tunnels) are required to calculate and report embodied carbon and monetary incentives are used to encourage the reduction of embodied carbon below specified targets.

India

The country is investing heavily in expanding its road networks with current plans to increase the size of its network by about a third in the next few years (representing approximately 40km of new highways per day). While decarbonisation is a key part of the long-term strategy, in the short-term the focus is on the rapid expansion to support national economic growth through the use of conventional methods of construction. However, there are elements that

[40] Transitioning to a low-emissions and climate-resilient future: Emissions reduction plan discussion document. Transitioning to a low-emissions and climate-resilient future: emissions reduction plan discussion document | Ministry for the Environment

support the principle of reduced emissions, e.g. since 2015, all new roads are mandated to have LED lighting.

Overall, NRAs are looking into developing maintenance options to support decarbonisation with more effort being put into identifying low carbon options. For example, smooth pavement surfaces with reduced rolling resistance can reduce fuel consumption and reduce GHG emissions.

- **Encouraging public transport:** The modal shift from private to public transport (buses, trains) is a global ambition but a challenge both in HICs and LMICs. The transition, for example, to cleaner electric-buses can be challenging. Bloomberg[41] reported that at the end of 2020, there were around 598,000 e-buses globally and of these, 585,000 were in China. Government subsidies combined with stringent city targets have enabled the transition in China. Other LMICs are finding the cost of the transition a serious barrier and any progress may well require coordinated action by international funding agencies.

In the UK for example, Government supported funding plans have helped to grow the number of e-buses for use in towns and cities with a longer-term aim of stopping sales of buses powered by fossil fuels, partly or wholly, by 2032 at the latest.

New EU policies aim to ensure that 25% of public sector purchased buses will be e-buses by 2025, increasing to a third by 2030. Transformation to e-buses has been underway in Netherlands for a long time and by the end of 2021, 81% of its fleet was electric. More rapid progress is also being made in selected cities, with Paris, Berlin, London, Copenhagen, Barcelona, Rome and Rotterdam aiming to reach fossil fuel free buses by 2025.

Some limited progress, though slower, is also being made in some LMICs. UNEP is helping African cities in their drive towards soot-free public transportation, including electric-powered buses[42]. The World Bank has been active in supporting the move to cleaner public transport in South America with e-fleets being introduced in a number of cities across the continent[43].

- **Decarbonisation of corporate emissions:** In addition to the carbon emissions associated with construction, maintenance and use of the road network, National Road Administrations (NRAs) give rise to significant sources of carbon emissions from the operation of the road network (lighting, tunnel operations, etc.), vehicle fleets, buildings, IT systems and employee travel. Since these activities are under the direct control of the NRA, they are often an initial focus for monitoring and decarbonisation.

2.3 QUESTIONNAIRE FINDINGS

A simple questionnaire was circulated, designed to capture information such as the adoption of targets for reducing carbon emissions, the strategies being adopted and a willingness to participate in further discussions.

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[41] https://www.bloomberg.com/news/newsletters/2021-08-13/electric-buses-are-poised-to-get-a-u-s-infrastructure-boost
[42] African cities turn to green buses in fight against pollution. UNEP. African cities turn to 'green' buses in fight against pollution (unep.org)
[43] Electric buses: where are we? Electric buses and charging infrastructures in the world - IES-Synergy

A total of 34 responses was received from 25 countries, including 8 LMICs. The geographical spread and number of returns in each country are indicated in Figure 6.

Figure 7 confirms the high proportion of countries with a national target date for achieving net zero (83% of the countries that provided a response) or carbon neutrality (54%). Seventeen countries reported national targets for both carbon neutrality and net zero, which perhaps reflects the interchangeable use over these terms. The importance of a national target date being in place is clear: in countries where a national target date for net zero is in place, 60% of respondents reported a target date for the road administration. Similarly, where a national target to achieve carbon neutrality is in place, 40% of road administrations had also adopted a target date. Only one country reported having a target for the road administration 21econe there was not a corresponding national target.

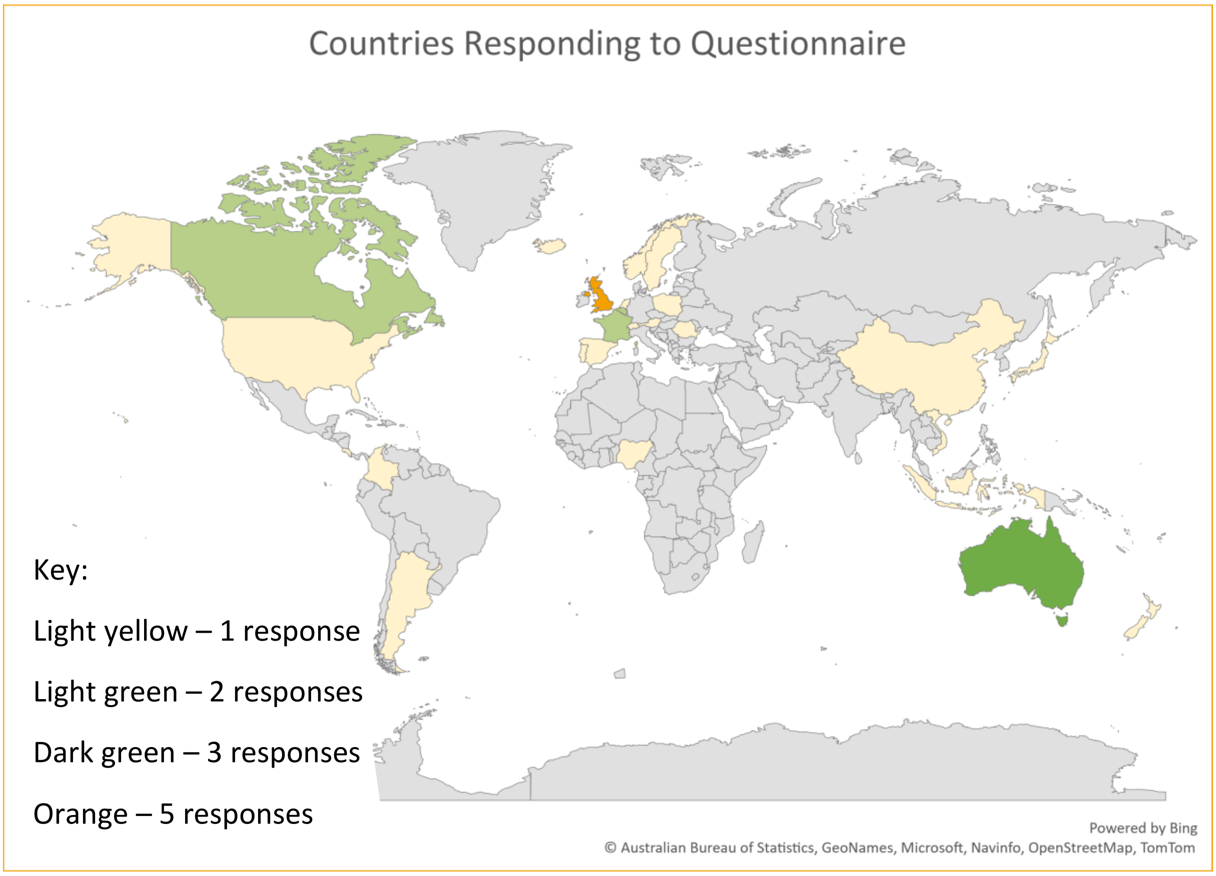

Figure 6. Geographical spread of the questionnaire responses received

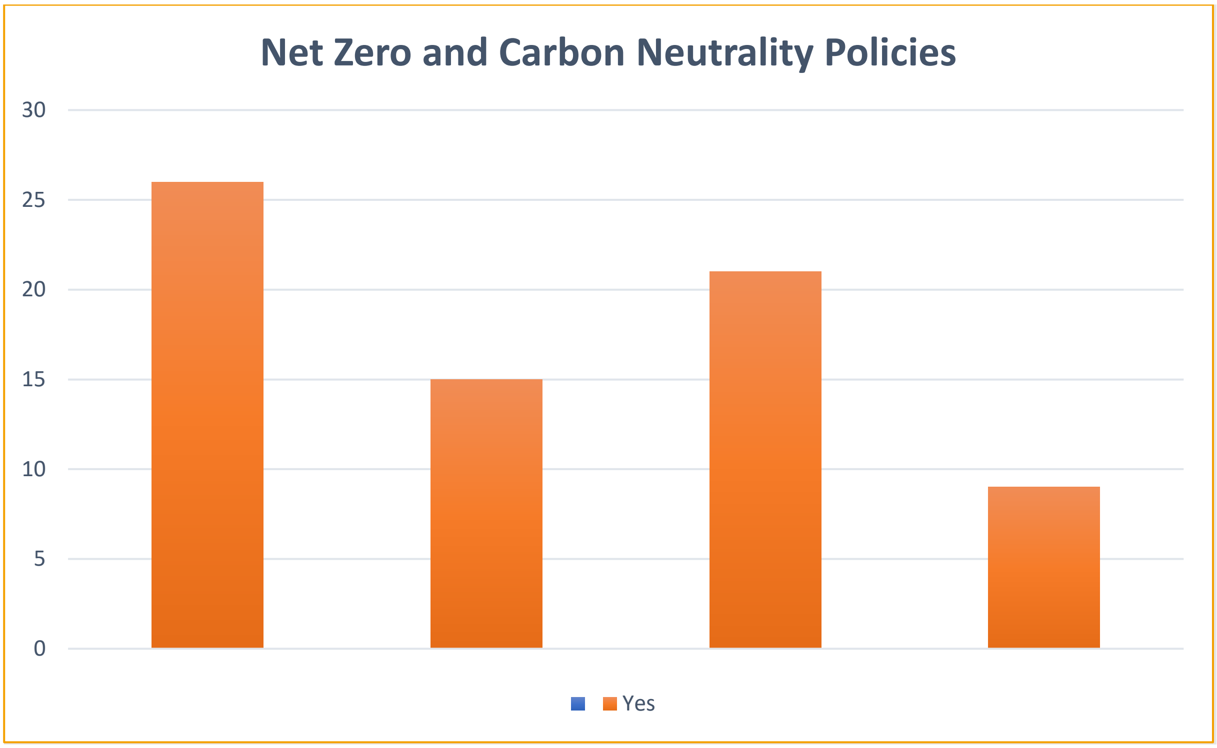

Figure 7. Responses indicating presence of net zero or carbon neutrality policies

Figure 8 shows that, irrespective of whether they have targets in place, NRAs are adopting a range of strategies for reducing carbon emissions. A high proportion of positive responses was seen in all areas, and 80-90% of those responding reported that fleet vehicles, road maintenance and road construction were areas that are being pursued.

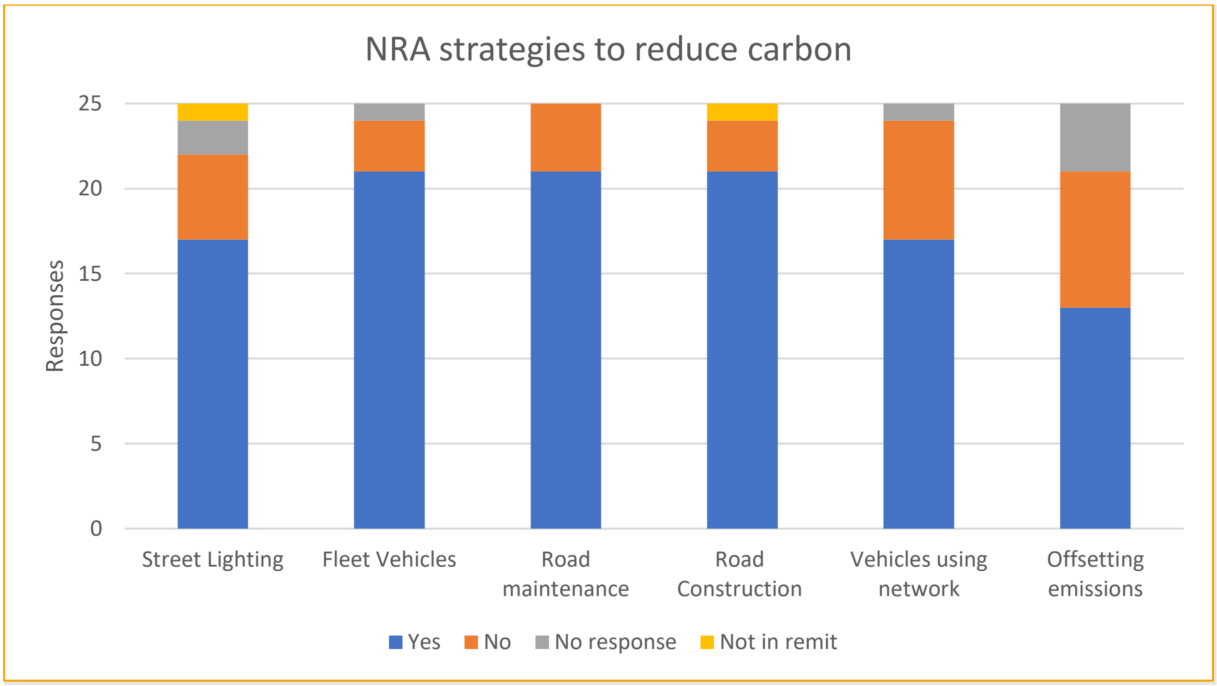

Figure 8. Strategies being adopted for reducing carbon emissions

2.4 Case Studies

While road administrations in most countries follow the policy direction set by their national government, there are examples where NRAs have taken additional measures beyond the minimum requirements set out in the national policy to further reduce emissions. For example, Norway[44] has been making significant progress in greening infrastructure with zero emissions construction sites (through use of fossil fuel free machinery), reducing or eliminating carbon intensive materials etc.

2.4.1 National Highways: Net Zero Strategy

In response to the UK Government's national Net-zero 2050 target, National Highways has developed and set out its Roadmap to Net Zero 2050 for the strategic road network in England, with interim target dates to achieve Net Zero in:

- Corporate emissions 2030
- Maintenance and Construction 2040
- Road users 2050

[44] Business Norway (January 2021). Norway is greening the construction Industry. Norway is greening the construction industry - The Explorer

Key actions that NH has identified to deliver its commitment to net zero include:

- 75% reduction in the company's own carbon emissions by 2025
- 100% electric car fleet by 2030
- Replace 70% of all lighting with LED by 2027
- An extra three million trees planted by 2030
- First net-zero road enhancement scheme by 2030
- Develop a zero carbon 2040 roadmap for cement, concrete and asphalt by June 2022
- Make digital roads an integral part of Road Period 2, and build this into Road Period 3 strategy and beyond from 2023
- By 2023, publish a blueprint showing how EV charging services should be provided on motorways and major A-roads
- By end 2022, report to Government on approach to zero carbon HGV trials on their roads

2.4.2 UK: Carbon neutral road improvement project

An £8m carriageway reconstruction project in Cumbria, UK (reconstruction and resurfacing of A590) was the first project in the UK that is carbon neutral by design[45].

- Early collaboration and carbon modelling experts working with Highways England and the scheme contractors and suppliers measuring the carbon benefits led to significant reductions in carbon through materials reduction and reuse, lower energy consumption and efficient transportation
- The project resulted in 43% less carbon emissions compared to traditional working practices
- Choice of materials and recycling on site reduced lorry movements and thereby delivered a saving of 230 tons of carbon emission
- Solar powered generators and electric vehicles on site contributed to energy efficiency and a saving of 70 tonnes on carbon emission
- A number of carbon credits (carbon credits discussed in more detail in 2.5) were obtained throughout the project enabling carbon neutrality at finish

2.4.3 Canada: Carbon neutral major reconstruction project

The remodelling of a major motorway junction (6-year, C$3.7bn project) serves to demonstrate that large, complex projects can be delivered in a carbon neutral way. 80% of the project was delivered by the contractor under a design and build contract, much against the norm in North America, but very conducive to innovation and designing to need.

- The motorway junction, which carried about 300,000 vehicles per day had reached its end of life and the Quebec Transport Ministry decided to deliver 'more than a direct replacement'
- The construction site measured 7 km by 3 km and involved rebuilding 145 km of traffic lanes, as well as creating 10 km of bus lanes and 8 km of new cycle lanes
- Traffic was kept moving throughout the work by persuading users to use mass transit; reserved bus lanes and a new bus terminal enabled free flow

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[45] Designing 'UK first' carbon neutral road improvement project. 2021. https://www.amey.co.uk/bolder-steps-together/our-social-value-stories/designing-uk-first-carbon-neutral-road-improvement-project/

- Continuous and up to date communications with stakeholders, including residents was needed and was maintained throughout the project
- Earthworks were a major part of the challenge, 8 M.m3 of material was moved, and about 65% of the soil was dried out with lime to allow it to be re-used
- The main Canadian National Railway corridor, with 4 railway lines and carrying 50 trains a day, went right through the middle of the site. The work required 7 km of railway track to be relocated. All work was carried out without any disruption of train services
- This was a long and complex project that took 6 years to complete. From the information in the public domain, there is no mention of carbon neutrality as an initial ambition. Instead, there was a target for recycling (80 to 85%) which was exceeded with 95% of materials from the site being reused or recycled. In addition, the 148,500t of CO_2 emitted during the project was offset by a combination of planting trees and carbon credits.

The project itself was therefore finally delivered as a carbon neutral project and in addition created 31 ha of green space which has been planted with 61,000 shrubs and 9,000 trees, from what used to be a concrete jungle.

2.5 Procurement of low carbon Options

2.5.1 Contract Specifications

Procurement is a powerful strategic tool in enabling organisations to bring together technical and functional requirements in the acquisition and delivery of goods and services. NRAs, as public bodies with substantial purchasing power have recognised that they can and have to play a significant role in ensuring environmental sustainability by embedding appropriate measures and assessment techniques within their procurement processes.

The EU has developed a set of Green Public Procurement (GPP) documents to encourage the inclusion of green requirements within a wide range of public procurement areas. The documents aim to facilitate the preparation of tender documents such as specifications and tender evaluation documents where procuring authorities can incorporate all or some of the recommendations with the aim of providing a balance of technical performance, environmental performance, cost consideration and market availability. Technical specifications outline the minimum compliance requirements for tenders to meet, and it is vital that the characteristics of the work are clear and understood by all operators. In 2016 the EU GPP criteria for Road Design, Construction and Maintenance was published to provide guidance to public authorities on the achievement of higher environmental standards in the procurement of road projects[46].

In 2017, SPP (Sustainable Public Procurement) Regions published a Best Practice Report on Performance/Output Based Specifications to provide guidance on the use of performance-based contracting, facilitating a move towards SPP and has received funding from the

[46] Garbarino E., Rodriguez Quintero R., Donatello S., Gama Caldas M. and Wolf O.; 2016; Revision of Green Public Procurement Criteria for Road Design, Construction and Maintenance. Technical report and criteria proposal; EUR 28013 EN; doi:10.2791/683567

European Union's Horizon 2020. The focus of performance-based specifications is on the required outputs from a contract rather than specifying inputs, encouraging innovation by giving contractors freedom to determine how to meet the specific requirements of the contracting authority[47]. Output based specifications provide tenderers scope to suggest innovative solutions or materials, while also achieving minimum required technical performance. Allowing for a collaborative approach from the beginning, as part of the pre-tendering phase, conversations with market stakeholders can be insightful to gain knowledge of materials/methods/processes available on the market to aid the development of specifications to produce better outcomes and reduce time scales. Early engagement with stakeholders is crucial. Appropriate training needs to be provided to personnel preparing tender documents to ensure a sufficient level of expertise in sustainable procurement and performance/output-based specifications[48]. Where environmental indicators are embedded into functional specifications within the tendering process, monitoring systems can be put in place to report on progress, track and demonstrate improvements and to adopt innovative solutions for use, reuse and repurposing of materials, or waste minimisation.

In the EU, for the evaluation of tenders, the criteria for assessment depends on the nature and complexity of the project and the tendering procedure. The assessment can be based on pass/fail criteria or a more complex numerical scoring methodology to rank tenderers. The contract is often awarded to the Most Economically Advantageous Tender (MEAT), considering one of the following approaches:

- Price only
- Cost effectiveness (e.g., life cycle costing)
- Best price/quality ratio taking account of qualitative social aspects

The cost effectiveness approach allows for the consideration of the operational costs, end of life related costs and environmental costs, as well as the direct cost of works.

The Netherlands was the first European country to formalise the process for sustainable procurement, with the Dutch Government establishing clear goals as early as 2005 and embedded this further into their procurement processes in 2010 when the Dutch House of Commons ruled that all public authorities must implement 100% sustainable procurement by 2015.

In response to this, Rijkswaterstaat (the Department of Public Works of the Ministry of Infrastructure and the Environment) developed a methodology for infrastructure projects where the functional specification of the tender together with the quality input from the client ensure an innovative and high-quality solution. The criteria that formed the basis of assessing

[47] Douglas, A., 2017, Performance/Output Based Specifications - Best Practice Report, SPP Regions Project Consortium, ICLEI – Local Governments for Sustainability, European Secretariat (SPP Regions: Publications)
[48] Douglas, A., 2017, Performance/Output Based Specifications - Best Practice Report, SPP Regions Project Consortium, ICLEI – Local Governments for Sustainability, European Secretariat (SPP Regions:: Publications)

the sustainability attributes of tenders were CO_2 emissions and environmental impact. The following two tools were developed to measure CO_2 emissions and environmental impacts, and are now mandated to be used by all tenderers:

- The CO_2 performance ladder – a certification system with which a tenderer can show the measures to be taken to limit CO_2 emissions within the company and in projects, as well as elsewhere in the supply chain
- "DuboCalc" – a life-cycle analysis (LCA) based tool which calculates the sustainability value of a specific design based on the materials to be used. Bidders use DuboCalc to compare different design options for their submissions. The DuboCalc score of the preferred design is submitted with the tender price

Rijkswaterstaat (RWS) has identified the role that procurement can play in focussing delivery on the core objectives, creating a scale for suppliers and achieving a consistent and long-term commitment to sustainability goals[49]. The scale and long-term approach are beneficial to suppliers and enable investment in improved technologies and approaches.

The Conference of European Directors of Roads (CEDR)[50] funded project "Circular Economy in Road Construction and Maintenance" (CERCOM)[51] is currently developing an inventory of the systems / approaches appropriate at different stages of the journey towards circularity. CERCOM is investigating how a circular economy (CE) could work in the context of highway construction and maintenance and what barriers and opportunities exist for its adoption. One of the aims of CERCOM is to deliver an innovative risk-based framework and management tool to facilitate a step change in the adoption of resource efficiency and circular economy principles in procurement and multi-lifecycle management by NRAs. As part of the project, deliverables, guidance, training seminars and on-line materials for managers and practitioners will be provided to aid in the move from a linear to circular economy.

2.5.2 Financial incentives / models

Carbon reductions are often considered by road operators in terms of implementation of Energy Conservation Measures (ECMs), with the idea of reducing carbon cost while also improving profitability. The implementation of such ECMs often requires large capital investments to be made, or the application of drastic measures to achieve operational efficiency improvements. Such costs often outweigh the benefits of the carbon reductions, causing road administrators to reconsider the feasibility of these initiatives.

As an additional motivation to promote the uptake of ECMs across industries including road infrastructure, many governments have introduced financial models and tax incentives to increase the pace at which ECMs are introduced. This section of the literature review will

[49] Versteeg (2019) Dutch procurement approach for a more sustainable infrastructure. Presentation to the International seminar on Asphalt Pavements 4-5 May 2019.).
[50] CEDR (2020), https://www.cedr.eu/peb-call-2020-resource-efficiency-and-circular-economy)
[51] Circular Economy in Road Construction and Maintenance - CERCOM (cedr.eu)

examine financial incentives and models aimed at achieving carbon reductions and carbon neutrality in LMICs and HICs, both at a government and road operator level.

Carbon Pricing – a general overview

Carbon pricing is an instrument that is intended to capture the external costs of greenhouse gas (GHG) emissions, i.e. the consequences of emissions that the public pays for, such as damage to crops, health impacts from heat waves and droughts, and loss of property from flooding and sea level rise. It is meant to tie them to their sources through a price, usually in the form of a price on the CO_2 emitted[52]. A price on carbon aims to help shift the burden for the damage from GHG emissions back to those who are responsible for it but can avoid the costs of the damage caused. Instead of dictating who should reduce emissions where and how, a carbon price provides an economic signal to emitters, and allows them to decide to either transform their activities and lower their emissions or continue emitting and paying for their emissions. The two most common types of carbon pricing are emissions trading systems (ETSs) and Carbon Tax[53].

An **ETS** – sometimes referred to as a cap-and-trade system – caps the total level of greenhouse gas emissions and allows those industries with low emissions to sell their extra allowances to larger emitters. By creating supply and demand for emissions allowances, an ETS establishes a market price for greenhouse gas emissions. The cap helps ensure that the required emission reductions will take place to keep the emitters (in aggregate) within their pre-allocated carbon budget.

A **carbon tax** directly sets a price on carbon by defining a tax rate on greenhouse gas emissions or, more commonly, on the carbon content of fossil fuels. It is different from an ETS in that the emission reduction outcome of a carbon tax is not pre-defined but the carbon price is.

An alternative mechanism for carbon pricing is an **offset mechanism** which designates the GHG emission reductions from project- or program-based activities, which can be sold either domestically or in other countries. Offset programs issue carbon credits according to an accounting protocol and have their own registry. These credits can be used to meet compliance under an international agreement, domestic policies or corporate citizenship objectives related to GHG mitigation.

Governments around the world are using sustainability tax measures to reduce emissions, meet their commitments on carbon neutrality and tackle climate change, as well as to raise revenue and fund important policy objectives. While these goals are shared, the policies established to achieve them vary greatly. For businesses that wish to act on climate change, secure valuable incentives to enable these actions and avoid costly surprises, staying on top of the evolving sustainability tax landscape across the globe is critical. However, staying

[52] What is Carbon Pricing? | Carbon Pricing Dashboard (worldbank.org)
[53] Pricing Carbon (worldbank.org)

current as policies rapidly evolve can be a challenge, especially for global businesses. Ernst and Young (EY) offer a snapshot of sustainability incentives, carbon regimes, environmental taxes and environmental tax exemptions present in 45 jurisdictions, through their EY Green Tax Tracker[54].

Table 2. Countries surveyed under EY Green Tax Tracker[54]

<table>
<tr><td>Argentina</td><td>Colombia</td><td>Hong Kong</td><td>Luxembourg</td><td>Peru</td><td>South Africa</td><td rowspan="2">United Kingdom</td></tr>
<tr><td>Australia</td><td>Cyprus</td><td>India</td><td>Malaysia</td><td>Poland</td><td>South Korea</td></tr>
<tr><td>Austria</td><td>Denmark</td><td>Indonesia</td><td>Mexico</td><td>Portugal</td><td>Spain</td><td rowspan="2">United States</td></tr>
<tr><td>Belgium</td><td>Finland</td><td>Ireland</td><td>The Netherlands</td><td>Romania</td><td>Switzerland</td></tr>
<tr><td>Brazil</td><td>France</td><td>Italy</td><td>New Zealand</td><td>Russia</td><td>Taiwan</td><td rowspan="2">European Union</td></tr>
<tr><td>Canada</td><td>Germany</td><td>Japan</td><td>Norway</td><td>Singapore</td><td>Thailand</td></tr>
<tr><td>China</td><td></td><td>Lithuania</td><td>The Philippines</td><td>Slovakia</td><td>Turkey</td><td>Vietnam</td></tr>
</table>

At the time of writing, 27 of the 45 jurisdictions were implementing an ETS, while 11 had an ETS under construction. 18 countries were currently implementing a carbon tax while 8 had a carbon tax under construction. 11 countries had both an ETS and a carbon tax system in place. The green tax tracker also keeps a record of sustainability incentives, environmental taxes and environmental tax exemptions. 34 of the 45 countries currently offer incentives to switch to alternative fuels for vehicles / infrastructure. It should be noted that of the 44 countries (excluding the European Union) included, 28 are High Income Countries and 16 are Middle Income Countries (12 UMICs and 4 LMICs).

Clearly there is a universal consensus on the application of carbon pricing to reduce carbon emissions, but there are questions on the success of the strategy. There are few works that have conducted an ex-post analysis, examining how carbon pricing has actually been performed. A recent study[55] has made several observations in this regard. First, most studies suggest that the aggregate reductions from carbon pricing on emissions are limited—while there is considerable variation across sectors, generally reductions range between 0% and 2% per year. Secondly, in general, carbon taxes perform better than emissions trading schemes

[54] ey-green-tax-tracker-edition-3-v3.pdf

[55] Green, Jessica F. "Does carbon pricing reduce emissions? A review of ex-post analyses." *Environmental Research Letters* 16.4 (2021): 043004.

(ETSs). Finally, studies of the EU-ETS, the oldest ETS, indicate limited average annual reductions—ranging from 0% to 1.5% per year. To set this in context, the IPCC (Intergovernmental Panel on Climate Change) states that emissions must fall by 45% below 2010 levels by 2030 to limit global warming to 1.5ºC[56].

Overall, the evidence indicates that carbon pricing has limited impact on emissions. However, it should be noted that the current review has indicated that many countries are still in their infancy in terms of implementing actionable carbon pricing, with many countries starting off with lower tax rates to leverage a policy evaluation approach which leverages economic theory and machine learning for counterfactual prediction[57]. Abrell et al. used this method to analyse the emissions and cost impacts of the UK CPS, a carbon tax levied on fossil fuel power plants[57]. The results indicate that in the period 2013–2016 the CPS lowered emissions by 6.2% at an average cost of €18 per ton. Again, with recent renewed focus in this domain, the relative carbon reductions will be expected to increase in coming years. A common consensus in the research is that the effectiveness of carbon pricing is heavily impacted by relative fuel prices.

The following sections examine some country specific incentives and sanctions at a closer level.

[56] Intergovernmental Panel on Climate Change 2018 Global Warming of 1.5 ◦C (World Meteorological Organization)
[57] Abrell, Jan, Mirjam Kosch, and Sebastian Rausch. "How effective is carbon pricing? —A machine learning approach to policy evaluation." *Journal of Environmental Economics and Management* 112 (2022): 102589.

2.5.3 High and Upper Middle-Income Countries

Canada (HIC)

Canada's sustainability tax programs at both the federal and provincial levels have been in place for several years and continue to evolve. Over time, the two levels have worked together to harmonise the application of environmental regulations including water, air, land and environmental assessment. In 2016, Canada adopted the Pan-Canadian Framework[58] (PCF) which focused on pricing carbon pollution, complementary actions to reduce emissions economy-wide, adaptation and climate resilience, and clean technology, innovation and jobs. There are currently federal sustainability funding programs, federal accelerated depreciation for qualifying clean energy investments and several provincial sustainability programs, most taking the form of grants or rebates. Canada established a carbon pricing framework in 2018. Flexibility was provided to provinces and territories to establish their own pricing plans with a federal backstop implemented if a local plan did not meet federal standards.

There are two systems operational in Canada[59] according to the needs of the provinces. Jurisdictions can implement (i) an explicit price-based system (a carbon tax like British Columbia's or a hybrid system comprised of a carbon levy on fuels and performance-based emissions trading system like in Alberta) or (ii) a cap-and-trade system (e.g. Quebec).

Transport is Canada's second highest carbon emitting sector, contributing 186 Mt CO_2 per year (25% of all emissions), behind the oil and gas industry which emits 191 Mt CO_2[60]. Nearly eighty five percent of this sector's emissions come from on-road transportation, and light-duty vehicles alone count for half of the sector's emissions. While greenhouse gas emissions from the light-duty vehicle sector have increased every year since 2015, it has also become the sector with the most advanced zero-emission vehicle offerings in the entire market, making these vehicles a key component of transportation decarbonisation. To tackle this issue, the Canadian Government has set aside funding of CAN$400 million for zero-emission vehicles (ZEVs) charging stations, in support of the Government's objective of adding 50,000 ZEV chargers to Canada's network. In addition, the Canada Infrastructure Bank will also invest $500 million in ZEV charging and refuelling infrastructure. The Government will also put in place a sales mandate to ensure at least 20 percent of new light-duty vehicle sales will be zero-emission vehicles by 2026, at least 60 percent by 2030 and 100 percent by 2035. To reduce emissions from medium- and heavy-duty vehicles (MHDVs), the Government of Canada aim to achieve 35 percent of total MHDV sales being ZEVs by 2030. In addition, the Government will develop a MHDV ZEV regulation to require 100 percent MHDV sales to be ZEVs by 2040

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[58] https://scics.ca/en/product-produit/pan-canadian-framework-on-clean-growth-and-climate-change/#:~:text=The%20Pan%2DCanadian%20Framework%20has,clean%20technology%2C%20and%20create%20jobs.
[59] https://www.canada.ca/en/services/environment/weather/climatechange/pan-canadian-framework/guidance-carbon-pollution-pricing-benchmark.html
[60] 2030 Emissions Reduction Plan – Canada's Next Steps for Clean Air and a Strong Economy - Canada.ca

for a subset of vehicle types based on feasibility. The ZEV standard is undertaken at a Federal[61] and Provincial level, with Québec the first Province to have one[62].

South Africa (UMIC)

South Africa is the 14th largest greenhouse gas emitter in the world and has a prominent role to play in resolving climate change[63]. Section 12L of the South African Income Tax Act contains an Energy Efficiency Saving initiative which provides an opportunity for South African businesses to apply for and benefit from a tax incentive for measured and verified energy efficiency savings. The incentive is administered by the South African National Energy Development Institute (SANEDI) that has the role of implementing and overseeing the application process of the incentive[64]. Any consumer of energy in South Africa that implements an ECM is eligible to apply for this benefit. The incentive began on the 1st November 2013 and is currently running to 1st January 2023. The Act provides for an additional allowance in respect of energy efficiency savings at a rate of 0.95 Rand per kWh of measured and verified energy efficiency savings[65]. An audited approvals process is engaged for each ECM and the associated energy savings are calculated. The tax benefit is then claimed as a deduction in the company's income tax return. The incentive is designed to mitigate the impact of the first phase of carbon tax as more than 70% of South Africa's emissions are energy related[65].

In addition to the section 12L incentive, South Africa's Carbon increased to R144 (about US$9.27) per tCO_2e, effective from 1 January 2022. This rate is low in comparison with international commitments. The intention is to give large emitters time to transition to lower carbon practices. To uphold South Africa's COP26 commitments, the rate will increase each year until it reaches US$20, and from 2026, the South African government intends to escalate the carbon price more rapidly every year to reach at least US$30 by 2030, and US$120 beyond 2050[66]. Effective carbon rates are highest in the road sector, which accounts for 10.7% of South Africa's total CO_2 emissions from energy use.

A recent study has shown that carbon pricing has a relatively low impact on emissions in the road transport sector in South Africa[67]. This is mainly because a separate projection was made for carbon pricing on synthetic fuels, which accounts for most carbon emissions from road transport.

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[61] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://emc-mec.ca/wp-content/uploads/ZEV-Standard-Best-Practices-EN-FINAL.pdf

[62] https://www.environnement.gouv.qc.ca/changementsclimatiques/vze/index.htm#:~:text=La%20Loi%20visant%20l%27augmentation,nationale%2C%20le%2026%20octobre%202016.%E2%80%99

[63] Section 12L Energy Efficiency tax incentive applications on the rise (esi-africa.com)

[64] Section 12L Energy - Efficiency Savings - SA Institute of Taxation (thesait.org.za)

[65] Incentives can help companies address the challenge of climate change (deloitte.com)

[66] South Africa's carbon tax rate goes up but emitters get more time to clean up (theconversation.com)

[67] Carbon Pricing in Times of COVID-19: Key findings for South Africa (oecd.org)

2.5.4 Lower Middle-Income Countries

Other incentives and carbon taxes have been in place across LMICs for several years.

India (LMIC) has well established sustainability tax programs, primarily at the national level, though there are also local taxes on fuels and incentives granted for clean energy initiatives. There is no formal carbon tax, but there are high taxes on petrol and diesel, which have increased sharply since 2014 and are possibly the highest in the world at over 100% (combining the impact of excise duties and value added taxes). Additionally, there are lower taxes on electric vehicles, only 5% goods and services tax vs. 28% for internal combustion powered vehicles. There are fiscal measures proposed that would incentivise domestic manufacturing of ACC batteries, manufacturing of solar panels and other qualifying activities. Also, the government has approved a proposal to levy a "Green Tax" on old vehicles which are polluting the environment. A Production Linked Incentive (PLI) scheme has been proposed to boost domestic manufacturing capabilities of the automobile industry, including electric and hydrogen fuel cell vehicles[54].

In **Indonesia (LMIC)**, the government has stated plans to introduce a carbon tax. Under Indonesia's Proposed Tax Bill that is still being reviewed and discussed by the Parliament, carbon emissions having a negative impact on the environment will be subject to a minimum carbon tax of IDR 75 per kilogram of CO_2e or other equivalent measurement unit (equivalent to around US$5.2 per tCO_2e).

In **Vietnam (LMIC)**, sustainability tax programs, mostly at the national level, have been established for a quite long time with a Natural Resources Tax in place since the 2000s and Environmental Protection Tax since 2010s. However, new measures are still emerging. The Law on Environmental Protection will come into force from 1 January 2022. Additionally, the Vietnamese government is actively working to implement new measures and will release the detailed guidance on an emission trading system soon. The government has also enacted incentives and assistance for business activities related to environmental protection to encourage enterprises to seize opportunities from sustainability, clean energy transition and waste reduction[54].

2.5.5 Business models

Business models underlying the management of highway networks are fundamentally based on a linear approach, 'Take, Make, Waste' or Cradle to Grave. Over the last decades as sustainability and the need to reduce carbon emissions have grown in importance, NRAs, to varying degrees, have adapted their approaches to take on board aspects such:

- External costs associated with the management of road networks, e.g. emissions
- Carbon footprint of activities
- Use of recycled and secondary materials
- Life Cycle Analysis inherent in decision making

The transition to carbon neutrality requires a fundamental change in approach to value chains, and for new Business Models that address the key principles of the circular economy, a cyclical Cradle to Cradle approach, i.e., not just minimising resource consumption but designing out waste and pollution, keeping products and materials in use for as long as possible. One of the aims would be to enable an increase in resource efficiency to be underpinned by a reduction in the use of primary materials.

The move to carbon neutrality is in the very early stages and while some NRAs have made progress with regards to some of the attributes related to circularity, there are no examples of the adoption of a circular business model by any NRA. Essentially, NRAs still function with linear business models, with a greater bias towards 'lowest first cost' considerations.

Circular business models contribute to carbon neutrality by reflecting the fundamental principles underlying carbon reduction and key attributes are expected to include:

- Designing out waste and pollution at the design stage
- Materials management approach that supports value retention rather than a waste management approach
- Innovative ownership models, including for example provision of infrastructure as a service
- Early contractor involvement
- Extended contractor/supplier responsibility, with responsibility extending to end-of-life-options for products, materials etc
- Incentivising innovations and enabling risk and benefit sharing
- Focusing on outcomes rather than outputs
- Mitigating climate change impacts
- Reducing consumption of new resources

While the transition from a linear to a circular business model is yet to make a mark with respect to the construction and maintenance of roads, there are good practice examples from NRAs testing options within individual projects that are precursors to the transition. For example, pilot projects have been used to test the feasibility and learn lessons from introducing aspects relevant to CE based Business Model:

- Infrastructure as a service contract – pilot project in Netherlands
- Early contractor involvement to identify and collate opportunities for circular approach – major projects in the UK
- Innovative solutions for reuse of 'waste' materials in road maintenance – project in Finland
- Resource Exchange Mechanism – development in the UK contributing to mitigating resource scarcity

2.6 Lessons from rail sector

As with highways, the rail sector also has targets for decarbonisation. Whilst noting the differences in the sector, specifically that the rail sector has control over the vehicles using the network and tends to have large sections of the network which are electrified, rail operators also operate large infrastructure networks, and there is potentially valuable information to share. Below is a summary of good practice implemented by rail operators.

Eurostar (UK, France, Belgium, Netherlands)

Eurostar measure CO_2 across their entire operation (depots, contact centres, stations and offices). They have targets to reduce CO_2 and track it through Greenstone carbon data management system. This has enabled them to become accredited to the Certified Emissions Measurements and Reduction scheme (CEMARS). This certification covers CO_2 emissions associated with the UK operations. They are certified to ISO15001:2011 which is energy management certification, and 14011:2005 for general environmental certification. From 2020, they are planting a tree for every service that runs – around 20,000 trees per year across UK, France, Belgium and Netherlands[68].

Eurostar has a 10-point plan from 2018 where they committed to science-based targets for the energy efficiency of their business. In accordance with 2016 Paris Climate Agreement, they are significantly reducing their corporate emissions to limit global warming to under 2 degrees C.

Of the ones related to carbon, they plan to reduce train energy by 5% by 2020, have energy meters on board and energy efficient driving by 2020, introduce alternatives to fossil fuel energy for all journeys by 2030. The Netherlands section of their journeys is already 100% wind powered. They are conducting research into options for renewable energy at the depots and are installing EV chargers at the UK depot, allowing purchase of EVs from 2020[69].

Transport for London (UK)

Transport for London (TfL) is one of the largest consumers of electricity in the UK, requiring 1.6TWh per year, the equivalent of around 420,000 homes. London Mayor, Sadiq Khan plans to make London a zero-carbon city by 2030 and a programme is underway to procure renewable Power Purchase Agreements (PPAs) – long term contracts direct with energy generators that guarantee energy is supplied from renewable sources.

Work is also underway to develop a financing solution used to build wind and solar farms. A fund will be created for public and private investors to invest directly into new renewables projects, which will supply the GLA (Greater London Authority) group.

The first PPA will cover 10% of annual electricity use (guaranteed renewable power from Spring 2022). Another PPA will cover a further 10% from renewable generation from 'new build assets'[70].

[68] https://www.eurostar-treadlightly.com/en/environment.php
[69] https://www.eurostar-treadlightly.com/en/tread-lightly-10-point-plan.php
[70] https://airqualitynews.com/2021/04/01/mayor-of-london-announces-plans-to-power-tfl-on-renewables/#:~:text=TfL%20will%20shortly%20begin%20procurement,to%20TfL%20from%20Spring%202022

Thalys (Netherlands, Belgium, Germany France)

From 2020 Thalys has been using electricity certified as being 100% green origin from wind farms and solar panels located in Belgium, France and Germany. The trains in the Netherlands are operated entirely by wind power and have been since 2017. From 2010 to 2020, Thalys halved their carbon emissions[71]. On green electricity and purchases, they state:

"Faced with the impossibility of accessing 100% green electricity on its entire network, Thalys has been committed to balancing its energy footprint through the purchase of certified Guarantees of Origin since 1 January 2020.

By purchasing Guarantees of Origin, Thalys supports the production of green energy, which is better for the environment and which is produced at the heart of its network, more particularly in Belgium, France, and Germany"[72].

Netherlands – ProRail (infrastructure manager) and NS Dutch Railways (passenger railway operator)

ProRail is undertaking a range of activities, installing solar panels at stations, along the railway and trialling solar panels integrated into noise barriers. Point heating using natural gas is being replaced with electric point heating and diesel trains are being replaced by green electric, hydrogen or battery alternatives.

ProRail has an active energy policy looking at both their own and their transporters energy consumption. They are installing LED lighting at 400 stations and sensors dim the lights if they detect that there are no people on the platform. They are also transitioning to diesel free construction sites and purchasing 100% green electricity and gas[73].

On 1 January 2017, Netherlands became the first country to power every electric train run by the NS Dutch railways on the Dutch rail network by wind energy. This has resulted in significant reductions in electricity consumption per passenger kilometre. A saving of 1.43 bn kilograms of CO_2 by 2020 has been reported.

Danish State Railways (Danske Statsbaner (DSB))

DSB is investing to ensure full electrification and conversion of fleet of trains and targeting zero emissions by 2030. They signed a 15-year loan of EUR400 million in 2020 to finance electric rolling stock. DSB invests in trains, locomotives and workshops and Danish state invests in the infrastructure including EUR 10 billion on new rolling stock, workshops and full electrification of existing lines[74].

[71] https://www.linkedin.com/pulse/thalys-full-speed-ahead-green-electricity-bertrand-gosselin/
[72] https://www.thalys.com/fr/en/about-thalys/thalys-is-taking-action-for-a-sustainable-world
[73] https://www.prorail.nl/toekomst/duurzaamheid/energie
[74] https://www.themayor.eu/en/a/view/eur-500-million-to-accelerate-the-sustainable-transition-of-danish-railways-9837

In 2022, the European Investment Bank signed a 25-year, EUR 500 million lending agreement to help DSB finance the acquisition of 100 new electric trainsets, to begin operation in 2024.

Network Rail (UK)

Network Rail has a detailed plan for transitioning to a low emissions railway by 2050 from a 2020 baseline (2045 in Scotland). They will use science-based targets based on the most ambitious target of limiting emissions for their operations to 1.5°C warming scenario. This implies reducing their emissions by 98% by 2050[75].

For their Scope 1 (direct emissions from sources owned by Network Rail, e.g. heating buildings or fuel for vehicle fleet) and Scope 2 emissions (indirect emissions from the electricity, heat or cooling purchased), they will source all non-traction electricity from renewable sources from 2020, transitioning their road fleet to ultra-low emissions. Network Rail operate the railway infrastructure, but not the trains themselves. The train operating companies operate the vehicles, which fall outside of Network Rail's control (scope 3) so they will work with the supply chain so by 2050 at least 75% will have their own science-based targets, and with the UK Government to enable traction diesel to be reduced by at least 27.5%% by 2030. They are looking to use solar at stations and lineside, including direct supply trials (Riding Sunbeams). Currently, they state that traction electricity is sourced from zero carbon nuclear energy. This indicates the importance of system limits since, given the large amounts of embodied carbon in nuclear plants, it could be argued that it is not truly zero carbon. They have specific interim targets for 2020 – 2029 and then 2030 – 2050[76].

[75] https://www.networkrail.co.uk/wp-content/uploads/2020/10/Our-ambition-for-a-low-emission-railway-Science-based-Targets.pdf
[76] https://www.networkrail.co.uk/sustainability/a-low-emission-railway/

Indian Railways (India)

Indian railways is one of the largest railways in the world, one of the largest consumers of electricity in the country and responsible for 4% of the country's total emissions. It has set an ambitious target of achieving net-zero by 2030 with a detailed multi-faceted strategy[77]. In addition to redevelopment and upgrading of assets, the key approaches include[78]:

- Electrifying the complete network by the end of 2023; according to the Railway ministry, with 42,354 route kilometre having been electrified, as of January 2021, the Government has achieved 66% of its overall target (e.g. between 2018-2019, more than 5000km of rail were electrified, compared to 251 km in the UK)[79]
- Using solar power to meet its electricity needs with a stated ambition to install 20 gigawatts of solar for both traction loads and non-traction. This will include building massive solar power plants on its vacant land. During the coronavirus disease (COVID-19) pandemic, the railways built a 1.7-MW solar power plant in Bina, Madhya Pradesh, in July 2020, making it the first solar energy plant in the world to directly power railway overhead lines, from which locomotives draw traction power. Work has started on a second 2.5-MW solar project with state transmission unit as well as on a third pilot with a capacity of 50 MW
- In addition to traction power, solar panels have been installed at over 960 stations to meet railway station energy needs. Bids have also been submitted for 198 MW solar power panels on the rooftops of another 50 railway stations
- Another innovative initiative is the installation of a first-of-its-kind 16kW solar power plant in Sahibabad Railway Station that doubles as a platform shelter. This reduced the total cost of the platform's shelter and rooftop solar plants and provides solar power to meet the non-traction demand

2.7 POTENTIAL IMPACTS OF POLICIES AND STRATEGIES ON SOCIAL INEQUALITIES

The ultimate success of reversing/stopping further climate change will depend upon Net Zero/Carbon Neutrality being achieved globally. Measures to achieve the transition will succeed in delivering the desired outcomes only if they are seen to be fair and not contribute to increasing or introducing new social inequalities, both between and within countries.

Transport sector is the faster growing sector contributing to economic growth and it is also the fastest growing major contributor to emissions in the developing countries. An evaluation by the Asian Development Bank projected that the large increase in motorised vehicles in these countries (including 2,3 wheelers, cars and other light duty vehicles) meant that there may well be a three- to five-fold increase in CO_2 emissions from transportation in Asian countries by 2030 compared with emissions in 2000[80].

Discussions at UN Climate Change Conference (COP26) gave clarity to the critical need to strike the correct balance in the roles and responsibilities of different countries in achieving

[77] Decarbonisation and the Indian Railways | Economic and Political Weekly (epw.in)
[78] Indian Railways likely to become world's first 'net-zero' carbon emitter by 2030 (downtoearth.org.in)
[79] Decarbonization-of-Indian-Railways_full-report.pdf (climatepolicyinitiative.org)
[80] AADB (2010). Reducing Carbon emissions from transport projects. 47170274.pdf

decarbonisation. The current commitments are presented in Table 1. LMICs, in contrast to most of the wealthy countries of today, did not benefit from the period of unrestricted industrialisation and therefore bear no historic responsibility for accumulated emissions. At the same time, since these countries are more seriously affected by the effects of climate change, there is an expectation that the 'wealthier' countries will shoulder what they perceive as a fair share of the costs. This includes ensuring that any measures undertaken do not impede their economic growth which is very much in the early growth phase in many countries. For example, the announcement by India of a 20-year delayed Net Zero target year at 2070 received mixed reactions:

- The more countries that set delayed targets, rather than adopting science-based targets consistent with the goals of the Paris Agreement, the lower the possibility of avoiding the worst consequences of climate change
- It was welcomed as India had not committed to a target previously; its economy is still very dependent on fossil fuels for energy consumption and as a heavily populated but strongly growing economy, its energy requirements are expected to increase more than that of other countries
- The Indian government itself made it clear that the country was taking a responsible stand and would need to incur considerable cost in meeting the target
- As part of setting the target, the Prime Minister of the country also made it clear that the country expected the world's developed nations to make available $1 trillion to finance the transition

The disparities are not just between countries but within countries too, with regional differences in wealth, income levels, facilities, climate, infrastructure etc. To succeed any policy to instruments to enable transition to net zero or carbon neutrality will need to take account of the social conditions, such as the additional financial burden of adapting to new technologies on the already disadvantaged sections on society. For example, in the UK, Government funding for electric buses is seen as being more generous in England and Scotland compared to what is available for Wales. There are also differences in the needs in urban and rural areas and the ban on fossil fuelled cars may have a disproportionate effect on rural areas, with limited access to public transport and more dependence on car ownership for work and leisure purposes.

In recognition of the importance of addressing these very issues, the European Commission has allocated 72.2bn Euros to support low-income individuals/firms from the additional costs of the Emission Trading System (ETS2) for the period 2025-2032[81].

An on-going discussion within the development of contemporaneous policies to achieve carbon neutrality is how the burden for reducing emissions should be shared, how to balance responsibility and costs for historical emissions (that contributed to economic growth and wealth generation in some countries) and current emissions (where enforced reductions

[81] Generation Climate Europe (2022). The road to net-zero is paved with social (in)equality.

could disproportionately impact economic growth of poorer countries). This is particularly relevant as HICs have, in general, well developed road infrastructure, whereas LMICs are in a phase of rapid expansion of theirs.

The 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27) took place in November 2022. The overriding themes of COP27 were justice and ambition. On the theme of justice, the conference concluded with a historic decision to establish and operationalise a loss and damage fund to provide funding for vulnerable countries where climate disasters and extreme weather affected their physical and social infrastructures[82]. The fund for financial assistance has been sought for decades, and finally achieving agreement at COP27 is a significant milestone[83]. A transitional committee with representatives from 24 countries will be set up in 2023 to establish the best means to implement the funding mechanism and determine the intended source of finance[84].

82 COP27: Delivering for people and the planet | United Nations
83 What are the key outcomes of Cop27 climate summit? | Cop27 | The Guardian
84 COP27 - Results, Key Findings and Summary - DFGE - Institute for Energy, Ecology and Economy

PART B – Technical Solutions

3 CONSTRUCTION AND MAINTENANCE OF ROAD INFRASTRUCTURE

3.1 NEED FOR ROAD CONSTRUCTION

Road building generates carbon emissions from a variety of direct and indirect sources, including[85]:

- Construction work, such as land preparation, production of concrete, asphalt, steel and other raw materials, and operation of construction plant and vehicles
- Tree felling to make way for roads, reducing carbon capture
- Ongoing maintenance and servicing
- Provision of roadside lighting, traffic signals and tunnel operations
- Increased mileage and higher vehicle speeds enabled by the additional capacity
- Stimulation of further development that relies on motor vehicle transport as the primary mode for travel and movement of goods

Whereas an effective system of road transport is vital for a flourishing economy, many countries face a spiralling demand for road capacity, where the convenience and relative affordability of road travel has led to increased vehicle ownership and increased road use. Economic models justify the expansion of road capacity, construction of which further underpins new developments (housing, business, retail) that are increasingly reliant on road transport. Use of these facilities fuels further vehicle use, and further increases demand for road capacity.

In this situation, NRAs are faced with a difficult challenge to balance the demand for road capacity against the challenge of reducing carbon emissions. A strategy set out by the Welsh Government[86] in the UK includes a pause and review of existing proposals and a new methodology for assessing the appropriateness of future road schemes. The terms of reference for the review state that the priority and focus for road investment, in accordance with the Wales Transport Strategy, are [87]:

- The avoidance of action which leads to increases in carbon emissions from operating, maintaining and improving the road network, especially in the next 15 years when most vehicles in use will still be powered by fossil fuels
- The reallocation of existing road infrastructure to achieve a shift to sustainable and accessible forms of transport
- The adaptation of existing road infrastructure to cope with climate change

[85] McNaught, D., (2021), *"How roadbuilding projects create CO2 emissions and what can be done to reduce them?",* Infrastructure Blog, Institute of Civil Engineers (ICE) 15th April 2021
[86] Welsh Government (2021). "Net Zero Wales Carbon Budget 2 (2021-25)"
[87] Sloman (2022) "Wales Roads: initial panel report" - https://gov.wales/wales-roads-review-initial-panel-report-html

- Investment which maintains the safety and serviceability of the existing road network in compliance with statutory duties
- The improvement of biodiversity alongside major transport routes

Furthermore, the review considers the sustainable transport hierarchy when considering new infrastructure (Figure 9).

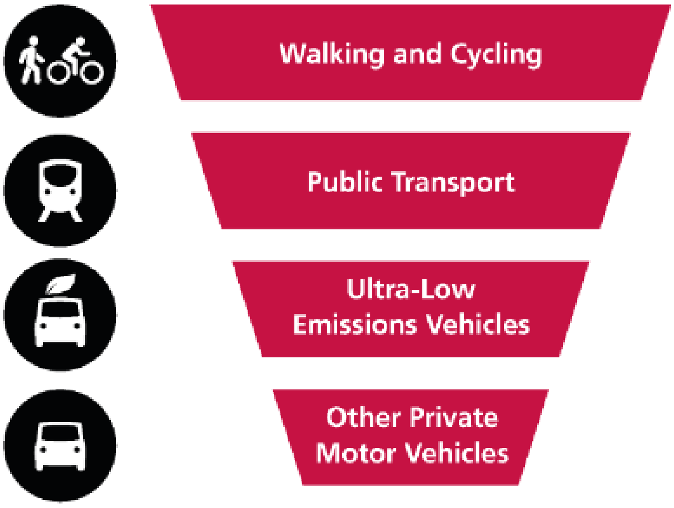

Figure 9. The sustainable transport hierarchy[87]

These types of hierarchical approaches in road construction thinking can have significant impacts in lifecycle carbon emissions.

3.2 ROAD MAINTENANCE AND LIFE EXTENSION

3.2.1 Pavements

An important concept of the circular economy which is sometimes overlooked is the importance of "sweating the asset" or keeping assets in service for as long as possible. The concept can be applied to any road infrastructure object (pavement, bridges etc.). However, the effectiveness of regular maintenance on asset condition must also be considered: road networks that have low levels of maintenance and high levels of deterioration will lead to higher long-term maintenance and reconstruction costs, with associated higher CO_2 emissions[88]. A pavement that is well maintained, smooth and in good condition will also lead to lower emissions from vehicles using the road. Over the lifetime of a highly trafficked road, the main impact in terms of emissions is from vehicles using the road. Embodied impacts from construction are approximately 1% or 2% over a 30-year time period[88]. Deteriorated roads with a rough and uneven surface, rutting, potholes and deteriorated joints all contribute to rolling losses and increased CO_2 emissions from vehicles. Regular maintenance and extending

[88] Road Pavement Industries highlight huge CO2 savings offered by maintaining and upgrading roads. EAPA, EUPAVE and FEHRL, 2015, eupave-eapa-fehrl-co2-savings-by-maintaining-and-upgrading-roads.pdf.

the life of roads can take place as part of regular road asset management and form part of CO_2 saving strategies[88]. The value of maintaining pavements in good condition has been described by Mahoko et al[89], where they report increased emissions of between 20 and 37%, depending on speed, on South African roads in poor condition, with an IRI (International Roughness Index) of 8, compared with those in good condition with an IRI of 1.

Estimates of CO_2 savings associated with application of chip seal / crack seal maintenance in place of thin overlay (per 1km 4-lane highway)
Chip seal – 39.5 tonnes / km
Crack seal – 45.1 tonnes / km

However, carbon impacts vary considerably for different maintenance options Considering the three preservation treatments of thin overlay, chip seal and crack seal, CO_2 emissions per lane mile have been shown to be equal to 18.6 tonnes, 2.7 tonnes and 0.41 tonnes respectively[90]. These savings are generally associated with significant reductions in manufacture of raw materials. Considering a 4-lane, 1 km highway, this equates to values of 46.1, 6.6 and 1.0 tonnes per km, respectively. This highlights potential savings associated with maintenance planning. It is highlighted that these figures should be built into a detailed LCA (life cycle assessment) methodology considering the number of reapplications over the service life.

3.2.2 Bridges

Bridges are a key element of transport infrastructure, and many bridges that were built in the 1950s-1970s are reaching the end of their design service lives. Replacing and building new bridges requires the use of steel and concrete, the production of which results in significant CO_2 emissions. To reduce the yearly production rate of these materials and associated CO_2 emissions, there are 2 options[91]:

- Optimising design to use less of these materials during construction
- Extending the service life of the structures

Studies have been conducted to examine the impact of methods of Structural Health Monitoring (SHM) to increase the lifetime of bridges reaching the end of their design service lives, thus reducing the CO_2 emissions associated with repair/replacement[91]. SHM uses a system of instrumentation and analysis to determine structural performance more accurately. Raeisi et al. examined the impact of the application of SHM of two medium span steel girder bridges built in the 1960s[91]. It was concluded that extending the lifetime of these bridges using SHM reduced carbon emissions. Assuming the use of SHM extends the life of the bridges by

[89] Mashoko et al (2014). Investigating the environmental costs of deteriorating road conditions in South Africa. Proceedings of the 33rd Southern African Transport Conference (SATC 2014). Proceedings ISBN Number: 978-1-920017-61-3
[90] Wang, H., Al-Saadi, I., Lu, P., & Jasim, A., Quantifying greenhouse gas emission of asphalt pavement preservation at construction and use stages using life-cycle assessment. International Journal of Sustainable Transportation, 14(1), 2020, 25-34.
[91] Raeisi, F., Algohi, B., Mufti, A., Thomson, D.J., Reducing carbon dioxide emissions through structural health monitoring of bridges, Journal of Civil Structural Health Monitoring, 2021.

5-10 years, it is estimated that the CO_2 emissions due to bridge reconstruction would decrease by 9-17%[91].

There are additional theoretical studies in the literature proposing LCA and LCC methods to evaluate and reduce the environmental impact of concrete bridges[92,93]. Increasing concrete strength in design, optimising maintenance and the use of alternative materials are some of the areas being examined in the literature to reduce associated CO_2 emissions associated with bridges[94,95,96,97].

3.3 LOW CARBON CONSTRUCTION

There has been significant progress made in carbon neutral construction and operation practices. Many innovative road construction and rehabilitation projects have been carried out in recent years aiming at reducing carbon emissions. The following examples will provide some oversight.

A590, United Kingdom

In terms of low carbon road construction, the recent A590 dual carriageway resurfacing and reconstruction project is of note. The project was an £8m National Highways carriageway reconstruction in Cumbria, UK.

Carbon modelling experts from Amey Consulting worked with National Highways and contractors, including Aggregate Industries, A E Yates and HW Martin to measure the carbon benefits of the scheme. The works resulted in significant carbon reduction across three main areas; materials reduction and reuse, energy reduction and transportation efficiencies. As is often the case in low carbon construction, early consultant and early contractor engagement was critical. This allowed carbon efficient solutions to be developed and calculated through a bespoke carbon calculation model. Key initiatives which reduced emissions during the construction stage included the ex-situ foam-mix recycling of existing road surface plainings, by producing a site batched cold recycled asphalt. In total the project reduced carbon by up to 43% compared to traditional road construction solutions and saved almost £3m.

The application of foam-mix recycling on site erased approximately 6,000 HGV movements from the operation, saving 230 tonnes of CO_2e. This also shortened the construction

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[92] García-Segura, T, Yepes, V., Frangopol, D., Yang, D., Lifetime reliability-based optimization of post-tensioned box-girder bridges, Engineering Structures, Volume 145, 15 August 2017, Pages 381-391.

[93] Gokasar, I., Deveci, M., Kalan, O., CO2 Emission based prioritization of bridge maintenance projects using neutrosophic fuzzy sets based decision making approach, Research in Transportation Economics, Volume 91, March 2022.

[94] Pedneault, J., Desjardins, V., Margni, M., Conciatori, D., Fafard, M., Sorelli, L., Economic and environmental life cycle assessment of a short-span aluminium composite bridge deck in Canada, Journal of Cleaner Production, Volume 310, 10 August 2021.

[95] Habert, G., Arribe, D., Dehove, T., Espinasse, L., Le Roy, R., Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges, Journal of Cleaner Production, Volume 35, November 2012, Pages 250-262.

[96] Xie, H. B., Wu, W. J., Wang, Y. F., Life-time reliability based optimization of bridge maintenance strategy considering LCA and LCC, Journal of Cleaner Production, Volume 176, 1 March 2018, Pages 36-45.

[97] Asadollahfardi, G., Katebi, A., Taherian, P., Panahandeh, A., Environmental life cycle assessment of concrete with different mixed designs, International Journal of Construction Management, 2021.

programme, reducing road diversions and traffic management impacts which had added to the carbon savings. In addition to the carbon benefits associated with the pavement solution, significant carbon reductions were also realised as a result of energy efficiency measures. The use of solar powered generators, lighting, signage, CCTV and catering facilities, along with the use of electric vehicles saved approximately 70 tonnes of CO_2e[98].

During construction, contractors Aggregate Industries removed the top 32cm of the existing pavement surface and used it to produce an ex-situ cold recycled asphalt. This was then mixed with the contracting company's SuperLow asphalt to make a carbon neutral paving surface. A total of 50,000 tonnes of material was extracted from the original pavement, of which around 38,000 tonnes was recycled over the course of just six weeks. This included roughly 11,500 tonnes of asphalt and 27,000 tonnes of foamix, which was laid using wide pavers. Aggregate Industries said a further 20,000 tonnes would be reused on other projects[99].

Concrete Pavements in the United States

Loijos[100] assessed the life cycle impacts of concrete pavements and discovered that the level of CO_2 emissions varies widely depending on the type of road scheme, from 404 metric tons CO_2e/km for a local rural road to 6500 metric tons CO_2e/km for an urban interstate, varying by an order of magnitude. The large increase in emissions for highways/interchanges can be attributed to the larger structures required and the road design (thicker concrete slab, wider road etc.). For concrete pavements, CO_2 emissions can be reduced by optimizing design and by replacing cement with secondary cementitious materials (SCM). These measures were found to reduce emissions by 10% and 17% respectively, while also reducing construction costs[101].

A12, Netherlands

A further example of low carbon construction and implementation of the circular economy is the A12 reconstruction between Ede and Grisjoord junction in Netherlands[102]. Rijkswaterstaat used the Most Economically Advantageous Tender (MEAT) approach which enabled the selection of the bid that offered the best ratio of price to quality including assessment of CO_2 mitigation and reduction of environmental impacts. In addition, the consideration of 'use and disposal' at the planning and procurement stage of the project represented an explicit move

[98] Designing 'UK first' carbon neutral road improvement project (amey.co.uk)

[99] Tatum, A., (2021), "First carbon neutral road improvement project in the UK is completed", Highways News

[100] Loijos A (2011) Life cycle assessment of concrete pavements: impacts and opportunities. Massachusetts Institute of Technology. https://dspace.mit.edu/handle/1721.1/65431
746765257-MIT.pdf

[101] https://cshub.mit.edu/sites/default/files/documents/factsheet-pavements-UpdatedAug2018_FINAL.pdf

[102] Jones, Sohn and Bendsen (2017b). Circular Procurement Case Study Collection. ICLEI – Local Governments for Sustainability, European Secretariat, downloaded from https://sppregions.eu/fileadmin/user_upload/Resources/Circular_Procurement_Case_Study_Collection.pdf?msclkid=b61465cdd14311ecba3e935ef3e6cf47 on 9/5/2022.

by Rijkswaterstaat towards carbon reduction. Below are some outcomes and lessons learned from the A12 relating to carbon neutrality:

- CO_2 emission reductions were achieved through design and materials choices, e.g., road surfacing materials that extended the standard expected product lifetime
- Optimising product lifetime created greater whole embodied carbon benefits when compared with standard practices
- Setting targets for environmental performance assisted in embedding carbon reductions in the early stages of the project, particularly when considering long term contracts that include maintenance, in-use management and disposal of assets/ infrastructure

Concrete Bridges in Sweden

Ekström et al. examined several concrete bridges in Sweden and proposed opportunities to reduce greenhouse gas emissions[103]. Figure 10 illustrates that the life cycle assessment of the level of emissions associated with the construction industry in Sweden is on par with that from passenger cars. The production of steel and concrete for the construction of roads, railways, bridges and other structures accounts for a large portion of emissions in the construction of roads, as illustrated in Figure 11. The study examined measures that could be implemented both in materials and in design and construction. For example, by including additives into concrete mix designs and reducing the cement content, the carbon footprint can be reduced significantly. The paper examined areas of design where reductions in environmental aspects may be feasible. The study concluded that for a large reduction in climate impact in bridge and road infrastructure construction, combined efforts of all stakeholders will be required. Given the long design service life of bridges, most of the life cycle is post construction, so it is vital that a sustainable approach is followed in design and construction to reduce carbon costs associated with maintenance and rehabilitation[103]. The client, as well as all parties involved in the design and construction, need to follow a more sustainable approach to allow for a reduction in carbon emissions in the construction and maintenance of road infrastructure[103].

[103] Ekström, D., Al-Ayish, N., Simonsson, P., Rempling, R., Climate impact optimization in concrete bridge construction, et al (2017), 39th IABSE Symposium, 2017.

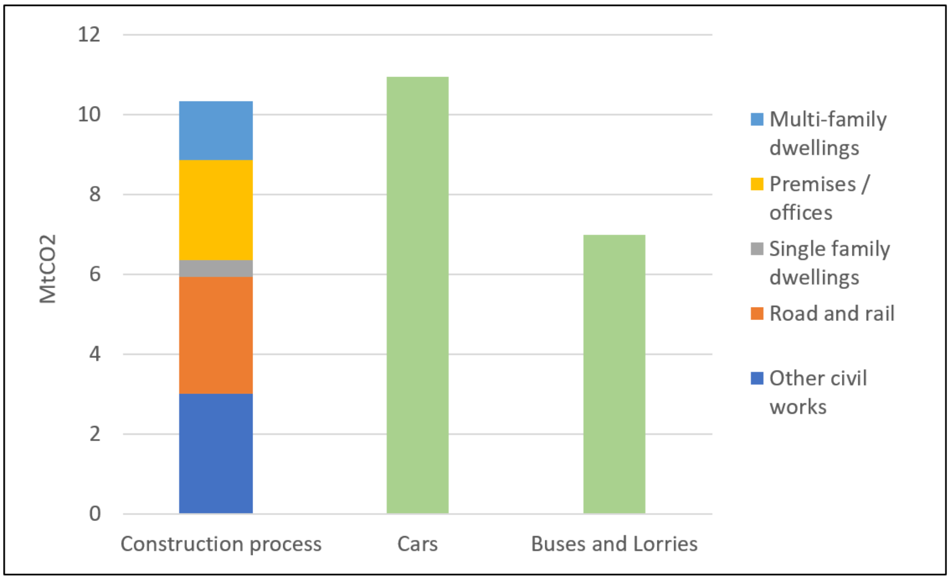

Figure 10. A comparison of CO_2 emissions from the construction sector in Sweden (reproduced from [103])

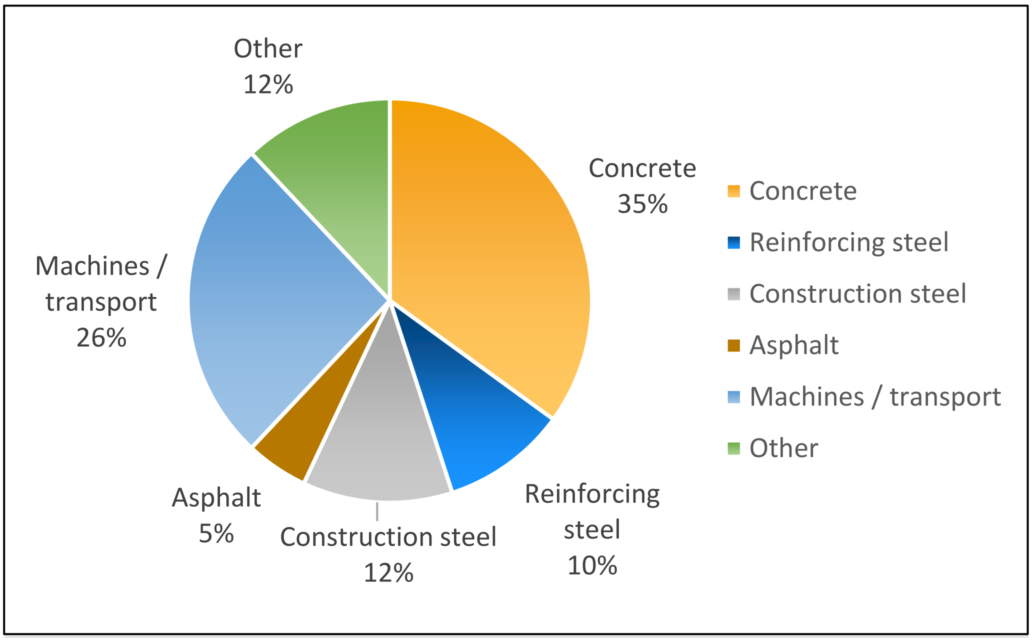

Figure 11. Distribution of emissions in the Swedish infrastructure sector (reproduced from [103])

The research shows that significant carbon savings can be made particularly through how concrete is manufactured and specified for construction. Research shows that local roads and urban interstate concrete roads have a CO_2 cost for construction of around 200 tonnes and 1,083 tonnes per lane km, respectively[104]. It has been shown that cement contributes to around 60% and 50% of this CO_2 for local and urban interstate roads, respectively[105]. Again, considering a 4-lane highway, a 10% reduction in cement content could result in carbon savings of 49 tonnes and 217 tonnes of CO_2, respectively.

3.4 Circular economy and resource efficiency

Circular economy (CE) and resource efficiency (RE) for road maintenance means, by design:

- Minimising consumption of natural resources
- Designing out waste and keeping resources in use and at their highest level of utility
- Optimising the value obtained within each lifecycle
- Improving environmental performance and contributing to societal development

Adopting an approach based on CE and RE has the potential to make a significant contribution to decarbonisation, with road pavements inherently suited to reuse of materials. Asphalt concrete is a fully recyclable material and Reclaimed Asphalt Pavement (RAP) is widely used although significant challenges remain in reusing material at the same level rather than downcycling it into lower value applications such as replacing aggregate in unbound pavement layers. The proportion of RAP permitted in hot mix and warm mix asphalt mixes varies considerably in different countries. Studies have demonstrated the feasibility of producing bituminous mixtures with a high (over 40% wt.) or very high (up to 100% wt.) proportion of RAP, and negative perceptions can be addressed by good management practices to control the quality of the RAP, novel production technologies and advanced mix design. Tarsi et al.[106] recently reviewed the state of the art.

Estimates of CO_2 savings associated with 10% replacement of cement with GGBS in road construction per 1km of 4 lane highway
Local Roads – 49 tonnes CO_2/km
Urban Interstate – 217 tonnes

It is noted that while asphalt is fully recyclable, there is still ongoing research into innovative methods, where additional materials (e.g. waste materials such as plastic or crushed glass) are added to the binder or aggregate during construction. Research into the ability to recycle these materials is ongoing, a factor that should be considered as part of multi-Life Cycle Analysis prior to using non-traditional mixes.

[104] Santero, N., Loijos, A., Ochsendorf, J., Greenhouse gas emissions reduction opportunities for concrete pavements, Journal of Industrial Ecology 17.6 (2013): 859-868.
[105] Loijos, Alex Alexander Nikos. Life cycle assessment of concrete pavements: impacts and opportunities. Doctoral Dissertation. Massachusetts Institute of Technology, 2011.
[106] Tarsi, G., Tataranni, P., Sangiorgi, C. The challenges of using reclaimed asphalt pavement for new asphalt mixtures: a review. Materials 2020; 13(18), 4052. https://doi.org/10.3390/ma13184052

Circularity, however, goes beyond simply recycling and entails a fundamental re-evaluation of how valuable resources can be used at their highest value, i.e., efficiently used, reused, repaired, and repurposed, not just recycled. A key aspect is about designing out waste and pollution rather than addressing these downstream after they are produced or designing for reuse and repair. The overarching objective is not necessarily to minimise the cradle-to-grave flow of materials, but to generate cyclical, cradle-to-cradle metabolisms that enable materials to maintain their status as high-value resources.

Below are some examples of recent road construction projects where circular economy approaches were followed.

A303, United Kingdom

The A303 Amesbury to Berwick Down scheme commission, undertaken between September 2017 and June 2018, was the first scheme in the UK that adopted circular economy approaches from the preliminary design phase with the aim of raising awareness of, identifying and promoting circular economy approaches in the organisation[107]. The approach built upon the lessons learned from an earlier A14 Circular Economy Pathfinder Project:

- Early design stages have the greatest potential to improve resource efficiency and contribute to circular economy
- Identifying and implementing opportunities at this stage can enable significant reductions in cost, waste and greenhouse gas emissions and other sustainability benefits
- Over 100 opportunities for material, processes and environment / biodiversity gains were identified for the A303, and approximately one quarter of them were incorporated within the Preliminary Design
- Communication materials to raise awareness of significant sustainability benefits including, reductions in cost, waste and greenhouse gas emissions that CE initiatives can generate.
- Lessons learned for moving forward with the transition to CE
- Need to embed the key opportunities by for example developing a ‘live’ list, for review, development, investigation and continue to, in collaboration with stakeholders, identify further efficiencies and innovation
- Use contractual mechanisms to take forward the key opportunities
- Develop metrics to monitor and evaluate circular economy realisation and outcomes as well as sustainable resource management activities with the longer-term aim of quantifying the benefits realised and thereby helping to inform future work

Use of felt waste in road construction in Finland

The driver in this case was to enable CE through an innovative solution, developed by a local company (Tarpaper), of using waste materials from another sector. The aim was to use roofing felt waste in road construction and make this part of a normal procedure for the future. Pilot areas were provided by the procurer, the City of Lahti, for testing. Roofing felt waste from

[107] Highways England (2018). A303 Amesbury to Berwick Down. Circular Economy Approaches at the Preliminary Design Phase. AECOM, Mace, WSP HE551506-AMW-EGN-SW _ZZ_ZZ _ZZ-RP-EN-0006 P02, S4 (Report provided by National Highways)

demolition or refurbishing was processed and added as a bitumen source in the production of new asphalt. This exercise resulted in the production of quality asphalt with a reduced requirement for virgin bitumen and beneficial use of roof felt waste for use in the road sector.

Outcomes and lessons learned[108]:

- The innovator, Tarpaper Recycling Finland, was able to register a patent for the method to recycle roofing felt waste and thereby introduce a new environmentally friendly option for road maintenance
- The joint working between the City of Lahti and Tarpaper that resulted in accelerating the successful use of roofing felt waste as a material for asphalt highlighted the need for a collaborative approach between procurers and suppliers.
- The success of the approach catalysed the search and use for other materials to similarly deliver environmentally friendly outcomes and reduction in carbon emissions. Another example of alternative materials used in road construction projects is soil (extracted from construction sites) and ash resulting in reduced costs due to shorter transportation distances and the reduced need to purchase soil
- In relation to circular economy and multi-life cycle analysis, it is important to recognise the challenges and limitations of using innovative methods and materials. Research must be progressed to determine the future recyclability of these non-traditional materials

Circular economy approaches in general have significant potential to induce both carbon and economic savings in road construction and maintenance. Transport Infrastructure Ireland (TII), the NRA of Ireland, have put forward a bespoke Circular Economy Plan based on the principles of the 9 Rs of circularity[109]. This plan has been tested in a pilot study at route selection stage for an 11.2 km section of the major national road network.

Adoption of Circular Principles in Road Construction
Savings of over €800,000 and 600t CO_2 across an 11km scheme

3.5 Low carbon materials

3.5.1 Asphalt

While traditional ‘hot mix’ asphalt is produced at temperatures between 120 °C and 190 °C, it is now common for asphalt to be produced at lower temperatures[110], namely:

- Cold mixes, with unheated aggregate and bitumen emulsion or foamed bitumen
- Half warm asphalt, produced between approximately 70 °C and 100 °C
- Warm mix asphalt (WMA), produced between approximately 100 °C and 150 °C

[108] Nordic Council of Ministers (2020). Pre-Study: Indicators on Circular Economy in Nordic Countries.
[109] Lynch J. TII circular economy plan: TII standards training https://www.tiipublications.ie/training/SRT22/day1/05_j_lynch_TII_circular_economy_plan.pdf
[110] https://www.eapa.org/warm-mix-asphalt

For lower temperature asphalts, additives or foaming techniques are used to reduce the viscosity of the bitumen so that it remains workable. A paper[111] by the European Asphalt Pavement Association quotes reductions of the order of 20 to 40% in plant stack emissions of CO_2 for half mix and warm mix asphalt, compared with hot mix, as well as reductions in other greenhouse gases. The asphalt paving association of New Mexico also quotes[112] a 20% reduction in fuel consumption for warm mix, during manufacturing. The reduction in energy use will be partially offset by the requirement for additives or additional processes. Lower temperature materials have other benefits[113] including a reduction in the production of potentially hazardous fumes and a longer working window and / or range of ambient temperature for application. Extended service life is also claimed because of improved compaction and reduced binder oxidation (due to the lower temperatures involved in production). However, the cooler material benefits from modifications to the paving and compaction process to achieve a good result.

In the Assam State of India[114], a trial of 500 km cold mix asphalt showed the material to be highly suitable for local conditions. In this region, conventional hot processes are often disrupted by intermittent rainfall and the transport of construction plant to site is complicated by the hilly terrain. Conversely, cold mix is a practical alternative, requiring only simple, low-cost machinery, which was found to result in higher rates of construction under these conditions. It was calculated that the fuel saving, compared with hot mix, would amount to 1,500 l/km, or 4,200 kg CO_2 emissions per km constructed, a 90% reduction. Considering the scale of road building in India, if cold mix was adopted for the 50,000 km constructed per year it would translate to 200 million kg reduction of CO_2 emissions annually. The material is reported to be durable in service, due to the anti-stripping agents incorporated into the mixture, although it has a higher initial cost. It is also seen as providing green employment opportunities, particularly increasing the opportunities for female workers, with reduced exposure to hazardous working conditions. The lifecycle considerations presented are reproduced in Table 3.

Table 3. Lifecycle cost considerations for cold mix asphalt deployed in Assam (source [114])

Warm mix asphalt
Estimates of CO_2 savings from using warm mix asphalt in place of hot mix asphalt (per 1 km of 4-lane carriageway) Saving at construction – 8 to 16 tonnes

[111] The use of warm mix asphalt, EAPA position paper, European Asphalt Pavement Association, Belgium, 2014
[112] https://apanm.org/warm-mix-asphalt-wma/
[113] https://www.worldhighways.com/wh3/feature/reduced-temperature-asphalt-road-construction
[114] Das, R. K., Bhushan, R., Boro, M. C., Agarwal, R., Cold mix – a "green" black-topping technology for rural roads delivering higher durability and socio-economic and environmental benefits to society. 25th World Road Congress, Seoul, 2015

Black-topping type	Cost of laying per m2 (in x Rs)	Usage cost & concerns	Maintenance costs	Disposal cost & concerns	Safety, Health and Environmental
Hot mix	X	High fuel use Pollution Temperature control Limitations in use	Renewal after 5 years	Uses more binder when recycled	Productivity, safety – low Environmental impact – high
Cold mix	X + 15%	No fuel [needed] for heating Green technology Extended paving window	Renewal after 7 years – presence of anti-stripping agents	Uses less binder when recycled	Environmental impact – minimal Productivity, safety – high

WMA materials are well-proven. Over 40 State highway agencies in the USA have adopted warm mix specifications[115] and, even in 2010, this technology was used to deliver 42 million tons of material, nearly 12% of total asphalt production. In Europe, use of WMA approximately doubled between 2013 and 2020, to over 8 million tonnes, although this represents only a modest proportion of total production of approximately 275 million tonnes[116].

In 2021, England's National Highways began asking all its suppliers to use WMA by default, estimating[117] that the 15% CO_2 reduction compared with hot mix materials will save around 60,000 tonnes of CO_2 a year. As an approximate indication of the potential CO2 saving from adoption of WMA, scaling the data from various sources[118, 119, 120, 121] and assuming, where necessary, that 450 tonnes of asphalt is required to surface 1 lane km of carriageway (3.6 m width) to a 50 mm depth, suggests a saving of between 1 and 5 tonnes CO2 / lane km could be attained compared with HMA. Taking data from a further study, suggested a saving of

[115] https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/pdf/wmafnlweb.pdf
[116] EAPA Asphalt in Figures - provisional figures 2021 https://eapa.org/asphalt-in-figures/
[117] https://www.gov.uk/government/news/highways-england-accelerates-switch-to-lower-carbon-asphalts
[118] Lu Y, Wu H, Liu A, Ding W, Zhu H Energy consumption and greenhouse gas emissions of high RAP central plant hot recycling technology using lifecycle assessment. https://publish.illinois.edu/lcaconference/files/2018/01/32_Revised-Paper-ENERGY-CONSUMPTION-AND-GREENHOUSE-GAS-EMISSIONS-OF-HIGH-RAP-CENTRAL-PLANT-HOT-RECYCLING-TECHNOLOGY-USING-LIFE-CYCLE-ASSESSMENT%EF%BC%9ACASE-STUDY.pdf
[119] Mazumder M, Sriraman H, Kim HH, Lee SJ. Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA). Int Journal of Pavement Research and Technology (2016) Vol 9, Issue 3, p 190-201
[120] https://www.hanson.co.uk/en/blogs/low-energy-asphalt-the-future-roadworks
[121] https://uploadstarmaccom.blob.core.windows.net/uploads/sites/2/2022/08/UltiLow-case-study-Birley-Spa-Lane-Sheffield-1-1.pdf

between 18 and 32 tonnes CO2 / lane km, depending on the type of road[122.] This value is substantially higher than other estimates, and the limited detail provided did not allow a comparison to be made with the other sources. However, the difference that it is possible to achieve in practice will depend on the local situation, as they are influenced by the capability and utilisation of plant, the type of energy source deployed, ambient weather conditions and the moisture content of materials. The effective management of stockpiles to reduce moisture levels can also have a dramatic influence on the energy needed for drying[123].

3.5.2 Concrete

The production of cement and concrete results in a large amount of CO_2 emissions. Studies have been carried out on processes and design procedures to reduce the environmental impacts associated with concrete without compromising quality and safety.

According to Habert et al.[124], using alternative fuels to produce concrete, improvements in cement kiln and substituting clinker with alternative materials could have the effect of reducing CO_2 emissions associated with the cement industry by a factor of 2. Industrial by-products such as pulverised fuel ash and ground granulated blast-furnace slag are examples of standard clinker replacement materials in the production of cement in Europe. Limestone or natural pozzolans are also used. These additions of supplementary cementitious materials (SCM) can also be made during concrete production rather than cement production. A project funded by the Swiss Agency for Development[125] is developing a limestone calcined clay cement, name LC3, which could potentially reduce CO_2 emissions by 30% compared to standard cement mixes. Asadollahfardi et al.[126] indicated that replacing cement with Geopolymer resulted in a reduction in global warming indicator of nearly 26% compared with Ordinary Portland Cement (OPC) concrete. A case study by Hossain et al.[127] used life cycle assessment techniques to evaluate the advantages of using volcanic ash as a potential alternative SCM. The results indicated that for the same strength concrete, using volcanic ash as a SCM has the potential to reduce GHG emissions by 25% and 19% compared to OPC and more traditional SCM concretes. A study by Rangelov et al.[128] assessed the impacts of reducing cement and concrete volume in paving mixtures in the United States. As well as investigating

[122] Lokesh K, Densley-Tongley D, Marsden G (2022) Measuring road infrastructure carbon: a critical in transport's journey to net-zero https://decarbon8.org.uk/wp-content/uploads/sites/59/2022/02/Measuring-Road-Infrastructure-Carbon.pdf
[123] Simmons GH. Technical paper T-129 Stockpiles. https://documents.pub/document/stockpiles-intigobar-stockpiles-by-george-h-simmons-jr-technical-paper.html?page=1
[124] Habert, G., Billard, C., Rossi, P., Chen, C., Roussel, N., 2010. Cement production technology improvement compared to factor 4 objectives. Cem. Concr. Res. 40, 820e826.
[125]https://www.eda.admin.ch/deza/en/home/projekte/projekte.html/content/dezaprojects/SDC/en/2013/7F08527/phase1
[126] G. Asadollahfardi, A. Katebi, P. Taherian & A. Panahandeh (2019):
Environmental life cycle assessment of concrete with different mixed designs, International Journal
of Construction Management, DOI: 10.1080/15623599.2019.1579015
[127] Hossain, M. U., Dong, Y., & Ng, S. T. (2021). Influence of supplementary cementitious materials in sustainability performance of concrete industry: A case study in Hong Kong. Case Studies in Construction Materials, 15, e00659. doi:10.1016/j.cscm.2021.e00659
[128] Readily Implementable Strategies for Reducing Embodied Environmental Impacts of Concrete Pavements in the United States - Milena Rangelov, Heather Dylla, Brian Dobling, Jagan Gudimettla, Nadarajah Sivaneswaran, Michael Praul (2022) Transportation Research Record, 2676(9), 436–450. https://doi.org/10.1177/03611981221086934

decarbonising strategies outlined in the literature, they analysed data associated with paving concrete mixtures from 27 projects across the United States between 2011 and 2019. The opportunities for embodied carbon reduction were identified for the analysed dataset. The study concluded that use of supplementary cementitious materials is beneficial but is already quite common in practice. Thus, for further reduction it is essential to avoid mixture overdesign and lower the cement content in concrete paving mixes. The study also highlighted the need for appropriate specifications and consistent environmental reporting in decarbonising concrete road construction.

Concrete waste from demolition can be used in the construction of roads, for building concrete structures or in mortar production, along with other applications[129], thereby reducing CO_2 emissions and reducing waste going to landfill. Braga et al.[129] carried out a cradle to grave life cycle assessment to compare concrete using virgin materials and recycled aggregates. Using recycled concrete has potential to reduce environmental impacts and costs, attributed partly to the higher structural performance of using recycled concrete in the mix. Although the design of concrete roads and structures follow different design procedures, the composing material is essentially the same and the use of recycled aggregate is also applicable in rigid pavement construction[130]. However, as with other uses of secondary materials, the impacts of processing and transporting the recovered material needs to be considered.

Another option is to reduce overall concrete volume. A study by Habert et al.[131] examined the environmental impact of using a high-performance concrete over traditional concrete mixes for bridge construction. Life cycle assessment was carried out to determine if a high strength concrete mix with a higher cement content and associated higher embodied carbon was more environmentally friendly considering the life cycle of the concrete structure. Using a high-performance concrete allows for a lower quantity of concrete to be used, which on average can lead to a net decrease in CO_2 emissions. The reduced porosity of high strength concrete also slows down the time of corrosion initiation of reinforcing steel, reducing the maintenance requirements and potentially increasing the lifespan of the structure.

Rehabilitation of the Log Čezsoški bridge in Slovenia took place in 2009, with the use of a novel Eco-Ultra-Fibre Performance Fibre Reinforced Concrete (ECO-UHPFRC)[132]. It is a single lane, 65m long, 3 span bridge. The rehabilitation involved the removal of the asphalt pavement, waterproofing membrane and 3 cm of mortar, and the addition of a continuous overlay of ECO-UHPFRC. A life cycle assessment was carried out to examine the environmental

[129] Braga, A.M., Silvestre, J.D., de Brito, J., Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates, Journal of Cleaner Production, 162, 2017, 529-543, doi.org/10.1016/j.jclepro.2017.06.057.
[130] De Brito, J., Agrela, F., & Silva, R. V. (2019). Legal regulations of recycled aggregate concrete in buildings and roads. New Trends in Eco-Efficient and Recycled Concrete, 509–526. doi:10.1016/b978-0-08-102480-5.00018-x
[131] Habert, G., Arribe, D., Dehove, T., Espinasse, L., Le Roy, R., Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges, Journal of Cleaner Production, Volume 35, November 2012, Pages 250-262.
[132] Habert, G., Denarié, E., Šajna, A., Rossi, P., Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes, Cement and Concrete Composites, Volume 38, April 2013, Pages 1-11.

evaluation of possible rehabilitation strategies. The study compared the novel ECO-UHPFRC application with a more traditional rehabilitation system using conventional concrete and a waterproofing membrane. It was concluded that CO_2 impacts using ECO-EHPFRC were approximately 60% of the traditional concrete solution considering a 60-year life cycle. As a comparison, it was demonstrated that the CO_2 impact of the traditional UHPFRC system was 73% of the conventional system of concrete and waterproofing membrane. The results are illustrated in Figure 12.

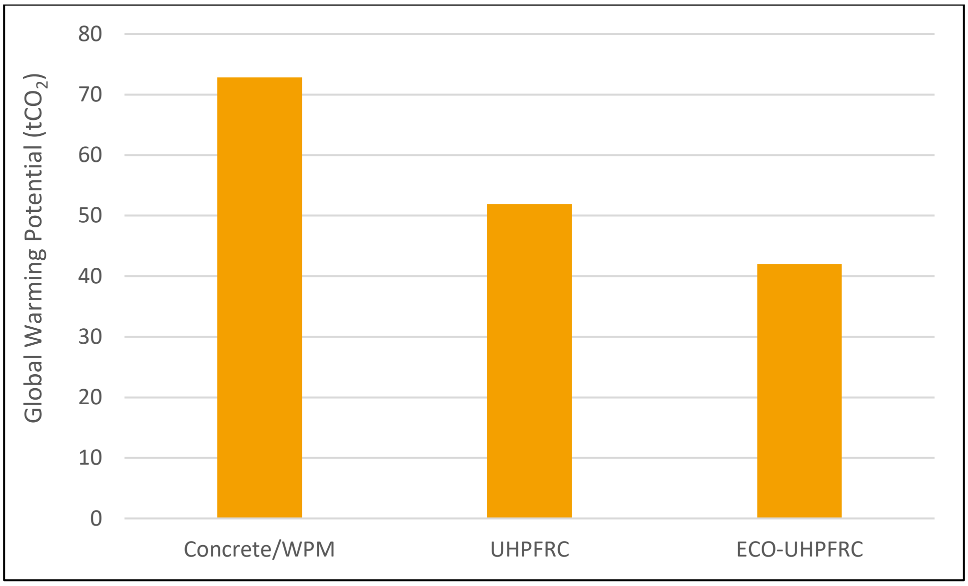

Figure 12. Effect of potential rehabilitation strategies on CO_2 emissions (reproduced from[132])

3.6 Low rolling resistance pavements

Careful construction of the pavement can reduce rolling resistance for vehicles using the road. As seen in Figure 4, this currently represents the largest component of overall CO_2 emissions. Most literature agrees that pavement surface texture and roughness contribute to rolling resistance and, hence, to vehicle fuel use. A selection of papers is reviewed by Ishigaki et al., who went on to construct two sections of Low Rolling Resistance Asphalt Pavement (LRRAP) in Japan[133].

Compared with a conventional porous asphalt, the LRRAP led to a reduction of 10-15% in rolling resistance and 2-4% reduction in the CO_2 emissions of a test vehicle traversing the pavements. The two types of LRRAP were constructed with smaller aggregate than the porous asphalt (2/5 grading rather than 5/13) and achieved both a smoother pavement (approximately 0.9 mm/m IRI compared with 1.12 mm/m) and lower texture (approximately 0.7 mm MPD (mean profile depth) compared with 1.6 mm). A conventional dense graded asphalt was also constructed. This had relatively large aggregate size (0/13 grading), low

[133] Ishigaki. T., Shirai, Y., Kawakami, A., Kubo, K., Low rolling resistance asphalt pavements for traffic energy saving and CO2 emission reduction. 25th World Road Congress, Seoul 2015. https://proceedings-seoul2015.piarc.org/ressources/files/4/IP0680-Ishigaki-E.pdf

texture (0.4 mm MPD) and a relatively rough surface (1.25 mm/m IRI). The performance of this material was also considerably better than the porous asphalt although not quite as good as the LRRAP – this suggests both texture and smoothness are important.

There are differences in the distribution of contact pressures between the tyre and the pavement surface for these materials (Figure 13) – the higher texture of the porous asphalt is apparent in the larger green areas of higher pressure, where the tyre is likely to be deformed more strongly. Mukherjee[134] notes that energy losses from the repeated deformation and recovery of the tyre as it rolls are the main causes of rolling resistance, and that both surface characteristics and structural characteristics of the road pavement contribute to this. The values of rolling resistance coefficient (C_{RR}) make clear the improvement in rolling resistance for concrete and asphalt pavements (C_{RR} of 0.013) compared with rolled gravel (0.02) and unpaved roads (0.5).

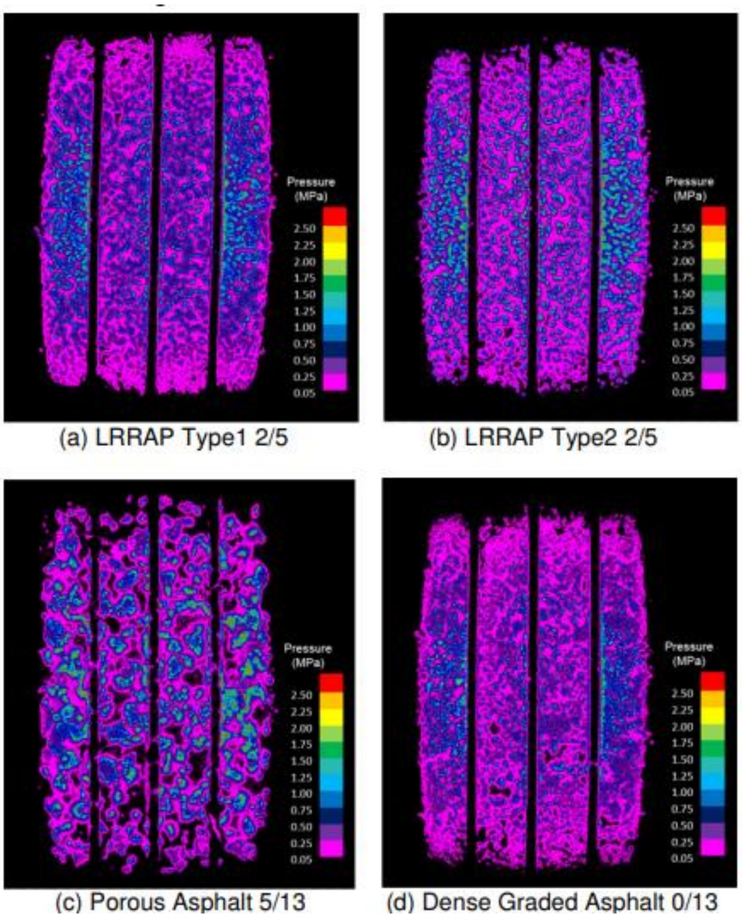

Figure 13. Contact pressures between the tyre and pavement surfaces from Ishigaki et al.133

[134] Mukherjee. D., Effect of pavement conditions on rolling resistance. American Journal of Engineering Research 2014, vol 3, issue 7, p 141

A smaller contribution to the rolling resistance comes from the pavement structure. This was investigated by Lengren[135], who used a falling weight deflectometer to investigate the deformation response of different pavement types. Lengren estimated that a rigid pavement would contribute between 2 and 6 times less to rolling resistance than a flexible pavement, but this was dependent on the type of construction and the stiffness of the surrounding soil. The temperature was also significant, and, in winter conditions, there is reported to be little difference between flexible and rigid construction. It is noted that, although use of lime and cement stabilization has a high carbon footprint, when designing the pavement this should be balanced against the reduction in traffic induced emissions due to the stiffer pavement structure.

Estimates of road user CO_2 savings associated with construction of smooth, stiff pavements, compared with conventional construction (per 1 km of high traffic, 4-lane carriageway during a 15-year life)

Lower estimate – 6,000 tonnes

Upper estimate – 12,000 tonnes

The 2-4% fuel saving found in the Japanese study is similar to that quoted by other sources[136]. In practice, the saving will depend on the number of vehicles using the road and on their underlying fuel efficiency. To provide an approximate indication of the scale of CO_2 reduction possible from pavements that are stiff, even and negatively textured, it was calculated that for a road carrying high traffic (25,000 vehicles / lane / day) with 15% trucks, a 2-4% fuel saving would correspond to a saving of 100-200 tonnes CO_2 / lane km /year. Over a 15-year life, this would translate to saving 1500 – 3000 tonnes CO_2 / lane km. For lower traffic levels, the saving will be correspondingly smaller, and the potential saving will also reduce as engines become more fuel efficient or less carbon intensive. This analysis assumed typical current emissions factors 252.5 gCO_2/km[137] and 2,022 gCO_2/km for trucks[138], assuming a 20 t load.

The MIT sustainability hub quantified excess fuel consumption associated with road stiffness and roughness, displaying the results as a strip map[139]. Their assessment was that proper maintenance to a small proportion of Virginia's interstate system (65 lane miles out of 5,000 lane miles total) would reduce the CO_2 emissions of the network by 10%.

3.7 DECARBONISATION OF CONSTRUCTION PLANT AND CONSTRUCTION OPERATIONS

[135] Lenngren, C. A., Different pavement types and rolling resistance, 2014 International concrete sustainability conference, Boston
[136] https://eapa.org/road-pavement-industries-highlight-huge-co2-savings-offered-by-maintaining-and-upgrading-road-view
[137] https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle#driving
[138] https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/
[139] Sustainable Pavements. MIT Concrete Sustainability Hub Factsheet (August 2018). https://cshub.mit.edu/sites/default/files/documents/factsheet-pavements-UpdatedAug2018_FINAL.pdf

It has been estimated[140] that the typical energy consumption breakdown of a road construction project is 75% material production, 20% transportation and 5% construction itself. Whilst the exact energy consumption will vary with factors such as material used, type of construction and transport distances, construction plant energy consumption is a small, but not insignificant, contributor to road carbon energy emissions. This is not surprising given the size of the machines involved and the weight of the materials they carry or move. A range of fuel consumption of typical construction and maintenance machines is presented in Table 4, below.

Table 4. Typical diesel use from construction plant[141]

Litres per hour diesel use	Mid-Range Fuel Consumption per hour (l)	8-hour shift fuel use (l)	5-day work week fuel use (l)	50-week work year fuel use (l)	Annual CO_2 emissions (kg) at 2.4kg/l	Annual CO_2 emissions (tonnes)
Bulldozers: 13 – 25	18.95	151.6	758	37,900	9,0960	91
Backhoes: 5.7 – 9.5	7.58	60.64	303.2	15,160	36,384	36
Small Trencher: 3.8	3.79	30.32	151.6	7,580	18,192	18
Large Trencher: 34 – 45	39.795	318.36	1,591.8	79,590	191,016	191
Grader: 38 – 45	41.69	333.52	1,667.6	83,380	200,112	200
Scraper: 64 – 72	68.22	545.76	2,728.8	13,6440	327,456	327
Excavator: 38 – 53	45.48	363.84	1,819.2	90,960	218,304	218

All the machines listed in the table above produce tens of tonnes of CO_2 per year and potentially in the hundreds of tonnes per year. Consideration of the sheer number of these machines worldwide demonstrates the high potential to reduce carbon emissions if diesel consumption could be replaced with cleaner alternatives. Potential options are presented

[140] https://pavementinteractive.org/energy-and-road-construction-whats-the-mileage-of-roadway/
[141] https://cpower.com/2021/11/16/types-of-gas-for-your-rental-construction-vehicle/

below. The Criminal Intelligence Agency (CIA)[142] report that there are around 12.7 million kilometres of paved roads worldwide. The potential maintenance carbon is estimated as follows.

Table 5. Estimate of worldwide, annual carbon emissions associated with use of plant

Data and assumptions	Calculations
Length of paved roads worldwide	12,717,850 km
Lane km – conservative estimate of each road being 2 lanes	25,435,700 km
Annual length maintained – assume maintenance every 10 years (i.e. 10% annual)	2,543,570 km
Energy associated with maintenance – assume 1TJ per lane km	2,543,570 TJ
Energy associated with use of plant – assume 5% of energy from plant	127,179 TJ
Estimate total fuel usage – 1 litre diesel = 38MJ	3.35 billion litres diesel consumed
Estimate of total carbon emissions associated with use of plant – 2.4 kg CO_2 emitted per litre diesel burnt	8 billion kg / 8 million tonnes

Reduction of demand

The first step before looking to replace a fuel will be to reduce existing fuel / energy use. Numerous sites[143,144] offer general advice on ways to maximise fuel efficiency of vehicles, including manufacturers of the equipment [145]. Some of the key themes are as follows:

- Maintain the machine to keep it in good condition, including checking oil and liquid levels, tyre pressures where appropriate, air filters
- Minimise idling and look for machines with start/stop features
- Use trained operators as they will operate the machinery more efficiently. Some machines have telematics that can improve operator training. Stein et al[146] reference a study where efficiency varied by 40% between operators undertaking the same task

[142] https://www.cia.gov/the-world-factbook/field/roadways/country-comparison
[143] https://www.construction-europe.com/news/6-ways-to-increase-fuel-efficiency-for-heavy-construction-equipment/8013326.article
[144] https://www.equipmentworld.com/equipment/article/15292688/reducing-diesel-fuel-consumption-in-construction-equipment
[145] https://volvoceblog.com/tips-to-cut-heavy-equipment-fuel-consumption/
[146] https://www.researchgate.net/publication/260058937_Fuel_efficiency_in_construction_equipment_-_optimize_the_machine_as_one_system

- Where machines have data collection, this can be used to provide early warning of inefficiency and enable preventative/early maintenance or repair to be undertaken
- Using the right machine for the job, so called 'right-sizing' improves productivity but also fuel by ensuring machines are paired together
- Some machines have eco pedals that push back in response to excessive accelerator use.
- For asphalt compaction there are programmes to maximise compaction requirements without excessive passes

Stein et al point out that there are three areas for reduction of carbon on construction sites:

With job site optimisation alone capable of enabling fuel savings of 30%, this combined with machine optimisation and machine control to increase efficiency, could potentially produce fuel savings of 50% on some

- Job site optimisation – refers to how the site is established, using the correct sized plant for the job, maximising turning circle improvements for smooth running and minimising queuing and waiting time. Whilst it is highly site dependent, they report that fuel savings of up to 30% have been identified.
- Machine use optimisation – this covers how the machine itself is used and the reported savings from having trained operators, using only the required force for the job. The savings (or losses from inexperienced operators) could be improved from machine control (see below).
- Machine optimisation covers the mechanics of the machine use including hydraulics and drivetrain. Stein et al report that peak power demand is in the bucket filling phase where hydraulics and drivetrain are both consuming up to the maximum engine power, accounting for around 40% of fuel consumption. This also gives a large potential to minimise losses in the phase through technologies such as charging energy storage in time of limited use, to use the power in times of need and attempting to optimise the balance between the power used for the engine, hydraulics and propulsion.

Connected and Automated Plant (CAP) / Machine Control

As with road vehicles, there has been research undertaken on connected and autonomous plant. For simple, repetitive tasks such as trench digging and loading vehicles, autonomous plant has been developed to undertake them remotely, with significant operator savings and fuel and equipment saving by undertaking the task perfectly and efficiently each time. This frees the skilled operator to undertake tasks that require the human dexterity that is beyond the capability of a robot.

Machines in the construction industry [147,148,149] range from machine assistance to examples of full autonomy. Fully autonomous vehicles have been developed for use in controlled

[147] https://cacm.acm.org/news/224172-autonomous-construction-vehicles-are-building-the-future/fulltext
[148] https://future-markets-magazine.com/en/markets-technology-en/autonomous-construction-machines/
[149] https://www.equipmentworld.com/tag/autonomous-construction-equipment/

environments such as open cast mines, where they autonomously collect material from the mine floor and bring it to the processing plant at the top.

The CEDR STAPLE (SiTe Automation for Practical Learning) project provides details of various research and development in the area. In the road construction and maintenance sector, applications are limited so far, although an area of research is in compaction equipment, as the correct level of compaction with an even number of passes has a strong influence on the subsequent road quality and longevity. Longer lived pavements with fewer maintenance interventions has a clear carbon saving.

Research in this area was reported in the STAPLE deliverables, detailing that BOMAG[150] has undertaken research to develop a fully autonomous tandem roller, containing GPS, Lidar and advanced position sensors, enabling it to be used fully autonomously in defined work areas.

Machine assist, or semi-autonomous plant is likely to be more relevant and is already in use in many machines. Trimble report[151] that over 100,000 earth moving (dozer) vehicles were fitted with machine control worldwide. Whilst such plant still needs an operator, it was reported that machine assist enables experienced operators to run 41% faster and 75% more accurately, whilst new operators will run 28% faster and 100% more accurately. Whilst the motivation is improved productivity, quality and safety, their increased efficient also delivers carbon savings.

For example, excavator depths can be set which not only avoid hitting know underground utilities, and achieve perfect grading, but prevent over digging, which wastes fuel. Given that bucket filling accounts for 40% of fuel consumption, significant carbon savings can be made, particularly for novice operators.

Electric Power

Many companies are introducing ranges of fully electric construction plant, which offer reduced noise as well as zero emissions. At this stage, this is limited to smaller, less powerful machines. For example, JCB offers a range[152] including 500 kg and 1 tonne site dumpers, mini excavators, forklifts and access platforms, plus a range of charging solutions, with a stated full typical day use on a single charge. Volvo[153] are another major equipment supplier offering battery powered mini excavators and wheeled loaders and have announced[154] that they will stop development of diesel engine compact wheel loaders and compact excavators.

There have been examples of large battery powered equipment, including an all-electric 26 tonne excavator with a 300kWh battery pack from Caterpillar[155], with the batteries alone

[150] https://www.bomag.com/ww-en/press/news-videos/future-study-fully-autonomous-tandem-roller/
[151] STAPLE (2020) Practical learnings from test sites and impact assessments, Deliverable No 4.1 & 4.2
[152] https://www.jcb.com/en-gb/campaigns/etech-range
[153] https://www.volvoce.com/global/en/our-offer/emobility/
[154] https://electrek.co/2019/01/17/construction-equipment-electric-volvo-ce/
[155] https://electrek.co/2019/01/29/caterpillar-electric-excavator-giant-battery-pack/

weighing 3.4 tonnes giving 5 – 7 hours of operation. Even larger, is a prototype 110 tonne converted Komatsu dumper with a 700kWh battery pack[156], working in a mine in Switzerland. An advantage of this operation is that whilst diesel trucks use fuel even on their way down a mine, the prototype vehicle can use regenerative braking to recoup 40 kWh on each trip down the quarry, totalling 800 kWh per day for the 20 journeys it makes. This can potentially offer massive savings given that a typical dumper truck of this type uses between 50,000 and 100,000 litres of diesel per year – taking the midpoint of the range equates to around the average fuel use per year of 37 cars in the USA and 110 cars in the European Union based on average annual milage and emissions[157]. Should this trial prove success, they may retrofit further vehicles of this type.

In another example[158], ABB and Hitachi have joined forces to develop a catenary powered electric dump truck.

Alternatives to diesel

Whilst there are examples of very large electric vehicles in development in quarries, the fixed nature of the sites does make them particularly suitable for an electric transition. The vehicles can be charged overnight or, with catenary charging can be charged for most of the route from the quarry floor, plus the potential for regenerative braking on downhill runs. The same is not necessarily the case for the more mobile equipment typically used in highway construction and maintenance.

As detailed above, many smaller machines are suitable for battery power, but for larger plant, due to the weight of batteries and charging times, other alternatives are being suggested, mainly biodiesel and hydrogen in various forms.

Biofuel has an obvious advantage in that it can be used as a direct replacement for existing machines, but there are concerns around land use, if biofuel crops are displacing land suitable for growing food. There are concerns around the relatively low efficiencies of some crops used for bioethanol, for example it is reported that ethanol from corn produces 30% more energy than that used to grow it[159], which is significantly higher than sugar and soy-based ethanol. The other concern is realistically how much could be grown. The potential for algae or kelp produced fuels shows promise and could be undertaken so as to not compete with agricultural land but requires development.

Many plant manufacturers see hydrogen as a solution for their machinery, with JCB seeing this as the solution for machinery over 5 tonnes. They have demonstrated a 20-tonne

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[156] https://electrek.co/2017/09/17/electric-dumper-truck-worlds-largest-ev-battery-pack/

[157] Average EU car efficiency = 6 litres per 100 km (https://www.iea.org/articles/fuel-economy-in-the-european-union) and average annual km 11,313 (https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html)l = 678.78 litres per car, per year. Average USA car fuel efficiency = 9.3 litres per 100km (https://www.epa.gov/automotive-trends/highlights-automotive-trends-report) and 21,687 annual km per year = 2,017 litres per car per year (https://www.fhwa.dot.gov/ohim/onh00/bar8.htm)

[158] https://www.australianmining.com.au/news/abb-hitachi-to-design-electric-dump-truck/

[159] https://biofuels-news.com/news/future-trends-in-biofuel/

excavator using a hydrogen fuel cell but consider that fuel cell powertrains are not yet sufficiently robust for the construction industry. Instead, they favour burning hydrogen in combustion engines and have demonstrated its use in a 4.8 litre backhoe excavator. They state the engine will cost the same as standard engines and can be retrofitted to existing vehicles, with hydrogen supplied on building sites in mobile tankers as diesel is now.[160]

Burning hydrogen in this way utilises much of the same diesel engine technology infrastructure, requiring only modification of the internal combustion engine to burn hydrogen instead of diesel. Burning hydrogen does still produce nitrous oxides although these can be minimised.

Fuel cells are more efficient than burning hydrogen and do not produce NOx, with heat and water vapour being the only tailpipe emissions. In March 2021, SANY announced it had launched a hydrogen fuel cell dump truck and mixer truck[161]. Meanwhile, Volvo has started testing the world's first prototype of a hydrogen fuel cell articulated hauler, having a range of battery electric solutions already. Volve CE has a Science Based Targets initiative (SBTi) with a commitment to net-zero value chain greenhouse gas emissions by 2040 and driving industry transformation towards carbon neutrality[162]. With hydrogen infrastructure remaining an issue, Volvo worked with Shell to provide the fuelling infrastructure at its test site. Both Volvo and Shell are founder members of H2Accelerate, a collaboration of companies working to develop conditions to roll out hydrogen trucks in Europe.

Keltbray has agreed a deal with AFC Energy to install hydrogen fuel cells on one of its construction sites, expected in the second quarter of 2022[163]. Keltbray has a company target of net zero carbon by 2040.

An issue with batteries and fuel cells is the low volume of machines, but there is likely to be a transition over the next 5 to 10 years as they become operationally and economically viable. A remaining challenge is around the fuelling infrastructure itself in terms of storage and distribution, with the final challenge being the cost of hydrogen and the production of green hydrogen, as most hydrogen produced today is a by-product of the petroleum industry.

> Road maintenance alone may account for 8 million tonnes of CO_2. A significant proportion could be saved through job site and machine optimisation. The remaining energy requirements could be met through a combination of clean electric or green hydrogen.

Many NRAs do not own their own fleet of construction vehicles, with construction and maintenance being undertaken by contractors. Contractors have incentives to invest in new

[160] https://www.autocar.co.uk/car-news/industry-news-manufacturing/under-skin-how-hydrogen-could-fuel-future-plant-machinery
[161] https://www.forconstructionpros.com/equipment/earthmoving/article/21940605/large-machinery-oems-explore-hydrogen-future
[162] https://www.worldhighways.com/wh2/news/volvo-ce-starts-testing-worlds-first-prototype-hydrogen-articulated-hauler
[163] https://www.constructionnews.co.uk/sustainability/keltbray-construction-site-to-be-powered-by-hydrogen-fuel-cell-in-uk-first-15-03-2022/

machinery for commercial reasons, for example, machine assist and semi or fully autonomous operation, and for their own corporate targets around carbon reduction for alternative fuel use. Road owners can play a role in accelerating the shift towards low carbon construction fleets through contract conditions, carbon targets and incentives.

3.7.1 Solar / hydrogen lighting replacing diesel generators

Diesel generators have typically been used to provide site lighting on road works and other construction sites. In recent years, there has been a range of solar alternatives becoming available for sale or hire. Not only do these prove to be a zero-carbon source of lighting, but they avoid the requirement for refuelling with diesel, whilst also having no emissions and lower or no noise. UK company Prolectric[164] has a lighting tower which has been used by Tier 1 contractors on rail and highways site and claims to work even in winter conditions with 16 hours of darkness.

In situations where this might not be suitable, there are solar hybrid options[165] with a diesel back up.

The use of hydrogen fuel cell powered lighting and site power has been trialled on London's Crossrail project[166] as well as other locations as an alternative to diesel power. It can be particularly useful in enclosed locations due to zero emissions.

Development of hydrogen generators for site work is likely to increase due to demand from other sectors. For example, they are popular with film and tv crews due to their silent operation, and for zero emissions music festivals. Whilst the immediate relevance to the road sector might not be obvious, the fact that there are other sectors who use hydrogen generators reveals that a market exists, which should bring costs down and see the mechanisms for hydrogen delivery improve.

Diesel Generator Contribution to Carbon Emissions

Estimating the contribution of diesel generators to carbon emissions is challenging due to the level of detail available on the type of generators and the location of their use. Many generators are used for direct electricity generation, for back up electricity production and to balance electricity produced by electricity grids. For those used on construction sites, there is no breakdown available as to whether they are used for road applications, or for other purposes, for example rail works or general construction activities, such as house building sites.

[164] https://www.prolectric.co.uk/lighting/solar-lighting-towers/prolight-solar-lighting-tower/
[165] https://www.sunbeltrentals.co.uk/lighting/tower-lights/9m-led-tower-light---solar-hybrid-1784/
[166] https://www.bechtel.com/projects/crossrail-london/

The use of diesel generation is likely to be significant, with one article[167] reporting that 15% of London's diesel emissions were due to construction site generators. BAM report[168] that a 60kVA generator for a small to medium sized construction site compound would use around 1,000 litres of diesel per week. Smaller, mobile 40kVA generators consume around 9 litres of fuel per hour[169]. Lighting towers with inbuilt diesel generators are also frequently used in road construction and operation for night-time working, lighting of contraflow entrances and exits and for site compounds. These tend to be smaller units, using between 0.4 to 2 litres of fuel per hour[170]. The exact number of generators and lighting towers in operation is difficult to estimate, in particular for those used for road operation, not least as they are used for many applications, such as buildings construction, rail, tv and films, festivals etc.

3.7.2 Potential Carbon Savings from Alternative Power Lighting Towers and Generators

There were 105,000 lighting towers sold in 2019[171], of which 55.4% of new models are diesel, with the remainder being solar or hydrogen. It is assumed that this proportion of solar and hydrogen models sold will increase over time as the technology becomes more widely adopted. It is also likely that most of the older models in use will be diesel operation.

Estimates of CO_2 savings possible for replacing diesel lighting towers with solar or green hydrogen alternatives
1,000 units – 5,000 tonnes
10,000 units – 50,000 tonnes
100,000 units – 500,000 tonnes

Based on a lower end estimate[172], each diesel unit burns 0.7 litres per hour. As these units are mobile, and potentially rented, an estimate might be for use 300 days per year at an average of 10 hours per day. Using these assumptions, a unit would burn 7 litres of fuel per day and 2,100 litres per year. As each litre of diesel burned[173] emits 2.4 kg CO_2, this equates to 5,040 kg of CO_2 (or 5 tonnes) per unit, per year.

No information was found on the overall number of lighting towers in use, or the proportion of the units used in road construction and maintenance. As such it is not possible to provide an estimate of the potential savings that could be made without making many assumptions,

[167] https://www.cbi.org.uk/articles/cleaning-up-construction-the-fuel-cell-alternative-to-diesel/
[168] https://www.bam.com/en/sustainability/innovations/alternative-power-sources-at-construction-sites
[169] https://www.ablesales.com.au/blog/diesel-generator-fuel-consumption-chart-in-litres.html
[170] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.jarvieplant.co.uk/assets/000/000/264/GAWL-11X_VB_9__Eco_Towerlight_Spec_Sheet_original.pdf?1618311941
[171] https://cpnonline.co.uk/news/diesel-light-towers-accounted-5-10-units-sold-2018/
[172] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.johnfhuntpower.co.uk/wp-content/uploads/2020/04/TL90-LED-Lighting-Tower-1.pdf
[173] https://www.researchgate.net/publication/235458666_Estimation_of_Carbon_Footprints_from_Diesel_Generator_Emissions

however a range of savings based on replacing diesel generators with solar or green hydrogen could be made as shown above.

Diesel Generators

There was no available data for the numbers of diesel generators in use for the road sector, only the permanent generators used for general electricity production or to back up / balance national grid (82.6 million[174]). It is likely that the number of diesel generators far exceeds the number of lighting towers, as they are used for multiple applications, potentially at any time of the day. The range of uses and the size of generator used accordingly can vary widely, from small 2 – 3 kVA petrol units designed to run a single small tool, to large generators of over 200kVA to run site compounds.

As an example, a mid-range 40 kVA generator operating at 75% load, uses 9 litres per hour[175], over 10 times that of a lighting tower. Assuming the generator would operate an 8-hour shift per day and 300 days per year, would use 21,600 litres of fuel per year (9 x 8 = 72 litres per day, 72 x 300 = 21,600). At 2.4 kg of CO_2 emitted per litre of diesel, 51,840 kg or 5.18 tonnes of CO_2 would be emitted, per unit, per year.

The potential savings from moving away from diesel generators to solar or clean hydrogen alternatives could be in the order of millions of tonnes per year. NRAs should ask their supply chain about the number and type of generators they use and set a roadmap for solar / hydrogen adoption.

Given the range in sizes and specifications, it is very difficult to make a realistic estimate of potential savings, not least as the infrastructure to replace the larger generators with hydrogen is not in place currently. Based on the example above, with a single unit emitting 5 tonnes of CO_2 per year and there being more generators in use, a range of 50,000 to 5 million tonnes of CO_2 per year, based on 10,000 to 1 million generators worldwide replaced with green hydrogen respectively.

The numbers above indicate that for lighting towers and generators, the CO_2 savings from switching from diesel generators to solar or green hydrogen alternatives could be in the order of millions of tonnes per year. These numbers make many assumptions and the exact quantity of potential savings, will be based on numerous factors including the exact number of units, the number of hours they are used and the breakdown of the power consumption of the units in operation. For diesel generators specifically, there is a large variation in the size of the units and the amount of time they are used.

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[174] https://askwonder.com/research/explore-topic-number-diesel-generators-u-s-globally-npadnargx#:~:text=Assuming%20that%20this%20proportion%20also,70%25%20of%20118%20million).

[175] https://www.ablesales.com.au/blog/diesel-generator-fuel-consumption-chart-in-litres.html

The exact savings available, will not only be affected by the factors outlined above, but on the choice of alternative operations. Solar power may be a viable option for lighting towers and small generators, whereas for larger generators, it is likely that whilst solar could provide some power in a hybrid operation, an alternative power source will be required. Hydrogen generators could be a viable alternative, and, as with solar, offer the benefits of silent operation and local air quality improvement. How the hydrogen is generated, will have an impact on the potential carbon savings, with green hydrogen powered by renewable energy offering 100% of the potential savings. Hydrogen produced by other means will have the energy intensity of the electricity grid from which it is produced.

For example, the average carbon intensity of electricity per kWh (as measured in grams CO_2 per kilowatt-hour) is 425 g worldwide[176], 482 g for upper middle and high income countries, 413 g for lower middle income countries and 313 g for low income countries, but there are large differences, for example, high income Norway having a carbon intensity of only 25 g/kWh due to the large use of hydropower. The proportion of energy generation sourced by renewable sources will determine the potential carbon savings achievable, as outlined in Figure 14. For example, Brazil, Canada, France, Sweden and Norway all produce electricity from 80% or more from nuclear or renewables, whereas Japan, Australia, India and South Africa each use over 70% of fossil fuel sources for their electricity production.

[176] https://ourworldindata.org/grapher/carbon-intensity-electricity

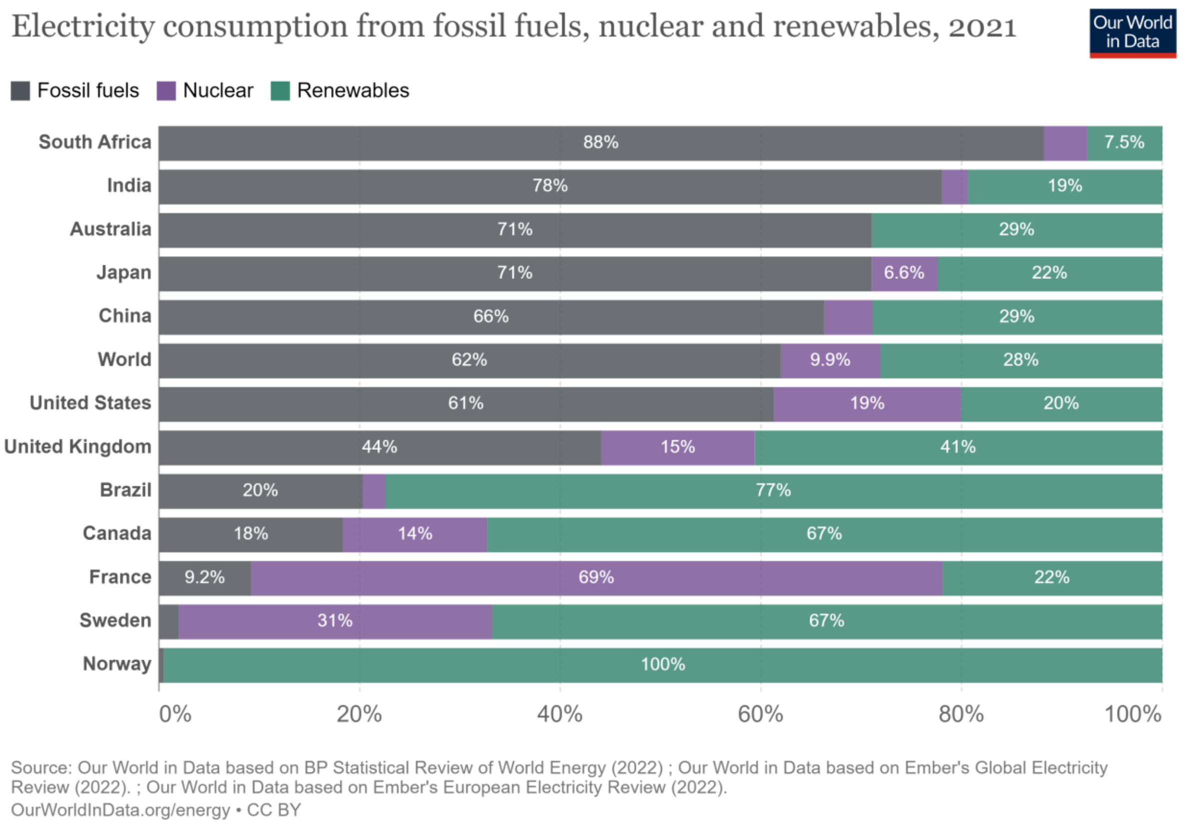

Figure 14. Sources of electricity production by country

4 DECARBONISATION OF ROAD USER VEHICLES

There are approximately 1.45 billion[177] vehicles in the world and whilst there are shifts in certain countries to promote increased active travel and public transport, it is likely that, as the global population grows and many LMICs continue to grow economically, there will be increased vehicle ownership in the future.

Figure 4 shows how vehicle energy use is far higher (around 18 times over its lifetime, depending on the road) than the energy used to construct the road. Currently, most vehicles are powered by internal combustion engines, although electric vehicle adoption is increasing and will continue to do so with upcoming bans on the sale of internal combustion engines for cars and vans in Europe and elsewhere.

Decarbonisation of vehicles can be split into 3 broad options: alternative fuels (mainly biofuels), electrification and hydrogen. As biofuels are designed to replace some or all the existing petrol and diesel used in existing combustion engines, these will be considered as a standalone section, with hydrogen and electrification considered across various vehicle categories, as the size and required range of the vehicle will in part determine which fuels are most suitable.

4.1 ALTERNATIVE FUELS / BIOFUELS

In Europe, most petrol sold on the forecourt contains 5% biofuel in the form of bioethanol, denoted as E5 with many countries now moving to 10%, E10. It is reported[178] that all new vehicles and those put on the market since 2011 would be able to run on a blend of 20% bioethanol. This would reduce greenhouse gas emissions by an equivalent 25.4Mt of carbon dioxide in the 27 EC states plus the UK, which is around 8.2% of current emissions. Whilst the UK has moved to E10, there is an obligation to also sell an E5 grade for those vehicles incompatible with the higher blend.

The USA started to Introduce ethanol into gasoline in 2007 and in most areas of the country, most retail gasoline in now 10% ethanol by volume.

The AA[179] states that diesel with a blend of up to 7% biodiesel is safe to use with a 5% (B5) blend commonly sold.

Whilst biofuel blends can be used in vehicles with little or no modification, there are concerns over the use of agricultural land to grow crops for fuel production, rather than food. Also, in some cases palm oil is used to produce biodiesel. Both these factors raise questions around the overall sustainability of current biofuels. Further, the properties of biodiesel can be

[177] https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/#:~:text=Two%20major%20countries%20are%20virtually,in%20the%20world%20in%202022

[178] https://ec.europa.eu/research-and-innovation/en/horizon-magazine/why-raising-alcohol-content-europes-fuels-could-reduce-carbon-emissions

[179] https://www.theaa.com/driving-advice/fuels-environment/biofuels

markedly different to standard oil depending on the composition. According to the AA, rapeseed is liquid at 0°C, but soy is solid, which can affect cold weather operation.

Current biofuels tend to be manufactured from plant matter. Second generation or advanced biofuels are manufactured from non-edible sources such as woody crops, wood chips and agricultural waste such as husks and stems. This is better from an agricultural standpoint as the edible crop goes into the food chain, whilst the 'waste' goes to biofuel production. Several demonstration facilities for this process have been built but it is not yet operational at an industrial scale.

Third generation fuels are those characterised by being based on algal production[180], which offers many potential advantages in terms of yield and diversity of organisms enabling a wide range of fuels to be developed. It is reported[181] that algal biofuels can be less stable than others, but the main drawback is economic viability. Exxon Mobil invested $600 million USD in research and development and concluded in 2013 that algal fuel would not be viable for at least 25 years. It should be noted of course that we are now almost 10 years into that timeframe, with technical and economic factors having moved on in that time.

There are also synthetic fuels, most of which are based on well-known and proven chemical processes which involve processing of syngas, a mixture of carbon monoxide and hydrogen into a liquid fuel. The syngas is usually derived from gasification of solid feedstocks such as coal, shale tar, biomass or reforming natural gas[182]. Gas derived from anaerobic digestion facilities can also be used for this process. Clearly fuel derived from anything other than biomass will not contribute to carbon neutrality and will likely be more carbon intensive than using current petrol and diesel.

Finally, another alternative being explored is efuels, which replicate the hydrocarbons in petrol or diesel by using carbon from the air and hydrogen from water[183]. The process is technically feasible although it takes a lot of energy, albeit that this could be sourced by renewables.

Porsche has invested $75 million USD into a Chilean start-up operating this process, working with Siemens and Exxon Mobil[184]. The plant captures CO_2 from the atmosphere and uses wind power to electrolyse water into hydrogen and oxygen. The carbon and hydrogen are used to create methanol, which in turn is turned into longer hydrocarbons using Exxon Mobil's methanol to gasoline process. The plant is targeted to produce 130,000 litres by the end of 2022 rising to 550 million litres by the end of 2026 at a cost of around $2 USD per litre. Whilst process efficiencies will improve, the cost and production volume mean it's unlikely that this

[180] https://academic.oup.com/af/article/3/2/6/4638639
[181] https://biofuel.org.uk/third-generation-biofuels.html
[182] https://www.sciencedirect.com/topics/engineering/synthetic-fuel
[183] https://www.autoexpress.co.uk/tips-advice/356000/what-are-synthetic-fuels-efuels-explained
[184] https://arstechnica.com/cars/2022/04/porsche-invests-75-million-in-chilean-synthetic-fuel-startup/

will replace the petrol and diesel used today, not to mention the timescale by which most vehicles, particularly in HIC will be electric. Further, the tailpipe emissions and local air quality issues remain. Porsche's motivation towards development of efuels is twofold:

- To keep the historic Porsche fleet globally moving
- To be used for racing, with Formula 1 moving to 100% renewable fuel in the mid-2020s with efuel as an option[185]

Efuel could be one part of an overall solution for decarbonisation and have a niche application in powering classic cars and other historic vehicles.

4.2 CARS AND VANS

Electrification

Electric vehicles (EVs) have developed in recent years to a stage where all major car brands either already have electric vehicles in their portfolio[186] or will have in the next 2 or 3 years. Whilst Tesla has always been 100% electric, other car brands have set dates for transition to an all-electric future; for example, Jaguar will be all electric by 2025, Volvo pledging to be 50:50 hybrid and full electric vehicles by 2025 and all electric by 2030, with many other companies setting a 2030 deadline[187]. This is no doubt being driven in part by the EC ban on internal combustion engine vehicles by 2035, with many countries having earlier targets[188], for example 2025 in Norway and South Korea, 2026 in Belgium, 2027 in Austria and 2030 in other countries including Sweden, Denmark, Israel and India.

It has been reported[189] that EV sales more than doubled to 6.6 million units in 2021, representing around 9% of the global new car market and tripling their market share from 2019.

Whilst limited range and 'range anxiety' was a real issue in early EVs, most now have a range of over 300 kilometres, with some having ranges of over 600 kilometres. Very few people drive this sort of distance on a regular basis, with average annual km driven per year in Europe and the USA equating to around 30 or 60 km per day respectively.

There is now a large range of electric vans available, with ranges from around 200 – 300 km. As many vans operate on fixed routes, this range is adequate, whilst the vehicles can be charged overnight. As part of its commitment to be carbon neutral by 2040, Amazon is working with start-up Rivian to produce 100,000 vans[190] in the USA, with the first ones being delivered in 2021 and the process of installing charge points is underway. For the UK and

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185 https://www.formula1.com/en/latest/article.pat-symonds-on-how-formula-1-are-creating-the-next-generation-of-100.6XCGNQ3ExMhbhYy338Qgi2.html
186 https://www.driving.co.uk/news/new-cars/current-upcoming-pure-electric-car-guide-updated/
187 https://www.abc.net.au/news/2021-11-10/which-cars-going-all-electric-and-when/100529330
188 https://insideevs.com/news/534890/countries-states-gas-car-bans/
189 https://www.iea.org/commentaries/electric-cars-fend-off-supply-challenges-to-more-than-double-global-sales
190 https://www.driving.co.uk/news/business/amazons-rivian-delivery-vans-roll-l/

Europe, Amazon has ordered 1,800 vans from Mercedes Benz, with other companies with large fleets following suit. For example, UPS ordered 10,000 vehicles from Arrival in the UK[191].

Given the direction of the major car manufacturers, battery electric power is likely to be the dominant vehicle type for cars and vans from 2030 onwards.

There remain some technical hurdles. More charge points, including fast chargers need to be installed to cope with the increase in EVs. There is a requirement for more battery recycling facilities to reduce the requirement for extraction of virgin materials. There is currently also a lack of trained technicians capable of maintaining EVs. The largest issue is likely to be the fuel mix that produces electricity to feed the grid which in turn powers the EVs. Energy sourced from renewable power provides the greatest savings in terms of carbon reduction.

A final issue is the manufacture of the batteries themselves. The cost of lithium-ion batteries has decreased dramatically and is predicted to drop further, meaning it will likely be the dominant battery source for the foreseeable future, but the question of available lithium and other metals remains. Generally, the opinion seems to be[192,193] that there are sufficient materials, but that the quality of lithium will decrease and/or the cost to mine will increase. There are some concerns[194] that demand could outstrip supply in the short to medium term given the long lead times in developing the factories and supply chains. This makes the development of recycling facilities for depleted EV batteries more important.

There have been initiatives exploring the feasibility of battery swapping as an alternative to charging of batteries at a station, with Chinese company Nio opening 700 stations in 2021[195]. It has also launched a battery as a service subscription[196] service where users pay $142 for a 70 kW battery with six monthly swaps. Realistically, the business case for battery swapping no longer exists. Whilst it was a promising idea in the early days of electric vehicles, with very low ranges and little dedicated charging options, it no longer appears to be a sensible approach. In fact, Tesla proposed this as an option for their vehicles, before coming down on the side of rapid charging. Along with the fact that it would require standard batteries for all cars, modern EVs have large ranges of several hundred kilometres and some fast chargers can charge a vehicle in 20 minutes, with improvements on this likely to be developed. Other issues are that the battery swap stations are very expensive, and whilst they use robots to remove and replace the battery, each station has a human operative.

Hydrogen Cars and Vans

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[191] https://www.vertumotors.com/news/amazon-orders-1800-mercedes-benz-electric-delivery-vans-for-uk-and-eu/
[192] https://www.nature.com/articles/d41586-021-02222-1
[193] https://medium.com/batterybits/is-there-enough-lithium-to-make-all-the-batteries-c3a522c01498
[194] https://www.bloomberg.com/news/articles/2022-04-22/mr-lithiumalr-warns-there-s-not-enough-battery-metal-to-go-around#:~:text=Lithium'%20Warns%20There's%20Not%20Enough,the%20electric%20car%20production%20planned.
[195] https://www.autotrader.co.uk/content/news/what-is-battery-swapping-and-is-it-a-good-idea
[196] https://spectrum.ieee.org/ev-battery-swapping-how-is-this-a-good-idea

Several years ago, hydrogen cars were seen as the future of transport, in large part due to the concerns over electric vehicle battery range, performance and long charging times. Progress has halted in that time, in large part due to lack of fuelling infrastructure and the production of hydrogen largely being from fossil fuels.

Whilst many vehicle manufacturers developed hydrogen demonstration vehicles, particularly in the early 2000's[197], only two production vehicles are currently available, the Toyota Mirai II and the Hyundai Nexo, although BMW, Land Rover and Vauxhall (Opel) plan models in the next 5 years[198].

Even with future models planned, there were only 26,000 hydrogen vehicles registered worldwide in 2020[199], concentrated in Korea, California and Japan, compared to 3 million EV sales in the same year. Toyota remains the only car manufacturer committed to promoting hydrogen fuel cells as a solution for cars, although it is also looking to develop the technology for heavy vehicles[200]. Many commentators think that Toyota is making a mistake in pursuing this ambition[201] due to the expense and complexity of fuel cells, whilst other motor manufacturers think that battery power is more favourable. The CEO of Volkswagen tweeted in 2021 that *"Green hydrogen is needed for steel, chemical, aero … and should not end up in cars. Far too expensive, inefficient, slow and difficult to roll out and transport."*

[197] https://en.wikipedia.org/wiki/List_of_fuel_cell_vehicles
[198] https://www.autoexpress.co.uk/electric-cars/93180/hydrogen-fuel-cells-do-hydrogen-cars-have-future
[199] https://www.wired.co.uk/article/future-buses-hydrogen-electric#:~:text=Registrations%20of%20hydrogen%20cars%20remain,largely%20California)%2C%20and%20Japan.
[200] https://www.toyota-europe.com/world-of-toyota/electrified/fuel-cell/
[201] https://medium.com/the-future-is-electric/did-toyota-make-a-mistake-with-hydrogen-and-the-mirai-952a179ee898

Figure 15. Hydrogen filling station at National Renewable Energy Laboratory, Colorado

©Maple Consulting

A continuing problem for hydrogen cars is the lack of infrastructure, with battery charging much easier due to the prevalence of the electric grid. There are currently very few hydrogen refuelling stations (e.g. 11 in the UK) and this needs to be increased significantly for hydrogen to be a viable fuel. This is unlikely to be feasible for passenger vehicles but could be achievable as part of larger transition to the hydrogen economy, for example for larger road vehicles, rail, aviation, shipping and power for heating in buildings.

4.3 BUSES

Electric Buses

Electric buses are not new. Many cities around the world had trolleybus services, where the buses are powered by overhead wires like a tram. Whilst 500 trolleybus services have been lost[202] (many were converted to standard bus fleets due to the improved flexibility without wires), there are 300 cities where they remain.

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[202] https://en.wikipedia.org/wiki/Trolleybus

Battery electric buses exist in many cities in the world, dominated by Chinese cities. Bloomberg reported[203] that at the end of 2020 there were 598,000 electric buses worldwide, of which 585,000 were in China. It was also predicted that there would be 1.7 million in operation in 2030. Many cities will be switching to e-buses as they seek to meet their carbon reduction targets and to improve urban air quality – buses are relatively heavy, have a high mileage and operate under stop/start driving conditions. Given the number of e-buses in operation now, the vehicle technology is clearly mature, with buses well suited to electric operation as they run on fixed routes and can charge overnight at the depot, or in some cases at points along the route. From an environmental point of view, e-buses can represent a good option for decarbonisation, as the same article states that every 1,000 e-buses on the road displace 500 barrels of diesel per day (1 barrel = 42 US Gallons or 159 litres). Based on 598,000 e-buses, operating 365 days per year, equates to 17,352,465,000 litres of diesel. According to a carbon calculator[204], this equates to 45,463,458 tonnes of CO_2. It is noted that not all this carbon will be removed unless the bus is powered by renewable energy.

> The 600,000 electric buses operating in China could reduce carbon emissions by over 45 million tonnes per year if they were powered by renewable energy.

For coaches running on interurban routes, range will be more of an issue. A company in the UK claims to be the first operator of a Chinese built 50 seat battery coach with a range of 200 miles[205] (321 km). This might not be a sufficient range for many coach routes, unless there are rapid charge points along the route.

Hydrogen Buses

Hydrogen buses have been trialled for several years and there are examples of them in operation. Transport for London has recently ordered 20 hydrogen buses to go with their 500 electric buses, with a target of an entirely zero emissions fleet by 2030[206]. Again, China has the vast majority of the global fleet with 5,300[207]. There are some advantages to hydrogen as the buses can be filled at the end of the day at the depot, which overcomes one of the infrastructure issues faced by hydrogen cars, as it is relatively easy to install a hydrogen tank and pumps to service a large fleet.

Hydrogen also has a higher energy density than battery power, though less than diesel. This can make hydrogen buses more suited to cities such as Hong Kong which are both hilly and

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[203] https://www.bloomberg.com/news/newsletters/2021-08-13/electric-buses-are-poised-to-get-a-u-s-infrastructure-boost#:~:text=There%20were%20about%20598%2C000%20e,nearly%201.7%20million%20in%202030.
[204] https://www.fleetnews.co.uk/costs/carbon-footprint-calculator/
[205] https://pelicanyutong.co.uk/coaches/tce12-electric-coach/
[206] https://www.london.gov.uk/press-releases/mayoral/englands-first-hydrogen-double-deckers-launched
[207] https://www.wired.co.uk/article/future-buses-hydrogen-electric#:~:text=Registrations%20of%20hydrogen%20cars%20remain,largely%20California)%2C%20and%20Japan.

humid, where both conditions have been shown to drain electric batteries[208]. Battery powered buses will operate perfectly well in relatively flat routes with short journey routes where it is not unusually warm or cold.

4.4 Heavy Goods Vehicles

A White Paper from the International Council on Clean Transportation[209] concludes that electric-drive heavy duty vehicle technologies are essential to fully decarbonise the transport sector, with freight trucks representing less than 10% of all vehicles, but responsible for 40% of emissions. They estimate that electric and hydrogen fuel cell technologies could be up to 30% cheaper to own, operate and fuel by 2030, although massive infrastructure investments would be needed.

Electric

There are trials in the UK[210], funded by the Department of Transport, of battery electric trucks to be used by the National Health Service and Local Authorities, with the objective of the trial to provide real world data to inform future buying decisions. These vehicles are provided by DAF who were one of the first manufacturers to offer a range of battery electric trucks for sale, including a 37-tonne vehicle with a stated range of 220 km[211]. Volvo has released a battery powered truck with a range of up to 300 km[212], compared to a range of over 900 km for a diesel truck in Europe from a single tank of fuel. In remote areas of Australia trucks have additional fuel tanks to achieve more than triple this range. Tesla is promoting is 'Semi' HGV with a stated range of either 300 or 500 miles[213] (482 to 804 km) with a network for fast truck charge points to be developed, although production has not yet commenced.

Whilst there could be some shuttle routes with charging at each end it seems unlikely that battery electric trucks with current range would be viable for many operators in the short term. Should longer range vehicles become available, with a suitable network of fast chargers where drivers need to take breaks, battery electric HGVs may become feasible. Although, there would be a large grid requirement and there could be logistics issues if vehicles had to queue to charge and potential safety concerns if many vehicles were fast charging at the same time.

There has been significant research, development and demonstration of electric road systems (ERS) in recent years, particularly in Sweden and Germany. PIARC commissioned a Special

[208] https://www.wired.co.uk/article/future-buses-hydrogen-electric#:~:text=Registrations%20of%20hydrogen%20cars%20remain,largely%20California)%2C%20and%20Japan.
[209] https://theicct.org/publication/transitioning-to-zero-emission-heavy-duty-freight-vehicles/
[210] https://www.leylandtrucksltd.co.uk/en-gb/news-and-media/news-article-folder/2022/battery-electric-truck-trial-hits-the-road
[211] https://www.daf.co.uk/en-gb/trucks/alternative-fuels-and-drivelines/battery-electric-vehicles/daf-cf-electric
[212] https://www.tu-auto.com/volvo-promises-full-electric-hgv-range-for-2021/
[213] https://www.tesla.com/en_GB/semi

Project on Electric Road Systems in 2018[214] which presents the type of technologies and advantages and disadvantages of each.

Whilst an ERS would require vehicle modification to add a pantograph or other charge mechanism to the vehicle, theoretically, this could give an electric truck an unlimited range if ERS were installed everywhere, but even electric driving and battery charging along parts of the route, could extend the range of existing battery electric trucks to make them viable alternatives to fossil fuel powered vehicles. There is a requirement for agreement of a common standard for ERS to facilitate cross border transport.

Figure 16, below, shows a trial section of electric highway on the E15 highway in Sweden. The lorry in this case is a hybrid, with a diesel engine to provide power when not on the trial section.

Figure 16. eHighway in Sweden

©Maple Consulting

Case study – Norway Coastal Highway Route E39

The Norwegian coastal highway route E39, located on the west coast of Norway (Figure 17), connects Kristiansand in the south to Trondheim in central Norway – a distance of 1100 km. The route E39 runs through six counties with a total population of 1.8 million people[215]. More than half of Norway's energy intensive industry is located along this road. The Ministry of Transport and Communications has given the project "Coastal Highway Route E39" a mandate

[214] https://www.piarc.org/en/order-library/29690-en-Electric%20road%20systems:%20a%20solution%20for%20the%20future
[215] SSB 2014. Population by counties.: Statistics Norway

to address challenges, possible technological solutions and to investigate social and economic benefits of building fixed connection instead of using ferry connections[216]. Examples of areas under investigation are how the infrastructure can be exploited to generate renewable energy and how the harvested energy can be used to reduce the ecological and environmental footprint of the road infrastructure.

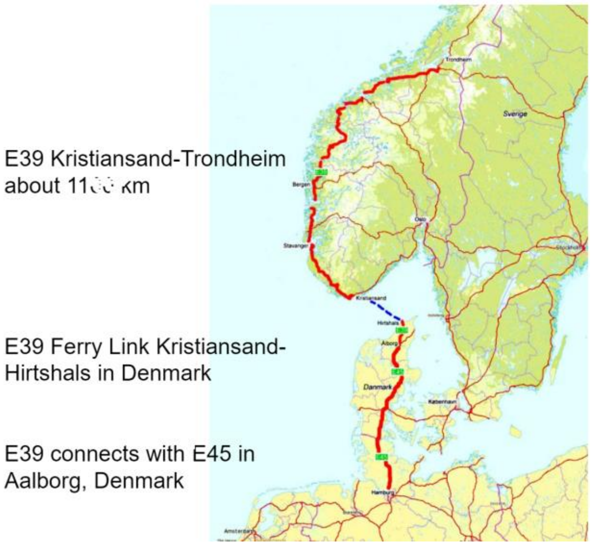

Figure 17. E39 Coastal Route Map[217]

Direct CO_2 emissions from fuel consumption associated with road transportation on the E39 has been estimated to be 750 kton for year 2014, assuming a CO_2 emission factor of 2.54 kg/l of diesel and 2.36 kg/l of petrol[218]. On this basis, significant research has been dedicated to investigating carbon reduction mechanisms on the route. One such investigation to reduce carbon was reviewed by Adl-Zarrabi et al.[219]. The research examined two biofuel blending scenarios for a low ambition scenario of 20% biofuel for road vehicles and a high ambition scenario of 40% biofuel. This was calculated to produce a 16% and 50% decrease in CO_2 emissions, respectively, assuming net zero CO_2 emissions from biofuels. For the E39, this would mean a reduction of ~120-370 kton CO_2/yr compared to the current level of 740 kton/yr, as seen in Figure 18. A change to hybrid electric vehicles, such as plug-in-hybrids, could technically reduce the energy needed per vehicle km by 30%, and then potentially reduce CO_2 emissions from E39 by approximately 220 kton/yr for the E39. However, to reach low or zero emissions of CO_2, a more complete transition to electricity or hydrogen seems to be required. Electrification of the E39 could imply electric cars, fuel cells, conductive or inductive charging integrated in the road infrastructure (for example over-headlines or

[216] STATENS VEGVESEN. 2012. Coastal Highway Route E39 [Online]. http://www.vegvesen.no/Vegprosjekter/ferjefriE39/English
[217] Ellevset, O., (2014), "Norwegian Coastal Highway Route E39", Norwegian Public Roads Administration Presentation, Available at https://www.cpci.pt/wp-content/uploads/2015/03/Autoestrada_E-39.pdf
[218] NILSEN, Ø. L., STRIDH, M, STRIDH, SPILSBERG, E. 2014. Ferjefri E39 Trafikkberegninger Fase 1
[219] Adl-Zarrabi, Bijan, et al. "Safe and sustainable coastal highway route E39." Transportation Research Procedia 14 (2016): 3350-3359

ground-level supply). In summary, a transition to electric vehicles will have, in the long-term perspective, the potential to reduce the CO_2 emissions to almost zero.

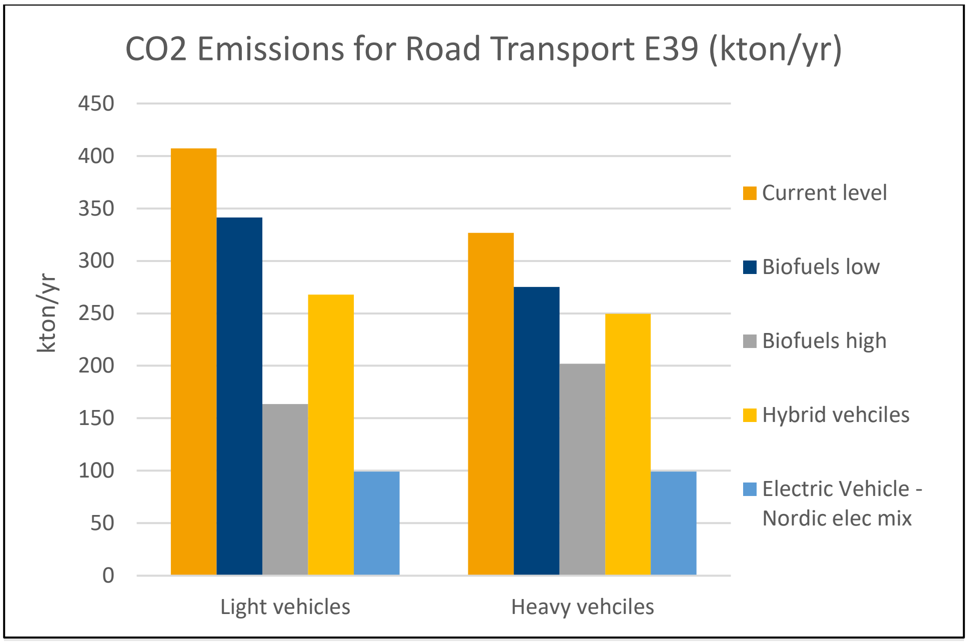

Figure 18. E39 CO_2 emissions when applying different possible reduction strategies (reproduced from [220])

Hydrogen

Hydrogen has been promoted as a compelling option for long distance freight. Hyundai manufactured the first mass-produced fuel cell truck[221], with a claimed real-world range of 400km. The first ten trucks were delivered to Switzerland in 2020, with American manufacturer Hyzon Motors moving into the European market in 2021. Hyzon has joined a European consortium which plans to deliver 100,000 hydrogen fuel cell trucks in Europe by 2030. Hyzon has also signed a memorandum of understanding with TotalEnergies to aid the transition of fleet owners to hydrogen and to develop the infrastructure. Hyzon will deliver 80 trucks to TotalEnergies' French customers by 2023[222]. DAF trucks' parent company PACCAR is exploring fuel cell technology with extensive trials around the Port of Los Angeles, whilst in the UK, DAF is developing an internal combustion engine running on hydrogen[223]. Volvo has unveiled a hydrogen fuel cell vehicle with a claimed 1,000-kilometre range, capable of being refuelled in 15 minutes[224], however, it was pointed out that a lack of refuelling infrastructure remains a hurdle with fewer than 60 stations operational in the USA, all in California, though this predicted to nearly double in 2023. In Australia[225] too, there has been investment in

[220] Ellevset, O., (2014), "Norwegian Coastal Highway Route E39", Norwegian Public Roads Administration Presentation, Available at https://www.cpci.pt/wp-content/uploads/2015/03/Autoestrada_E-39.pdf
[221] https://trucknbus.hyundai.com/global/en/products/truck/xcient-fuel-cell
[222] https://fuelcellsworks.com/news/the-first-hydrogen-trucks-are-rolling-in-europe/
[223] https://www.daf.co.uk/en-gb/trucks/alternative-fuels-and-drivelines/hydrogen
[224] https://www.theverge.com/2022/6/21/23177624/volvo-trucks-tests-hydrogen-fuel-cell-semi
[225] https://www.theguardian.com/environment/2022/jul/18/hydrogen-fuel-stations-to-be-built-between-sydney-and-melbourne-under-20m-plan

hydrogen infrastructure, with the Queensland, New South Wales and Victorian governments funding refuelling stations on the east coast between Brisbane, Sydney and Melbourne. Other manufacturers are also believed to be developing heavy hydrogen vehicles.

Not everyone is convinced that hydrogen has a future in road transport. Fraunhofer[226] reports that they consider hydrogen vehicles have lost the advantage they once had in terms of range and fast charging, and will be uncompetitive with battery electric vehicles. Even for heavy vehicles, they consider the target of 100,000 vehicles outlined above challenging with commercial production unlikely before 2027, by which time battery technology will have moved on, and with fast chargers and the requirements for drivers to take regular breaks, the range will be sufficient to satisfy most operations. They believe there may be use cases for very heavy vehicles in remote areas, but this will be a niche application.

It is also worth noting that at present, most hydrogen is produced in an energy intensive manner using fossil fuels (grey hydrogen), although blue hydrogen (carbon capture and storage of emissions) and green hydrogen (hydrogen produced by electrolysis of water, from renewable energy sources) are increasing.

Summary

Theoretically, all the vehicles on the road network could be powered from net zero or carbon neutral fuels. This could save over 5.6GT per year of CO_2.

This would require strong international support and coordination on standards and interoperability. NRAs will have a key role in helping implement the solutions on their networks.

The biggest savings to be realised in the short to medium term, would be from more efficient use of the

[226] https://www.rechargenews.com/energy-transition/-hydrogen-unlikely-to-play-major-role-in-road-transport-even-for-heavy-trucks-fraunhofer/2-1-1162055

5 OPERATIONS ON THE ROAD NETWORK

5.1 VEHICLES OPERATED BY ROAD ADMINISTRATIONS

Road administrations have fleets of vehicles of various kinds from cars and vans to trucks and maintenance equipment such as gritters and snow ploughs. Their use cases are essentially the same as those discussed above although there are some specialised cases such as patrol and recovery vehicles where the demands for payload and capability (e.g. towing) are more challenging. Road administrations have an important role in testing and demonstrating the use cases of alternate fuel vehicles, whilst helping develop the fuelling infrastructure as a single depot that can service many vehicles.

For example, the FEHRL scanning tour of the USA[227] in 2018 reports findings on a visit to Caltrans (California State Highway Department) who are actively pursuing a low emission fleet, with targets for adoption of electric and hydrogen vehicles. In 2015, 10% of the Caltrans fleet were EVs, with targets for 25% by 2020 and 50% by 2025 for light vehicles. For heavy vehicles, the targets were 15% by 2025 and 30% by 2030. At the time of the report publication, the fleet contained 73 battery electric vehicles, 152 plug in hybrid vehicles and 36 hydrogen fuel cell vehicles, as part of the overall light vehicle fleet. The response from users was generally positive, particularly as the vehicles had a higher spec than the standard vehicles, and no issues were reported with charging. There were at that time only 36 openly available hydrogen stations, mostly in the LA and San Francisco Bay areas.

5.2 LED LIGHTING

Images of Europe taken by astronauts from the International Space Station demonstrate a widespread shift from high pressure sodium lighting to LEDs, with particularly notable increases in Italy, Romania, Ireland and the UK[228]. Highway lighting can improve road safety and increase drivers' and pedestrians' levels of comfort. Adequate lighting has been found to reduce pedestrian accidents by around fifty percent[229].

Public street lighting can account for between 30-50% of a typical city's energy bill[230]. The electricity consumption of lighting could increase by over 10% by 2030. Although, current policies to improve lighting efficiency could decrease consumption to below current levels[231]. The momentum for energy efficient lighting is growing to meet carbon targets and reduce CO_2 emissions. Many countries are switching to LED technology to replace inefficient lighting associated with high energy consumption and maintenance costs. LED lighting provides a high

[227] https://www.fehrl.org/library?id=7721
[228] Highways Magazine, October 2022, A LED Paradox (Highways Magazine (pagesuite-professional.co.uk)).
[229] Box, P.C., Relationship Between Illumination and Freeway Accidents. IERI Project 85-67 Illuminating Research Institute, New York April, pp. 1-83, 1970.
[230] Pardo-Bosch, F., Blanco, A., Sese, E., Ezcurra, F., Pujadas, P., Sustainable strategy for the implementation of energy efficient smart public lighting in urban areas: case study in San Sebastian. "Sustainable cities and society", 2022, vol. 76, p. 103454:1-103454:12.
[231] United for Efficiency, Lighting - United for Efficiency (united4efficiency.org)

quality, efficient and low maintenance solution, with LED lamps lasting up to 20x longer than conventional lamps[231].

Lighting of highways and roadways is essential to enable high visibility, improve safety and security, allow for mobility, and improve the quality of life of citizens[230]. In 2012, one third of the worlds road lighting systems were running on technology dating back to the 1960s[232]. It is forecast that by 2027, 89% of the world's 363 million streetlights will utilise LED technology[230].

The primary source of power for street and highway lighting is the national grid. However, in more remote areas, alternative options are sometimes preferable, such as, solar PV power and wind power or hybrid systems. Solar panels convert solar radiation into energy during the day, which is stored in batteries for night-time use. A mini power station can be installed to house solar panels and batteries to power a group of lights, or panels and batteries can be installed on each pole[233].

The efficiency of LEDs can be further supplemented by smart controls. Considering energy savings, and the reduction in operation and maintenance costs, payback on initial investment can in most cases be in the range of 4-8 years [230, 234]. In many cases, existing lampposts and lighting systems cannot be adapted to incorporate smart technology, resulting in a high initial investment to purchase and install smart lampposts.

The business model in most European cities provides lighting throughout the night to ensure visibility. Approximately 20% of electricity consumption globally is attributed to nocturnal lighting systems[235]. Smart systems for public lighting integrate additional sensors and controls to optimise use and improve efficient and energy use[230]. By using smart technology, lighting levels and operations can be remotely controlled depending on the demand and site needs, using sensors, data analysis and control units. This allows for the optimisation of output and energy consumption[236]. The demand for Smart Street Lighting (SSL) has been increasing around the globe. As a reference, there was an estimated 80,000 SSL units throughout 14 countries in 2008, which increased to a demand for 21.8 million SSL streetlight conversions in 2017, with the fastest growing markets in the US, UK, Germany, France, Italy, China, Japan and South Korea[237].

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[232] Crowther, J., Herzig, C., Feller, G., The Time is Right for Connected Public Lighting Within Smart Cities, Cisco Philips Report, 2012.

[233] Gillard, R., Oates, L., Kasaija, P., Sudmant, A., Gouldson, A., Sustainable urban infrastructure for all: Lessons on solar-powered street lights from Kampala and Jinja, Uganda. Coalition for Urban Transitions (Policy Brief), March 2019.

[234] *State of the Nation 2020 Streetlighting Survey, UK Roads Liaison Group, CIHT (sotn-report.pdf (ciht.org.uk)).*

[235] Tannous, S., Manneh, R., Harajli, H., El Zakhem, H., Comparative cradle-to-grave life cycle assessment of traditional grid-connected and solar stand-alone street light systems: a case study for rural areas in Lebanon, J. Clean. Prod. 186 (2018) 963-977.

[236] Shehedeh, N.H., Sustainable Street Lighting: A Guide too Efficient Public Street Lighting for Lebanon, A UNDP-CEDRO Publication, December 2015.

[237] Al Irsyad, MI, Halog, A., Nepal, R., Smart grid technology for energy conservation in street lights: lesson learnt from six years' operation in Indonesia. 2019 International Conference on Technologies and Policies in Electric Power and Energy, pp 1–6, 2019.

Table 6 indicates the properties of different lighting technologies, comparing lifespan, capital expenditure (capex) and operational expenditure (opex)[236].

Table 6. Lighting technologies comparative table (reproduced from [236])

Lamp	Lm/Watt	Color rendering index (CRI)	Lifespan (hrs)	Dimmability	Capital cost	Operational cost	Application
GLS	5-15	⊗⊗⊗⊗∅	1,000	Excellent	⊕	*	General lighting
Tungsten Halogen	12-35	⊗⊗⊗⊗∅	2,000 - 4,000	Excellent	⊕	♦	General lighting
Mercury vapor	40-60	⊗⊗⊗∅∅	12,000	Not possible	•	•	Outdoor lighting
CFL	40-65	⊗⊗∅∅∅	6,000 - 12,000	Special lamps	⊕	⊕	General lighting
Fluorescent Lamp	50-100	⊗⊗⊗∅∅	10,000 - 16,000	Good	⊕	⊕	General lighting
Induction Lamp	60-80	⊗⊗⊗∅∅	60,000 - 100,000	Not possible	♦	⊕	Difficult maintenance applications
Metal Halide	50-100	⊗⊗⊗∅∅	6,000 - 12,000	Not practical	♦	⊕	Commercial buildings
HPS (standard)	80-100	⊗⊗∅∅∅	12,000 - 16,000	Not practical	♦	⊕	Outdoor street lighting, warehouse
HPS (color improved)	40-60	⊗⊗⊗∅∅	6,000 - 10,000	Not practical	♦	⊕	Outdoor, commercial interior lighting
LPS	80-100	∅∅∅∅∅	10,000 - 18,000	Not practical	♦	⊕	Outdoor lighting
LED	20-120	⊗⊗⊗∅∅	50,000 - 100,000	Excellent	♦	⊕	All in near future

Legend:

⊕	Low	∅∅∅∅∅	Very poor
•	Moderate	⊗∅∅∅∅	Poor
♦	High	⊗⊗∅∅∅	Fair
*	Very high	⊗⊗⊗∅∅	Good
		⊗⊗⊗⊗∅	Very good
		⊗⊗⊗⊗⊗	Excellent

Life cycle assessment was carried out to evaluate the environmental implications of two potential lighting systems in rural Lebanon from cradle-to-grave[238]:

- Traditional grid system (steel pole, high pressure sodium lamp and aluminium cables)
- Independent standalone solar powered system (a steel pole, a Light Emitting Diode lamp, a photovoltaic panel, a valve regulated acid battery, a controller, a dimmer, and copper cables)

Considering the raw material extraction and production, the study indicates the traditional system has less environmental impacts than the solar system. This is primarily due to the lead and electronics used as part of the solar system. However, considering the entire life cycle from raw material to end of life, including ongoing power requirements and recycling capabilities, the solar system shows less overall environmental impacts.

Further discussion on policy, case studies and economic aspects associated with LED lighting will be provided in Part 3 of this report.

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[238] Tannous, S., Manneh, R., Harajli, H., El Zakhem, H., Comparative cradle-to-grave life cycle assessment of traditional grid-connected and solar stand-alone street light systems: a case study for rural areas in Lebanon, J. Clean. Prod. 186 (2018) 963-977.

6 ROAD USER CHOICES

6.1 TRANSFER TO ACTIVE TRANSPORT

Non-motorised transport (NMT) infrastructure has significant health benefits for users, the environment and society in general. It has relevance across developed and developing countries. In 2017, UNEP published a report on the Cost Benefit Analysis of NMT Infrastructure Projects, as well as an accompanying Project Assessment Tool to estimate the potential environmental, social, economic and health benefits from an increase in NMT. According to the report, providing a well-planned, high-quality network of facilities for NMT is essential for developing economic and social equity in urban areas of developing countries[239]. Case studies are examined to provide insight into the implementation of NMT schemes in developing countries.

As an example, Thika Highway is a 45km highway in Nairobi, giving access to employment, education and other services. Issues with congestion, high accident rates and fatalities of non-motorised transport users, provided motivation to improve NMT services by constructing cycling facilities, pedestrian walkways and appropriate footbridges, with the aim of reducing NMT user fatalities. The scheme was expected to increase the number of walking and cycling trips, resulting in 3% reduction in CO_2 emissions (19,911 tons CO_2) from trips on the Thika Highway by 2030[239]. However, there has been criticism of the scheme since completion of the project, particularly in relation to the design and location of footbridges. As part of the Thika Highway scheme, motorised transport formed most of the project. Following completion of the project with improved NMT infrastructure, pedestrians still accounted for 84% of fatalities along the corridor, which is higher than pre-construction levels[239]. Based on the Thika Highway experience, the report provides recommendations for further schemes[239]:

- Design of infrastructure considering the requirements of NMT from inception (e.g. in relation to position of footbridges)
- Provide NMT services as part of a network rather than a standalone service along a single corridor
- NMT infrastructure should be provided along popular NMT routes rather than as an add-on to popular motorised routes

In terms of environmental benefits, as a comparison, it was predicted that the provision of NMT infrastructure along the 1.4 km Haile Selassie Avenue in Nairobi will reduce CO_2 emissions by 10% by 2030 (reduction of 12,909 tons CO_2) due to an increase in pedestrian and cycling activities along the route[239]. It is predicted that strategic NMT infrastructure along this short route will have significantly greater benefits than Thika Highway[239]. A theoretical study examining the effects of having an extensive walking and cycling network in the Nairobi metropolitan network predicts a potential reduction in CO_2 emissions of 5% by 2030 across

[239] UNEP, Cost Benefit Analysis of NMT Infrastructure Projects, 2017, Cost Benefit Analysis of NMT Infrastructure Projects | UNEP - UN Environment Programme.

Nairobi as a result of an increased uptake of NMT, resulting in estimated CO_2 emission savings of 624,867 tons[239].

Ghana has a large urban population of approximately 56%. Severe congestion in urban areas drove the need for more sustainable modes of transport, and the development of the Ghana NMT Strategy 2018-2028. The 10-year goals include[240]:

- Integrate NMT into transport infrastructure
- Provide basic NMT infrastructure
- Facilitate access to bicycles and promote the use of bicycles
- Improve road safety for NMT users
- Regulate the design of new and existing roadway facilities.

A study on non-motorised transport was carried out by GTZ on behalf of the Federal Ministry for Economic Cooperation and Development in Germany[241]. According to the report[241], to improve active user participation in NMT projects, users need to be involved in all aspects of the development and implementation of NMT projects. The following were suggested as examples to engage users in the process[241]:

- Focus Groups to identify current and potential problems and document them
- User Platforms to communicate and prioritise user needs in the planning and implementation of NMT
- User Associations to remain a major part of the maintenance and operation of the built NMT infrastructure

A comparison of road space reallocation measures taken in two UK cities (as a response to Covid-19 lockdown measures) found that only a relatively low proportion of the sample study participants had used one of the temporary measures (32%). However, the users regarded them overwhelmingly positively, particularly those measures that removed traffic[242].

Copenhagen and Amsterdam are both capital cities with a bicycle friendly infrastructure and high cycling uptake. In these cities, private motorised vehicle transport ranks third or fourth as a means of transport. To emulate this success, the Bicycle Referendum Initiative (Initiative Volksentscheid Fahrrad) was established in Germany 2016 to increase the modal split in cities with a low share of cyclists. As part of this initiative, in Essen, the following improvements are planned and should be put in place by 2030 to improve cycling culture[243]:

- Provide a continuous network for everyday bicycle users
- Make crossings safer for bicycle users

[240] Ghana Non Motorized Transport Strategy, UNEP - UN Environment Programme, Ghana Non Motorized Transport Case Study | UNEP - UN Environment Programme.

[241] Hook, W., Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Training Course: Non-motorised Transport, Federal Ministry for Economic Cooperation and Development, 2005, Training Course Non-Motorised Transport (unece.org).

242 Parkes, S., Weston, R., Gore, T. and Lawler, M. (2021) Room to Move: Impacts of road-space reallocation. DecarboN8. DOI: 10.7190/cresr.2021.0383487418

[243] Copenhagen and Amsterdam are not utopias, 2021, Copenhagenize your city | polisMOBILITY Magazine | polisMOBILITY (polis-mobility.com).

- Design bicycle paths and safe cycling lanes
- Set up continuous and uniform cycling lanes
- Increase the number of bicycle stands
- Promote cycling as a mode of transport consistently and transparently

A study by Rojas-Rueda et al.[244] examined data related to the public bicycle sharing initiative (Bicing) in Barcelona and concluded that the scheme had the effect of reducing annual carbon dioxide emissions by 9062 tonnes per annum in 2011, by comparing with previous journeys made by cars.

Estimated tonnes of CO_2 savings associated with a sustainable transport hierarchy, influencing various percentages of the UK population to change transport modes

Passengers switching to	Population percentage influenced		
	10%	20%	30%
Bus	5,800,000	11,750,000	17,650,000
Two passengers per vehicle	6,800,000	13,600,000	20,400,000
Cycling	13,600,000	27,200,000	40,800,000

In 2012, Chen[245] carried out a study to quantify the climate value of cycling in Dutch cities and the total avoided CO_2 emissions due to cycling. It was concluded that over a 5-year period, through cycling, Dutch people avoided 1.36 million tons of CO_2 per year[245].

Consideration of active and public transport initiatives at preconstruction stage have significant potential to impact the way the public use our roads. It can be shown that the average savings of an individual moving from private car travel to bus transport is around 0.9 tonnes CO_2/year[246], based on a UK average of 11,000 km. This value is around 1.0 tonnes/year for making trips with a minimum of two people per car.

In 2021, the Department of Transport in the UK published plans for Decarbonising Transport, highlighting the need to make public transport, cycling or walking the natural first choice for those capable of doing so[247]. In 2019, 58% of all private car journeys were below five miles and is an area with significant potential for behaviour change, switching from car journeys to walking or cycling. In the 16 months between March 2021 and June 2021, more than 300

[244] Rojas-Rueda, D., de Nazelle, A., Tainio, M. and Nieuwenhuijsen, M.J., 2011. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. BMJ, 343.
[245] Chen, Y., Assessing Climate Value of Cycling Under Different Urban Forms of Dutch Cities. Dissertation for the University of Twente, Faculty of Geo-Information and Earth Observation (ITC), 2012.
[246] Which form of transport has the smallest carbon footprint? - Our World in Data: https://ourworldindata.org/ travel-carbon-footprint
[247] Department of Transport, Decarbonising Transport - A Better, Greener Britain, 2021, Decarbonising Transport – A Better, Greener Britain (publishing.service.gov.uk).

cycling and walking schemes were installed, with many more proposed over the next 5 years. With a £2 billion investment, the aim is for half of all journeys in towns and cities to be cycled or walked by 2030. A massive 46 percent increase in cycling was observed in 2020, which was greater than the previous 20 years combined. However, it is also recognised that this increase is partly due to changes in habits and lifestyle due to the coronavirus pandemic. In the UK, new operating models are transforming traditional transport services, e-cycles as well as other emerging technologies are providing increased opportunities to travel distances that would have previously been considered too long to cycle. Based on the plans outlined in Decarbonising Transport, a reduction in car GHG emissions between 1 to 6 $MtCO_2e$ is predicted in England between 2022 and 2050.

In Wales, in addition to the Active Travel Act 2013, the new Wales Transport Strategy has set a target objective of 45% of journeys to be made by walking, cycling and public transport by 2040. To facilitate this modal shift, the dedicated budget for active travel infrastructure has been increased from £5 to over £20 per head of population per year between 2013 and 2021[248].

The government of British Columbia published a CleanBC Roadmap[249] to outline measures to reduce carbon emissions by 2030. In the document, a plan to encourage modal shift to more energy efficient forms of transport is outlined. As such, energy intensity targets for personal transportation will be established which will work to increase the share of trips made by walking, cycling and public transport by 30% by 2030, 40% by 2040 and 50% by 2050[249]. "*Move. Commute. Connect.*" Is British Columbia's active transport strategy to improve walking, cycling and other modes of active transport and make them safe and accessible for people of all ages and abilities. Infrastructure and planning grants are available to Indigenous and local governments to support active transportation improvements. Tax incentives are included to encourage the use of eCycles as an active transport option and $18 million was allocated in the 2021 budget towards provision of active transportation infrastructure[250].

As part of its Sustainable Mobility Policy, the Canadian Province of Québec has a 'RTI' strategy[251]; Reduce – Transfer – Improve, focusing respectively on reducing motorised trips and distances by integrating land use and transportation, transferring trips to lower emission options, such as public transport and active travel, and improving the efficiency of vehicles by reducing their carbon footprint, but also improve trips in terms of costs, quality and safety.

6.2 TRANSFER TO PUBLIC TRANSPORT

[248] Active Travel Act Guide, Llwybr Newydd, Welsh Government, 2021, Active Travel Act guidance (gov.wales).
[249] CleanBC Roadmap to 2030, Government of British Columbia, CleanBC Roadmap to 2030 (gov.bc.ca).
[250] Clean Transportation - How we're making it easier to get around without a car, Government of British Columbia, Clean transportation - Province of British Columbia (gov.bc.ca).
[251] https://participatoryplanning.ca/community/quebecs-sustainable-mobility-policy

According to the U.S. Department of Transport, bus is the most common form of public transport and using public transport instead of personal vehicles produces on average 45% less CO_2 per passenger mile[252]. A study conducted by the American Public Transportation Association[253] indicated that the most effective way to reduce household carbon emissions was to use existing public transportation instead of driving a private car, as illustrated in Figure 19. In the Public Transportation's Contribution to USA Greenhouse Gar Reduction report, Davis et al.[254] estimated a reduction of 6.9 $MtCO_2$ in USA in 2005 by using public transport due to the reduction in emissions from private cars and from reduced congestion (Table 7).

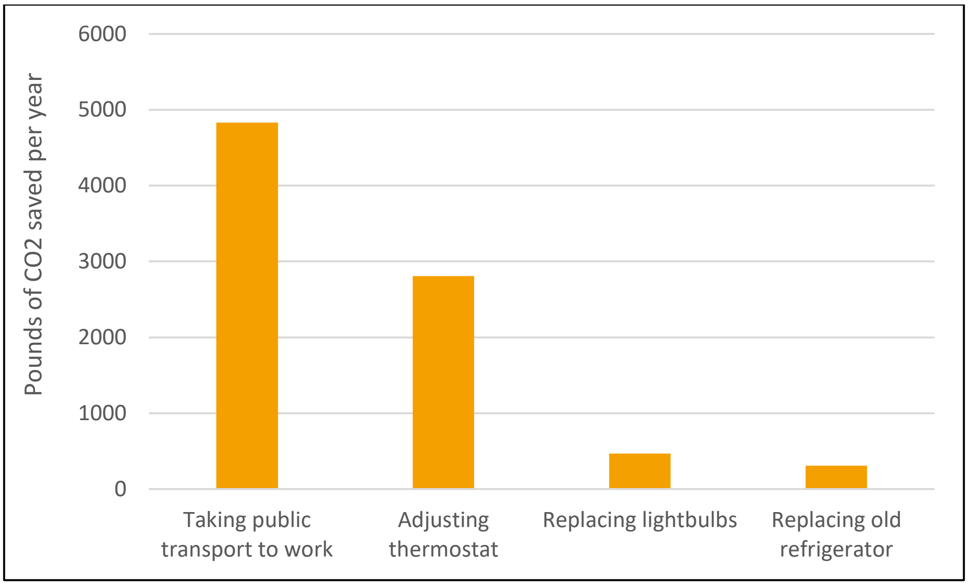

Figure 19. Household CO_2 savings from using public transport instead of private car (reproduced from [253])

Table 7. Estimate of the benefits of public transport in reducing CO_2 emissions in USA in 2005 (reproduced from [254])

Estimated CO_2 Savings in USA from Using Public Transport (2005)	Metric Tonnes
Carbon dioxide emissions from personal vehicles if no transit service	16.2 million
Carbon dioxide emissions from public transportation	12.3 million

[252] U.S. Department of Transportation, Public Transportation Trips Per Capita, 2015, Public Transportation Trips Per Capita | US Department of Transportation.
[253] American Public Transport Association, Public Transportation Reduces Greenhouse Gases and Conserves Energy, greenhouse_brochure.pdf (apta.com).
[254] Davis, T., Hale, M., Public Transportation's Contribution to U.S. Greenhouse Gas Reduction, Science Applications International Corporation, 2007, https://www.apta.com/wp-content/uploads/Resources/resources/reportsandpublications/Documents/climate_change.pdf

Net carbon dioxide saved from public transportation	3.9 million
Additional carbon dioxide saved from transit reduced congestion	3.0 million
Total carbon dioxide savings from public transportation	6.9 million

Public transport includes the use of buses, trains, coaches, and trams. A passenger centred approach is required to provide a genuine alternative to private vehicles. Incentives can be offered to help reduce the use of personal vehicles and increase the use of public transport. According to the U.S. Department of Transportation, reducing the cost of public transport to the user, including free or discounted bus, rail and/or tram, can be one incentive to increase public transport use. Other incentives including travel passes, reimbursements, tax reductions and subsidies have been shown to increase public transport use in the US. Considering upfront and ongoing costs of car ownership (e.g., vehicle cost, tax, insurance and ongoing maintenance), the costs associated with using public transportation are generally lower than costs associated with ownership of private vehicles[255].

However, for public transport to be effective it needs to be reliable, affordable and efficient. Integrated public transport, both door to door and adequate walking and cycling facilities to access public transport services and transfer between modes is essential. Up to date accurate information on journey times promotes user confidence, making movement between transport modes feasible and stress-free[256]. Public transport also needs simpler and easy to navigate payment systems, e.g. contactless payments and multi-modal tickets for trains, buses and trains. It also needs to be affordable, competitive with the cost of private transport, and with flexible tickets that fit new travel patterns. Examples of a single public transport payment card are Oyster (London), Leap (Dublin) and Octopus (Hong Kong).

As part of the UK target for net zero emissions by 2050, a fundamental reshape of the public transport bus network is planned. The aim is to provide more priority lanes for faster and reliable travel and lower, simpler fares, as well as zero emission buses. Policies like these have successfully contributed to modal shift in London:

- 20% decrease in the share of solo car trips at a national level
- 40% reduction in oil consumption in the transport sector below the level from 2013

[255] U.S. Department of Transport, Expand Public Transportation Systems and Offer Incentives, 2015, Expand Public Transportation Systems and Offer Incentives | US Department of Transportation.
[256] Campaign for Better Transport, Integrated Transport: A New Generation of Interchanges, 2018, integrated-transport-a-new-generation.pdf (bettertransport.org.uk)

The goal is to provide similar service in other parts of the UK, with simpler, cheaper fares, paid for using contactless cards and with daily and weekly price capping across different operators[247].

Hong Kong has an extensive public transport system. The compact nature of the city and a sophisticated network mean that public transport is accessible from almost anywhere. Benefiting from a clean, safe, fast, efficient service, almost 90% of the population use the public transport system[257]. Private vehicles are also discouraged by introducing parking fees and high taxes on imported vehicles[258].

Kenya has a high uptake in public transport use, with 63% of the population using public transport. This can be largely attributed to the high cost of car ownership, high fuel cost and severe traffic congestion, particularly in Nairobi[258].

Following a trial which began in September 2015, in September 2017, Dunkirk became the largest metropolitan area in Europe to remove fees on the entire public transport network, where one of the aims was to promote more sustainable travel within the city. The scheme included a major overhaul of the bus system, with 5 bus rapid transit (BRT) lines key to the operation of the network, with the ability to provide a high level of service due to dedicated rights of way along the lines. The aim was to provide a bus every 10 mins on each line between 7am and 7pm[259]. Eight months after the scheme was introduced, use of the bus lines had increased by 65% during the week and by 125% during the weekend. As well as an increase in use by people already using public transport, a study of automatic counting systems on buses along with a survey of 2,000 people found that there were also new users of the public bus system. Of people who had previously used the service, 50% indicated that they now used it for journeys previously travelled by car[260]. Of those surveyed, 10% of people indicated it removed the need for a car, with some deciding to relinquish ownership of cars and others decided against purchasing a new or second car[261].

Although Dunkirk is a relatively positive success story, studies indicate that the choice to use public transport over private vehicles has more to do with service quality than cost. In some cases, it is more effective to increase the cost of using a private vehicle, like fuel costs, congestion taxes or parking charges[262].

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[257] World Atlas website, The Top 10 Best Public Transit Systems in the World, 2018, The Top 10 Best Public Transit Systems in the World - WorldAtlas

[258] World Atlas website, Countries with the Highest Public Transit Use, 2018, Countries With the Highest Public Transit Use - WorldAtlas.

[259] Modijefsky, M., Free public transport launched successfully in Dunkirk, Eltis website, 2018, Free public transport launched successfully in Dunkirk | Eltis.

[260] Urbis magazine, Dunkerque: Le Bus Gratuit Séduit Les Automobilistes, 2019, Dunkerque : le bus gratuit séduit les automobilistes - URBIS le mag.

[261] Modijefsky, M., Free public transport in Dunkirk, one year later, Eltis website, 2019, Free public transport in Dunkirk, one year later | Eltis.

[262] Deutsche Welle (DW) website, Can free public transport really reduce pollution?, Can free public transport really reduce pollution? | Environment | All topics from climate change to conservation | DW | 14.02.2018.

A study carried out in Korea examined if the introducing free public transport would instigate a modal shift in transport. In a survey, 51% of participants indicated that free public transport would not alter their transport behaviour, stating inconvenient location for transfer to and from public transport[263]. The study concluded that while eliminating fares, increasing comfort and optimising routes increases public transport use, additional strategies like replacing car lanes with bus lanes, reducing parking and implementing congestion fees may be required to encourage users to switch from private vehicles to public transport[263]. The goal is to reduce private vehicle trips and not compete with non-motorised transport modes, a desirable outcome would be a public transport network that integrates and complements walking and cycling initiatives[263].

[263] Zhen, S., Free public transportation: Why we need it, and examples from Korean and European cities, ICLEI Korea – Sustainable Mobility, 2021, Free public transportation: Why we need it, and examples from Korean and European cities - ICLEI Sustainable Mobility.

7 CARBON OFFSETTING

The concept of carbon offsetting is simple; carbon emitted from one source (e.g. burning fuel to power a vehicle) is counteracted by carbon removed from the atmosphere by another means, (e.g. by planting a tree which absorbs CO_2 from the atmosphere as it grows). Various companies offer offsetting schemes: for companies these offer to offset operational emissions (e.g. energy used to manufacture a product) and, for individuals, to offset the emissions from their lifestyles (e.g. heating, lighting, vehicle use and diet, specifically meat consumption).

Different offsetting schemes (see below) have specific areas of focus, but the project choices are similar, such as funding renewable energy projects, tree planting, peat bog restoration, blue carbon restoration (mangrove plantations, saltmarsh creation or restoration and seagrass restoration), provision of low carbon stoves and prevention of deforestation. These schemes should be additional to actions that would have occurred anyway, to ensure there is a genuine and equal reduction in emissions to those being compensated for.

7.1 METHODS TO REMOVE CARBON

Carbon sequestration

Carbon sequestration refers to the methods in which carbon can be stored and therefore 'locked in', reducing overall CO_2 quantities in the atmosphere. There are doubts about the potential benefits, costs and technical feasibility of scale up of several methods of carbon sequestration. Reduction in carbon emissions should always be the first choice in the fight to keep global temperatures at or around 1.5^{O}C by 2050.

The UK Government has provided £70 million of funding for trials[264] of methods for the removal of greenhouse gases. The funding falls into the general categories listed below, with details on the specific projects funded available on the competition homepage[265].

Afforestation

Establishing new areas of forest though tree planting results in the removal of atmospheric CO_2, as the trees grow, as well as potential for increased biodiversity and improved soil condition. However, there are concerns about the use of non-native species and the amount of land required (and possible implications for food security). There is also a debate on whether to plant woodland, which has more biodiversity but is slower growing, and forests, which grow more quickly and therefore absorb CO_2 more quickly but may be lacking in diversity. A useful overview, summarising progress in afforestation in China, North Africa and India, is provided by Vartan[266].

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[264] https://www.theguardian.com/environment/2022/may/30/greenhouse-gas-removal-not-a-silver-bullet-to-achieve-net-zero
[265] https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition
[266] Vartan S (2022) What is Afforestation? Definition, Examples, Pros and Cons. https://www.treehugger.com/what-is-afforestation-definition-examples-5114137

Storing in soil

Soil naturally stores carbon and improving soils can therefore store it more effectively. There are concerns though about how long it stays in the soil and how to measure it. If it were releasing carbon soon after storage, it could still be counted in net zero targets, but not actually reducing carbon.

Enhanced weathering

This involves dropping small rock particles into the sea to cause chemical reactions that lock carbon in the ocean but is at an early stage. As the oceans stores carbon in higher concentrations than the atmosphere, it has potential and may even help reverse ocean acidification, however there might be unknown harmful effects on the ocean ecosystem.

Biofuels

The use of biofuels removes the need for fossil fuels to be used and so become cyclical, however there are concerns around land use and potential competition with food crops, and biodiversity loss as the growing of the crops often creates a monoculture, although presumably this can be managed.

Biochar

Biochar is a charcoal-like product produced from heating wood or other biomass in the absence of oxygen. It can be applied to land to sequester CO_2 in soils for an extended period. This could be relatively easy and cheap, but there are concerns as to how long the carbon would be stored, and whether it would have any negative impacts on the soil.

Direct air capture

Air is sucked from the atmosphere with a large fan and CO_2 extracted and stored permanently in rocks. The process has been technically proven, but it is very energy intensive and this needs to be reduced to make scientific sense as well and becoming commercially viable.

Rewilding

There have been examples of rewilding, including the reintroduction of missing creatures to restore a lost balance in the ecosystem which may in turn, help reduce carbon emissions; for example: conservation of sea otters[267] in the Pacific to feed on sea urchins, who if left unchecked decimate kelp forests, which are large carbon stores; the reintroduction of wolves in Yellowstone has restored an apex predator and reduced deer browsing, helping forests to return[268]. Rewilding Britain note[269] that trees self-seeding is generally a more effective means of tree planting whilst creating a richer habitat, whilst other environmental benefits not

[267] https://www.theguardian.com/environment/2016/jul/10/sea-otters-global-warming-trophic-cascades-food-chain-kelp
[268] https://www.theguardian.com/environment/2020/jan/25/yellowstone-wolf-project-25th-anniversary
[269] https://www.rewildingbritain.org.uk/support-rewilding/our-campaigns-and-issues/climate-emergency

related to carbon can be achieved, such as reintroducing beavers[270] into Devon (UK), where the dams have been shown to reduce flooding.

7.2 Offsetting schemes

All the schemes[271] listed below use 3rd party certified projects to give confidence that funds go to projects that actually reduce emissions. Examples include Gold Standard, Verified Carbon Standard, Climate Action Reserve, American Carbon Registry, Plan Vivo, Climate, and Community & Biodiversity Alliance. The schemes and the type of activities each employ are:

- **Native Energy** – emissions reduction and reforestation
- **Sustainable Travel International** – focussed on sustainable tourism – emissions reduction, reforestation and blue carbon (mangroves, sea grass and salt marshes)
- **Terrapass** – focus on large events – believed to be renewable energy and water restoration
- **Clear** – focus on commuting, efficiency of cookstoves, hydroelectric plants, wastewater treatment plants and sources of clean energy
- **Myclimate** – focus on household emissions – funds projects in Biogas, Biomass, Efficient cook stoves, Energy Efficiency, Hydro power, Land Use and Forestry, Solar, Waste Management and Compost, Water (Purification & Saving) and Wind
- **3Degrees** – focus on business – good for companies seeking large offsets. Works on carbon reduction and carbon removal and includes sustainable forestry, livestock manure management, landfill gas, and industrial processes.

7.3 Limitations of offsetting schemes

One limitation of offsetting schemes is the scale of offsetting needed to offset the emissions associated with road transport. In terms of tree planting, it is reported[272] that a tree will absorb around 20 kg of CO_2 per year when fully grown, whereas a sapling will absorb much less. Over a 100-year lifetime it is estimated that a tree will absorb around 1 tonne of CO_2. Emissions[273] from passenger cars alone in 2020 was around 3 $GtCO_2$/yr – to offset this by tree planting, even based on mature trees absorbing 20 kg per year with a 100% survival rate, would require 150 billion trees to be planted each and every year.

While tree planting has many beneficial aspects, these projects cannot lock carbon away permanently, or at least for thousands of years, as trees burn down, die from disease, or get chopped down. There has also been criticism[274] that many large tree planting schemes exist on paper only, as there is little follow up, so many trees have died or been harvested. The same report notes that 88% of a mangrove plantation in the Philippines failed after 5 years as

[270] https://www.exeter.ac.uk/research/creww/research/beavertrial/
[271] https://www.treehugger.com/best-carbon-offset-programs-5076458
[272] https://www.viessmann.co.uk/heating-advice/how-much-co2-does-tree-absorb#:~:text=How%20much%20CO2%20can%20a,around%20a%20tonne%20of%20CO2.
[273] https://ourworldindata.org/co2-emissions-from-transport
[274] https://www.bbc.co.uk/news/science-environment-61300708

the wrong type were planted. Furthermore, many large-scale projects do not have the data or follow up to even make such an assessment.

Similarly, while biochar can potentially lock carbon in for long periods of time (examples of biochar, several thousand years old, have been found in soils), in other situations it decomposes rapidly (considerably less than 50 years), releasing the carbon back in the atmosphere. A thorough literature review identified only 15 papers that measured indicators of biochar composition in soil, in settings as varied as Colombia, Kenya, Zimbabwe, Canada and USA[275]. While noting that biochar could be advantageous in the right circumstances, it concluded there is currently insufficient evidence to estimate the stability of biochar over time and recommended it is too early to be confident in it as an effective climate mitigation tool.

Some offsetting schemes prevent deforestation; however, Friends of the Earth reference a report[276] funded by the German government suggesting that, even in areas where there are high historic rates of deforestation, it is difficult to determine what will happen in future. Furthermore, even if a scheme does prevent deforestation in one location, it might just shift it elsewhere as the driver for deforestation (e.g. farmland for livestock or crops) remains.

They state that the EC report says that most schemes who claim emissions savings from changing from inefficient cooking stoves to efficient ones, exaggerate the savings, whilst noting a tonne of carbon is not always equal – a tonne emitted from a plane at altitude causes more damage than a tonne of carbon burnt at ground level.

Friends of the Earth[277] cites a study for the EC into UN sanctioned offset projects and found that three quarters were unlikely to have resulted in additional emissions reductions (as they would likely have happened anyway), with only 2% having a high likelihood of being 'additional'. For energy, it is reported that many typical schemes will go ahead anyway, because of a strong demand for energy combined with a market that will pay for it, and governments pledges to reduce emissions.

Overall, however, they pointed out that even the prospect of being able to offset prevents businesses and individuals taking action to reduce emissions, i.e. if there might be a 'get out of jail free' card in a few years' time, where we can plant some trees or have a machine suck carbon out of the air, we don't need to take significant action now.

Greenpeace[278] come to the same conclusions that whilst tree planting and providing efficient cooking stoves are good, they don't really offset the emissions to which they are linked and they should be done as well as cutting emissions directly, not instead of it. They also point out that it might take a tree 20 years to capture the carbon that a carbon offset scheme promises,

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275 The scientific basis for biochar as a climate change mitigation strategy https://www.ucsusa.org/resources/biochar-climate-change-mitigation-strateg

276 hhttps://climatefocus.com/publications/should-forest-carbon-credits-be-included-offsetting-schemes-such-corsia/

277 https://friendsoftheearth.uk/climate/does-carbon-offsetting-work

278 https://www.greenpeace.org.uk/news/the-biggest-problem-with-carbon-offsetting-is-that-it-doesnt-really-work/

so we would have to plant and protect a massive number of trees for decades. Wildfires, droughts and tree diseases could wipe out forests, whilst changes in the climate might put strain on forests in future (although in some locations, higher temperatures and higher levels of atmospheric carbon might promote faster growth).

PART C – Case Studies

8 LED LIGHTING

8.1 Current Guidelines and Targets

With many NRAs striving to reduce energy bills and CO_2 emissions, it is expected that LED lighting will become the dominant technology for street lighting. Guides and standards by the European Commission (EC) and United Nations Environment Programme – United For Efficiency (UNEP-U4E), as well as national bodies, assist in this transition by providing guidance and an outline of the options available.

In 2017, the European Commission published the EU GPP Criteria for Street Lighting & Traffic Signals, reviewing relevant technical, policy, academic and legislative literature to assess the potential for reducing environmental impacts and electricity costs by implementing recent advances in energy affecting lighting technology. The provision of lighting on 1.6 million km of roads in 28 EU countries costs public authorities almost €4000 million each year, with an electricity consumption of 35 TWh, accounting for 1.3% of total electricity consumption[279]. Similarly, the UNEP-U4E initiative published Green Public Procurement Technical Guidelines and Specifications for Energy-Efficient Lighting in March 2022[280]. Additionally, in 2017, U4E developed an open-source Efficient Lighting Savings Forecast Model, with the aim of helping users to model potential savings from moving to energy efficient lighting[281].

Specific examples from countries include:

- The Danish EPA has a Total Cost of Ownership (TCO) tool to evaluate the total cost over the lifecycle of a product, assisting procurers in assessing the possible advantages of purchasing resource efficient products and products with a longer lifespan. Using this tool, as part of a tender for lighting, Syddjurs Municipality in Denmark concluded that that the lifecycle costs of LED bulbs are 6 times lower than equivalent halogen bulbs[282].
- In the UK, National Highways has an ambitious aim for net zero travel on roads by 2050. Part of this plan is to replace 70% of all road lighting with LED technology by 2027[283]. Switching network lighting to LEDs will account for 12% of the overall emissions reduction target between 2017 and 2030[283].
- In 2017, the province of Alberta's Government published a LED Luminaire Specification focusing primarily on the specification for LED products to replace 150-400W High Intensity

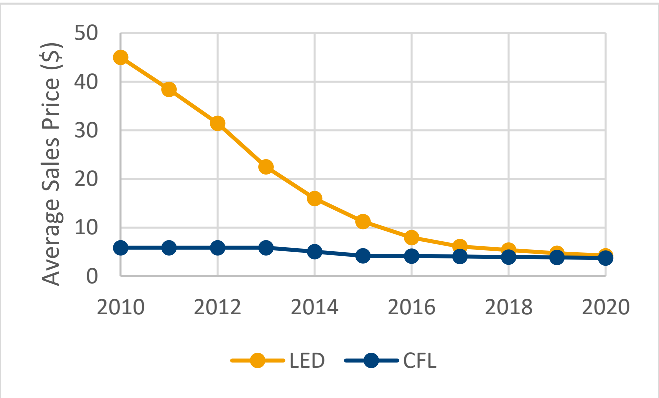
[279] European Commission (EC), EU GPP Criteria for Street Lighting & Traffic Signals, 2017.
[280] United Nations Environment Programme United for Efficiency (UNEP-U4E), Green Public Procurement Technical Guidelines and Specifications for Energy-Efficient Lighting, 2022.
[281] United for Efficiency (U4E - Model), Efficient Lighting Savings Forecasting Model - United for Efficiency (united4efficiency.org), 2017
[282] Jones, M., Kinch Sohn, I., Lysemose Bendsen, A. M., Circular Procurement Best Practice Report, ICLEI – Local Governments for Sustainability, SPP Regions, 2017.
[283] National Highways, Net Zero Highways: Our 2030 / 2040 / 2050 plan, 2021.

Discharge (HID) lighting systems. The goal of using LED technology for roadway illumination was outlined in a Specification document[284].

- In 2019, the province of British Columbia published a guidebook on converting to and purchasing LED street light luminaires, indicating the procedure for purchasing LED streetlights[285].
- The Second National Energy Efficiency Action Plan for the Republic of Lebanon outlines a strategy for implementing energy efficient street lighting, by replacing high-pressure sodium lamps with new LED lamps[286]. There are programs and initiatives in place in Lebanon to support a shift towards energy efficient street lighting using LED and renewable energy-powered lighting systems, mostly in the form of direct central government purchases and grants from international organisations[236].
- In 2018, the Republic of Rwanda Ministry of Infrastructure published an Energy Section Strategy Plan for 2018/19 – 2023/24, where several high-level targets were set out**.** One of the targets was to expand street lighting to all populated areas and main roads. The work was divided into three categories:
- Existing national roads
- Main roads in Kigali city and urban areas
- New main national roads and roads under construction
- High-quality LEDs or efficient Compact Fluorescent Lamps (CFLs) were recommended to reduce the electricity demand and operation and maintenance costs[287].

8.2 Business case – Case studies

Over the years, as the cost of LED lighting has reduced (Figure 20), the business case for moving towards energy efficient lighting has strengthened significantly. The economic benefits of the transformation towards energy-efficient LED street lighting are discussed through various case studies around the globe, where LED lighting offers longer lifetimes, reduced energy consumption, and lower maintenance costs when compared with older technologies. However, from the assessment of different case studies and targets in HIC and LMIC countries the requirements and challenges must be considered on a case-by-case basis to get the most effective solution.



[284] Alberta Government, Light Emitting Diode (LED) Luminaire Specification, 2017.
[285] British Columbia, How to Purchase LED Street Light Luminaires through the LED CSA, 2019.
[286] Lebanese Republic, The Second National Energy Efficiency Action Plan for the Republic of Lebanon NEEAP 2016-2020, Ministry of Energy and Water, 2016.
[287] Republic of Rwanda, Ministry of Infrastructure Energy Section Strategy Plan 2018/19 – 2023/24, 2018.

Figure 20. Reduction in sale price of retrofit LED lamps and CFLs replacement for a 60W incandescent lamp (reproduced from [288])

Case Study 1: Indonesia (LMIC)

In 2011, due to an electricity crisis, the Government of Indonesia ordered a reduction in energy consumed by streetlights by 50%, from midnight until dawn. This led to the introduction of a pilot Smart Street Lighting (SSL) initiative in the city of Jakarta in 2012, and encouragement for other municipalities to follow suit. The growth of SSL technology in Indonesia is expected to continue and has the potential to result in energy savings of up to 300 GWh/year[237].

Following the installation of SSL in 6 municipalities in Indonesia, it was recommended that the process be carried out in three stages. The first was to install energy meters and remove fixed price contracts. The second was replacement of traditional mercury vapour (MV), low-pressure sodium (LPS) and high-pressure sodium (HPS) with induction and LED lamps. These steps in Jakarta reduced total energy bills by up to 33%[237]. The third stage was the introduction of dimming capabilities of SSL. Implementing a schedule of dimming the intensity of lights at different intervals throughout the day resulted in energy savings of between 59% and 63% compared to conventional 250W HPS lamps without dimming.

As well as energy and carbon savings, there are additional benefits from SSL, including a reduction in the cost of routine patrolling of street lighting systems to detect vandalism. The SSL features also provides added capability to detect illegal connections[237].

Al Irsyad MI et al. reviewed the lessons learned 6 years after the introduction of SSL[237]. It showed that maintaining the operation of SSL at maximum efficiency over long periods would be difficult due to inexperience of staff and staff turnover. The ongoing cost of CMS systems and internet data was another challenge highlighted. One recommendation to improve long-term performance and efficiency was to promote cooperation with energy service companies to provide support with technical issues faced by municipalities[289]. This highlights potential for "lighting as a service" for expanding the use of LED technology for street lighting.

Case Study 2: Uganda (LMIC)

In the cities of Kampala and Jinja in Uganda, it proved more cost effective to install solar powered street lighting than conventional grid powered streetlights. In developing cities, the roads and streets can be unplanned, and services and infrastructure poorly managed. This, in some instances, results in narrow roadways, where additional roadside space for

[288] United for Efficiency, Accelerating the Global Adoption of Energy-Efficient Lighting, Policy Guide Series, 2017.
[289] Al Irsyad, MI, Halog, A., Nepal, R., Smart grid technology for energy conservation in street lights: lesson learnt from six years' operation in Indonesia. 2019 International Conference on Technologies and Policies in Electric Power and Energy, pp 1–6, 2019.

grid-connectivity can prove problematic. In such cases, standalone solar powered lighting units can be more advantageous and cost effective[290].

Solar lighting also has the added benefit of providing lighting for roads when there are power outages, particularly in many developing countries. The installation of solar lighting not only improved road safety, but also lowered crime rates and accommodated a more vibrant night-time economy, created jobs and increased property values[290].

At the time of publication by Gillard et al., the installation of solar powered lighting was in the early stages in both cities of Kampala and Jinja[290]. In Kampala, most of the 1,800 solar lights installed up to that point were on new or renovated roads, with a few replacing conventional lights. Even on new roads, the installation cost of solar powered lighting is generally lower than conventional grid powered lighting[290]. On average, for this initiative, the cost was reported to be approximately 1,600 USD per solar lighting unit, compared to $2,150 for an equivalent conventional grid powered lighting pole. Solar powered solutions offer almost zero operating costs and reduced ongoing maintenance costs[259]. The progress is being evaluated closely to determine the viability of expanding the initiatives to other cities.

Based on the success of the systems in Kampala and Jinja, the study by Gillard et al. indicated that installing and maintaining solar powered LED streetlights across sub-Saharan Africa could reduce installation costs by about 25%, electricity usage from street lighting by 40% and maintenance costs by up to 60% compared to conventional grid powered options. In Uganda alone, if the 2,800km of urban roads were fitted with conventional grid-based lighting, the cost would be approximately $238 million. Alternatively, installing solar powered street lighting would result in an initial cost of $178 million, with no ongoing electricity costs[290].

Case Study 3: India (LMIC)

The Street Lighting National Programme was launched in 2015 to replace conventional streetlights across India with smart and energy efficient LEDs. In 2021, in urban areas, Energy Efficiency Services Limited (EESL) installed over 10.9 million LED streetlights across India, resulting in energy savings of up to 7.34 billion kWh per year, resulting in savings of up to INR 51,300 million per year (approximately converts to 620 million USD) in electricity bills[291]. EESL also installed 2.6million LED streetlights in rural areas of Andhra Pradesh, Jharkhand, Goa and Telangana[291]. Progress and savings to date can be tracked on the EESL website, where the energy savings per year are estimated at 8,587 million units of electricity (1 unit = 1kWh), with GHG Emissions Reduction of 5.92 million tCO_2[292] (data reported on 24/05/2022).

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[290] Gillard, R., Oates, L., Kasaija, P., Sudmant, A., Gouldson, A., Sustainable urban infrastructure for all: Lessons on solar-powered street lights from Kampala and Jinja, Uganda. Coalition for Urban Transitions (Policy Brief), March 2019.
[291] JournalsOfIndia, Street Lighting National Programme (SLNP) , (Street Lighting National Programme (SLNP) - JournalsOfIndia), 2021.
[292] EESL website, Streetlight National Programme – Dashboard, (https://slnp.eeslindia.org).

Case Study 4: Lebanon (LMIC)

A UNDP-CEDRO publication in 2015 reviewed street lighting currently installed in Lebanon and assessed feasible options for future development[293]. In 2015, grid powered HPS were the most widely used form of lighting in Lebanon but there was growing interest in LEDs and solar street lighting. Considering current lighting in Lebanon and advances in energy efficient lighting available, 10 options were examined including HPS, LED and induction lighting, with different energy sources and varying levels of smart technology included in the assessment. Each of the 10 options was studied in terms of technical, financial and environmental factors for a variety of different road specifications.

Each option was analysed considering initial investment cost, operations and maintenance cost and replacement cost, for a 1 km roadway for a period of 20 years. The results indicated LED lamps to be the most cost effective for all road specifications, with grid powered LED lamps having the lowest lifecycle cost and HPS and inductive lamps having the highest costs[293]. Taking account of possible smart control systems, grid powered systems with advanced control presented the most cost-effective solution followed by grid powered with basic control (timer and photocell) and solar power with advanced control (intelligent control based on traffic, light, date and time, weather conditions). Environmental analysis demonstrated that renewable energy powered systems have the lowest emissions due to the absence of fossil fuel-generated power. A business analysis of possible retrofit options indicated that for all road types, new installation of grid powered LED lamps with basic control measures showed a higher Internal Rate of Return (IRR) than the retrofit of existing installations.

Case Study 5: San Sebastian, Spain (HIC)

San Sebastian has a system of over 30,000 streetlights with an annual energy cost of €3.5 million and maintenance cost of €1.8 million. Before beginning the switch to LEDs, most lighting relied on older generation High Pressure Sodium Vapour (HPSV) lighting. Pilot implementations were carried out to provide an intelligent lighting network including smart lampposts and sensors, resulting in a more efficient, cost effective and environmentally friendly system. For the pilot district, the scheme was divided into two zones depending on the intensity of lamps being replaced (52 x 250 W lamps relaced in Zone A and 38 x 150 W lamps replaced in Zone B). A payback study indicated that the initial investment of installing the smart lampposts would be recovered in 4 to 7 years, as outlined in Table 8, depending on the specification of the original lamppost being replaced[294].

[293] Shehedeh, N.H., Sustainable Street Lighting: A Guide too Efficient Public Street Lighting for Lebanon, A UNDP-CEDRO Publication, December 2015

[294] Pardo-Bosch, F., Blanco, A., Sese, E., Ezcurra, F., Pujadas, P., Sustainable strategy for the implementation of energy efficient smart public lighting in urban areas: case study in San Sebastian. "Sustainable cities and society", 2022, vol. 76, p. 103454:1-103454:12.

Table 8. Lighting costs in 2 pilot schemes in San Sebastian (reproduced from [294])

	Zone A			Zone B		
	PSB	LED	SMART	PSA	LED	SMART
Total cost investment per unit (€)	0	450	550	0	450	550
Differences in investment vs CS		-450	-550		-450	-550
Annual cost of maintenance (€)	55	14	17	55	14	17
Savings in maintenance €/year/lamppost vs CS		41	38		41	38
Savings in maintenance in % vs CS		75%	69%		75%	69%
Annual energy cost (4,100 hours year) (€)	149.24	51.73	37.35	76.12	51.73	37.35
Savings in energy €/year/lamppost		97.51	111.89		24.39	38.77
Savings in energy in %		65.34 %	74.97 %		32.04 %	50.93 %
Total cost of service (maint. + energy) (€)	204.24	65.73	54.35	131.12	65.73	54.35
Savings operation €/year/lamppost vs CS		138.51	148.69		65.39	76.77
Savings operation in % vs CS		68%	73%		50%	59%
PAYBACK (years)		3.25	3.7		6.88	7.16
NPV in 25 years (€)		2,288	2,536		1,306	1,554

Case Study 6: Buenos Aires, Argentina (LMIC)

In 2013, the installation of a smart energy lighting system began in the city of Buenos Aires, which was completed in 3 phases over a 3-year period. Initially, 11,000 LED lights were installed on main avenues and streets, with an additional 80,000 installed on secondary streets, upgrading 75% of the lighting in Buenos Aires. This resulted in a saving of 50% in operational costs and a significant reduction in CO_2 emissions[295].

Case Study 7: Hamilton, Ontario (HIC)

Since 2009, the City of Hamilton has been involved in three LED streetlight pilot projects, to investigate and verify the performance of different technologies. In 2015, over 10,000 high pressure sodium (HPS) streetlights were replaced with LEDs, including a pilot project of 50 adaptive controls[296]. Ageing HPS systems and associated high maintenance costs as well as the reduction in energy costs contributed to the motivation to upgrade to more advanced technology. Figure 21 outlines the outcomes of the pilot project, where the LED lamps performed even better than projected, reducing energy consumption by approximately 57%[296].

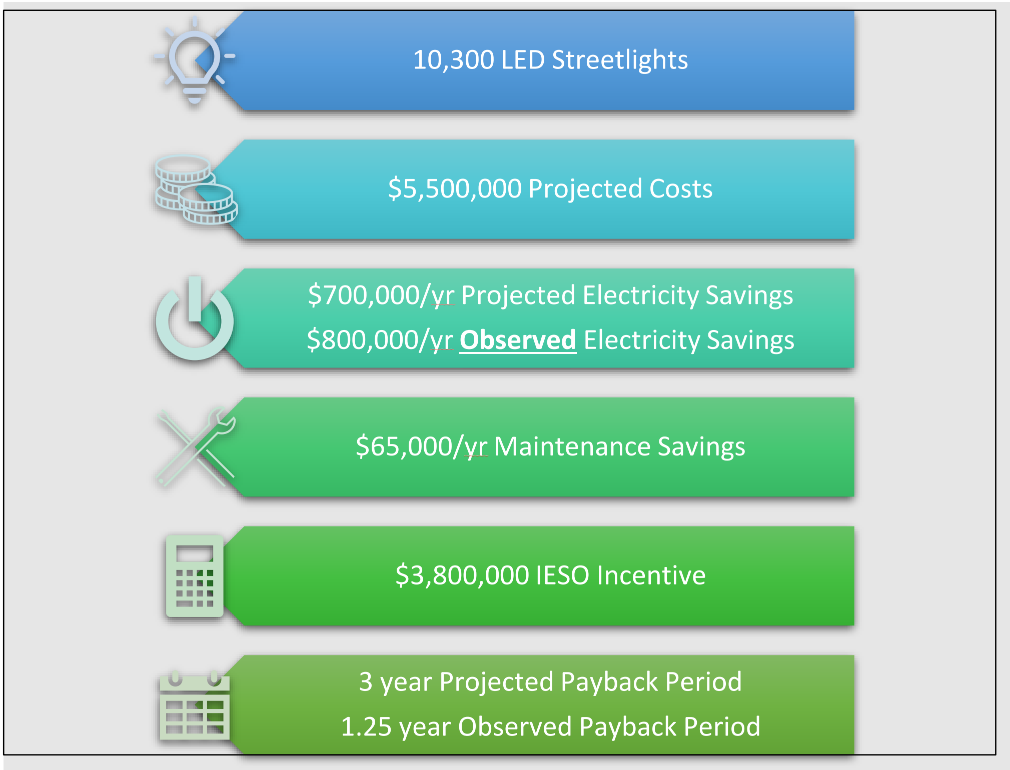

Figure 21. Business Case for Hamilton LED conversion (reproduced from[296])

[295] Philips lighting website, Buenos Aires: Pioneering Future-Proof Connected Lighting, CityTouch Buenos Aires – Philips lighting).
[296] Lightsavers Canada, City of Hamilton's LED Retrofit of High Wattage Streetlights, Canadian Urban Institute, (LightSaversCaseStudy.Hamilton.2017.07.18.pdf (squarespace.com)), 2017.

Case Study 8: Québec, Canada (HIC)

In 2022 the Ministry of Transport in Québec began a 6-year project to replace High Pressure Sodium lamps and some Mercury vapor lamps with LED lamps. The total project cost is CAD$190 million which includes CAD$93 million for the reconstruction of the 600 V electric system which is obsolete. To date, about 7,000 of the 80,000 road lamps have been replaced. This modernisation programme is financed by government funding. Part of the motivation behind the lighting overhaul was the difficulty in sourcing HPS bulbs, as they are no long being produced by manufactures. Some public bodies decide to just replace the bulb with an LED "bulb". In Québec, the decision was taken to upgrade the 600 V electricity system and replace old lamps and bulbs with LED lamps.

In Québec, 3 types of lamps are being installed, each providing a different function to fulfil the photometric requirements for the category of roadway lighting. There are different costs associated with each type, as follows (cost includes lamp and LED bulb):

- High-mast: CAD$2,200
- Pole: CAD$1,200
- Surface: CAD$1,200

In terms of operational costs, it is estimated that the scheme will reduce ongoing costs from CAD$2.4 million to approximately CAD$1.8 million, a saving of CAD$0.6 million per year. It is also estimated that annual energy costs will reduce from CAD$11.7 million to CAD$6.9 million upon completion of the scheme. Some lamps operate on a fixed price for power while others have energy meters monitoring power and consumption. The cost of recycling HPS and mercury bulbs was also highlighted. Since they contain hazardous materials, appropriate methods of recycling must be adhered to, adding an additional cost to replace each bulb. Overall, the payback period for the scheme is relatively long (greater than 20 years). This is attributed to the low cost of energy in Québec and the extensive scope of the scheme including the reconstruction of the 600 V power grid. Currently, smart systems are not included in the scheme, but the technology being supplied can be upgraded in the future to increase functionality.

Case Study 9: Western Australia (HIC)

A case study examining the use of solar/wind powered lighting units in remote areas of Western Australia was described in the Positive Energy Roads Report[297]. A total of 7 units, each costing approximately AUD$18,000, were installed to reduce the likelihood of road crashes and other accidents. The total cost was approximately a third of the cost of providing conventional grid powered street lighting wherein a significant proportion of the cost is associated with providing the grid connection. Figure 22 shows the results of a

[297] Lamb, M., Viner, H., Ramdas, V., McMahon, B., Positive Energy Roads - A PIARC Special Project, World Roads Association (PIARC), 2019

detailed evaluation of the many aspects of using solar/wind powered lighting in rural areas of Western Australia.

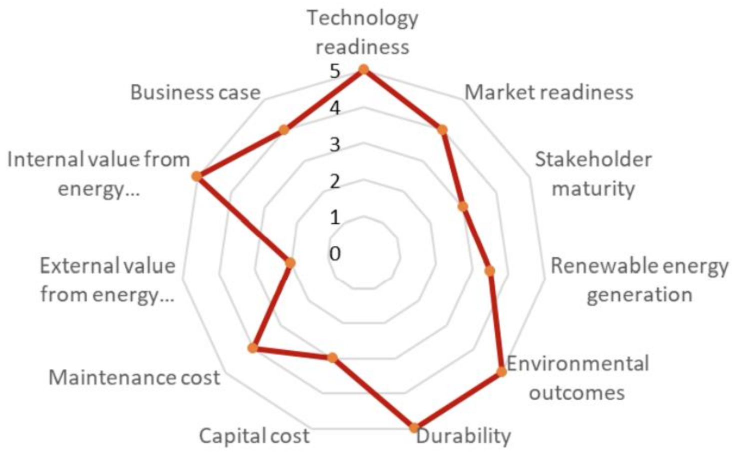

Figure 22. Evaluation of Solar/wind powered streetlights in Western Australia (from[297])

Case Study 109: South Australia (HIC)

In 2019, the Department of Planning, Transport and Infrastructure South Australia carried out an analysis of streetlighting replacement. The study examined the financial implications of replacing all low- and high-pressure sodium and mercury vapour lights with LED. The energy savings were valued at about AUD$693k per annum, with an associated capital cost of AUD$10.2M, resulting in a payback period of 14.7 years. The analysis didn't take account of lights that may be close to their end of life and require replacement when they fail regardless of the overall lighting replacement scheme. It was acknowledged that the payback would have been shorter if this aspect had been considered in the analysis.

Based on this analysis, the decision was made to replace high pressure sodium or mercury vapour light fittings with LED when they failed, rather than a complete overhaul of street lighting in the region. Current energy savings from lamp replacement and the use of LED instead of HPS on new installations is about AUD$78k per annum.

It was indicated that some local governments in South Australia had undertaken mass replacement programs, but in these cases the payback was shorter as they were often replacing less efficient light fittings. The energy saving from replacing the lighting systems was greater, so the reduced ongoing cost of operating the lighting made it more attractive on a cost basis.

Environmentally, there was no strong argument to implement a widescale replacement of streetlighting, as South Australia has a high percentage of renewable power, (a target of 100% renewable by 2030). Currently the grid emissions factor is 0.36 kgCO2e/kWh, which is low compared to other states such as Queensland and Victoria with higher emissions factors of 0.95 kgCO2e/kWh and 1.0 kgCO2e/kWh, respectively[298].

[298] National Greenhouse Accounts Factors – August 2021 (dcceew.gov.au)

Case Study 11: Greenwich, UK (HIC)

A 6-year contract has begun in Greenwich to replace 20,000 streetlights and park lights with LED lamps. It is forecast that this will save £1M per year in energy and maintenance costs, saving 6,770,589 kWh per year and reducing energy consumption from street lighting by 74% and CO_2 emissions by 2,080 tonnes per year[299].

Case Study 12: Leeds, UK (HIC)

In 2018, Leeds County Council approved a plan to invest £25.4M in new LED lighting, replacing 86,000 lights in the city with energy efficient alternatives. When the work is complete, it is estimated that the annual cost to run street lighting will be reduced by £3.4M (from current yearly spend of £4.8M). It is also estimated that energy consumed by street lighting will reduce by 62%, equivalent to 7,050 tonnes of carbon savings. The initiative includes a smart system to control the system remotely in real time to enhance efficiency[300].

Case Study 13: Wales, UK (HIC)

In Wales, the Department of Transport borrowed £4M for LED lighting replacement through the Green Growth Fund which provides funding for public sector projects that support the Welsh Government's energy efficiency strategy. In 2020, the conversion to LED lamps was about 60% complete[301]. From analysis of the ongoing data of the effects of LED lighting replacement, some limitations have been identified. The data indicates that conversion to LEDs on motorways does not produce carbon savings, as higher lumen bulbs are required to provide the level of lighting and dispersion required. Low pressure sodium can be more efficient in this scenario, but bulbs may require replacement more regularly. Another challenge was related to surrounding infrastructure and replacement of parts. Some controllers are on their third generation because the electronics driving the LEDs are failing. The investigation concluded that, in many cases, for LEDs to be an effective sustainable alternative, the infrastructure behind them also needs improving.

In relation to Smart Systems, some savings were observed but they were less than expected. Smart Systems demonstrated better efficiency at highway level but were not as effective for local authorities using lower intensity lighting. An ongoing challenge is the specialist knowledge that is often required to manage smart street lighting effectively. When specialists leave or are not available, local engineers who are not trained in the area are appointed to manage the system.

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[299] Ames, C., Greenwich borrows to invest in LED switch, Highways Magazine (Highways Magazine - Greenwich borrows to invest in LED switch), 2021.

[300] Highways Magazine, Leeds lights the way with £22.5m LED conversion, (Highways Magazine - Leeds lights the way with £22.5m LED conversion), 2021.

[301] State of the Nation 2020 Streetlighting Survey, UK Roads Liaison Group, CIHT (sotn-report.pdf (ciht.org.uk)).

Case Study 14: UK (HIC)

In the UK, there are approximately 7.2 million streetlights, with nearly 4 million of those LEDs (almost 55%). Of these LEDs, 30% are controlled by CMS (Smart Systems), 34% are part dimmed at night and 3% are part of night operations, demonstrating various forms of lighting management across the UK. There are still 3.2 million lanterns that are yet to be replaced. It is estimated that an investment of £755M could potentially save £6.8 billion of electricity cost and 5.1 M tonnes CO_2 over the next 25 years.

8.3 CONSIDERATIONS FOR ROADS AUTHORITIES

In general, there is growing acceptance of the case for LEDs to reduce energy consumption and carbon emissions (relative to traditional forms of lighting). However, the case studies presented also highlight some of the challenges associated with the replacement of all forms of street and highway lighting with LEDs. There is no "one size fits all" approach and the optimum solution for each scenario is generally scheme and location dependent. Having reviewed the outlined case studies and carried out interviews with various organisations, a list of points that should be considered when planning lighting for a new road scheme or an overhaul of existing lighting are outlined in Table 9. The considerations are split into headings but there is some crossover between points within each heading.

Table 9. Outline of considerations for planning lighting schemes

Category	Consideration	Discussion
Technology	Current system in place	Is current technology old or relatively new? Consider the relative benefits of replacement with LEDs. Options are to: • replace old bulbs with LEDs when replacement is required • change all bulbs on the grid to LEDs • replace lamps and bulbs • upgrade outdated power infrastructure to support extensive overhaul of lighting system • complete change to LEDs with smart system If the current system is relatively new, it may not always make economic sense to carry out a complete overhaul of existing lighting and/or power infrastructure.
	Lighting intensity required	The levels of lighting required for a local road and major highway are different. It is crucial to consider the type of lighting and intensity required (e.g., for a multi-lane highway, light from high pressure sodium bulbs may be more suitable than LED bulbs). The

		height of lighting poles also needs to be addressed to ensure provision of adequate levels of dispersion.
	Smart systems	For retrofit of existing lighting, consider extent of existing infrastructure to be upgraded if changing to a Smart System. For installation of LED lighting on new schemes, Smart Systems are an option to provide added flexibility which may lead to reduced ongoing operating costs and carbon savings.
	Dimmability	In the absence of Smart Systems, many modern LEDs are supplied with programmable dimming facilities (at little or no extra cost). A system with automatic sensors to change the light intensity to suit local conditions would have advantages in countries and areas where the number of daylight hours varies significantly through the year.
Economic	Finance	The sources of finance and/or grants to provide upfront capital cost (investment cost to install system) and ongoing maintenance/operational costs are important considerations.
	Payback	Economically sound business case, including evaluation of the period to obtain return on the investment are crucial. Some schemes can offer stronger value for money when the technological and other factors outlined are considered.
	Maintenance	Long maintenance contracts can be beneficial in maintaining efficiency and energy/carbon savings.
Location	Standalone systems	Evidence has shown that stand alone systems can be hugely beneficial when considering lighting systems in remote areas, and in some developing urban areas.
	Solar/Wind powered	Consider if this would be a preferential alternative to grid power in remote areas. In countries where solar gain is abundant, solar lighting solutions can provide drivers with a greater sense of security at night, and improvement in safety for all road users. Availability of sufficient wind or sunlight would need to be

		confirmed/checked. Solar would be most advantageous in areas that get sufficient consistent sunlight, with at least 10 hours of light per day in summer and winter, with latitudes between 0° and 33°N / 33°S from the equator[302] (e.g., areas of Singapore, Kenya, Ecuador, Columbia, Indonesia, Nigeria, Australia, India)
Environmental	Carbon savings	The potential carbon saving from switching to LEDs can vary widely depending on various factors. The source of power has the greatest impact. In a country/region where the power is largely renewable, the carbon savings from switching to LEDs would be negligible compared to a grid where the power is generated using fossil fuels. Other factors to be considered are the type of lights being replaced and the specifications of the LEDs required for the specific road scheme.
	Recyclability	HPS and mercury bulbs contain hazardous materials. Appropriate methods of recycling must be adhered to, adding an additional cost to replacement strategies.
	Biological impacts	LEDs have greater lower-wavelength blue emissions that potentially have increased likelihood of negative biological impacts (e.g., suppression of melatonin production which is crucial for many organisms)[303].
Other	Political factors	In some cases, LED lighting is not viewed favourably by the public[304]. This may influence policy decisions.
	Skillset	Skills required to operate systems must be acknowledged during and accounted for in the contract to maintain long term savings from smart systems.

[302] Daylight hours by latitude - EverybodyWiki Bios & Wiki
[303] Highways Magazine, October 2022, A LED Paradox (Highways Magazine (pagesuite-professional.co.uk)).
[304] Led Lights Save Millions, but People Hate Them | Digital Trends

9 ROAD CONSTRUCTION

Part B of this report summarises a range of technical solutions available to road administrations to reduce carbon emissions. This deep dive outlines the importance of assessing specific sources of carbon emissions and explores some areas of road construction in more detail, investigating the factors (costs, risks, etc.) that road administrations should consider in deciding whether these solutions are practical and appropriate in their own jurisdictions.

9.1 BASELINE LEVELS AND ONGOING STRATEGIES FOR CARBON REDUCTION

It is essential that roads authorities identify current sources of carbon emissions to understand where to prioritise reductions. For example, National Highways' (UK) Net Zero Plan[305] quantifies the sources of carbon emissions from maintenance and construction, as shown in Figure 23, which summed to a total of 734,000 tCO_2e in 2020. This information underpins the development of their strategy, which focusses on catalysing the decarbonisation of the asphalt, cement and steel sectors, as well as adopting lean construction practices and principles of circular economy.

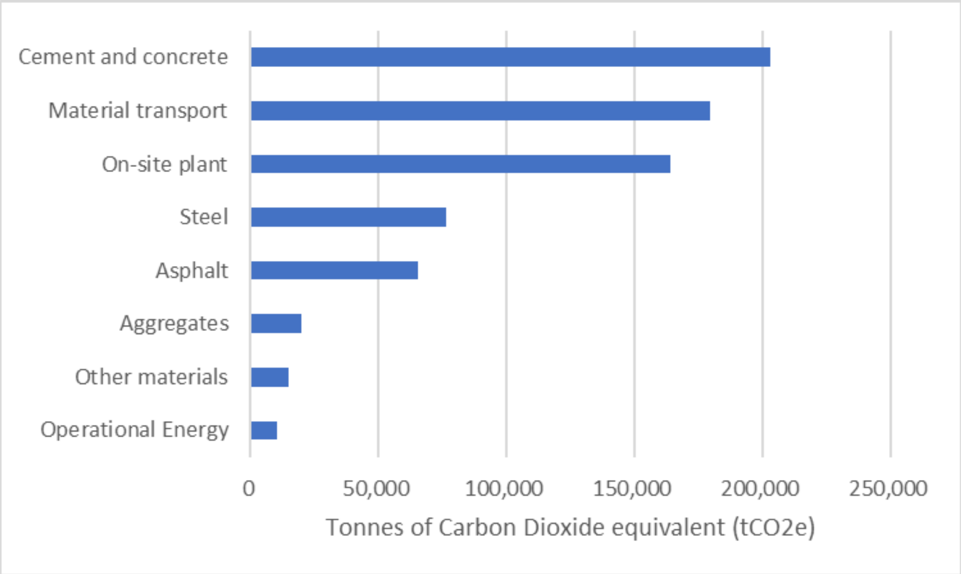

Figure 23. National Highways – sources of carbon emissions from construction and maintenance in 2020 (reproduced from [305])

Similarly, a GHG emissions inventory published by the US National Asphalt Pavement Association (NAPA)[306] points to opportunities to reduce the cradle-to-gate emissions by up to 24% relative to 2019 figures by adoption of measures including:

- Increased use of recycled materials
- Increased use of natural gas as a burner fuel
- Reduction of aggregate moisture content to reduce burner fuel consumption

[305] https://nationalhighways.co.uk/netzerohighways/

[306] GHG emissions inventory for asphalt mix production in the United States. Current industry practices and opportunities to reduce further emissions. National Asphalt Pavement Association Information SIP 106 (2022)

- Reduction of mix production temperatures through warm-mix technologies
- Reduced electricity consumption through energy efficiency measures

Compiling emissions figures requires data from road administrations' supply chain. Feedback from the interviews during this project suggests industry is not always adequately prepared to provide the data needed. In some cases, actions are being taken to engage with the supply chain and build stronger requirements into contract specifications with the aim of acquiring data as well as achieving carbon reductions. Some parts of industry are also being proactive and entering into voluntary arrangements. For example, NAPA outlines information that asphalt producers should incorporate into tender bids for projects to earn points or credits under all major green construction programmes in the USA. Under the Leadership in Energy and Environmental Design (LEED) scheme, this includes developing Environmental Product Declarations (EPDs) (described below) to document reduced impacts attributed to improved mix designs, disclose information regarding the raw materials used or use of RAP, etc.[307].

In tender evaluations, the use of EPDs should simplify the assessment of carbon emissions, as well as other sustainability impacts. The EPD presents information from a standardised lifecycle assessment in a simplified way, enabling a comparison to be made between products of the same type. The production of EPDs is described by ISO 14025[308] and ISO 21930[309]. However, there are several challenges for obtaining robust EPDs, which road administrations should be aware of and take appropriate steps to control[310]:

- Products can only be compared on a meaningful basis if the calculation methodology is consistent. This is defined by Product Category Rules (PCR) which are established for each product. However, not all products already have PCRs defined and global standardisation of PCRs is a challenge.
- Use of generic, rather than site-specific data in the calculations can lead to inaccurate declarations
- A detailed, third-party, critical review is beneficial to ensure the validity of the results presented as well as consistency in the way PCRs are implemented
- The cost of producing detailed LCA and EPD are not trivial and may be a particular burden for small scale companies and industries

The Federal Highway Administration in the USA has recently announced a two-year initiative in which technical assistance and staff training will be provided to facilitate the completion of lifecycle assessment and EPDs for 35 projects by 27 agencies[311].

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[307] NAPA (2018) Sustainability in Practice: Asphalt pavements and LEED v4: credits and opportunities. https://www.asphaltpavement.org/expertise/sustainability/sustainability-resources/leed-and-other-green-rating-systems

[308] ISO 104025:2006 Environmental labels and declarations – Type III environmental declarations – Principles and procedures

[309] 309 ISO 21930:2017 Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services

[310] https://en.wikipedia.org/wiki/Environmental_Product_Declaration

[311] 311 FHWA (2022) FHWA climate challenge – quantifying emissions of sustainable pavements https://www.fhwa.dot.gov/infrastructure/climatechallenge/projects/index.cfm

9.2 Optimised design

Transport Infrastructure Ireland (TII) are re-evaluating the way in which road pavements are designed, which will allow for greater efficiency in resource use and facilitate innovation in the use of different materials[312]. This will improve on the empirical pavement design models currently in use, which reference design curves that relate applied loading to the required pavement depth, but do not take account of the physical properties of the materials used or the environment in which they are to be constructed.

A new model, the Irish Analytic Pavement Design Model (IAPDM) enables these factors to be considered. It evaluates specific material properties for pavement design, thereby releasing the constraints on using alternative materials, and allowing options to reduce, reuse or repurpose materials to be considered. It also allows designs to be adjusted to take account of field evidence of local materials which may perform to a higher level than is assumed in the current empirical design guidance. This thinking is central to circular economy principles of obtaining the maximum value from material resources.

In operation, the tool collates data on site conditions and assesses how each layer of the pavement structure influences other layers and the pavement as a whole. Outputs are expressed as tonnes of materials saved, tonnes of carbon saved and cost savings. In a case study, the IAPDM was applied to a 4 km segment of road where the capping layer had been completed at the top of the foundation. Falling weight deflectometer readings showed significant variation in deflection response along the scheme length (Figure 24). The IAPDM allows engineers to design for additional strength to improve on lower layers where this is needed, and to save on these materials where sufficient strength can be verified.

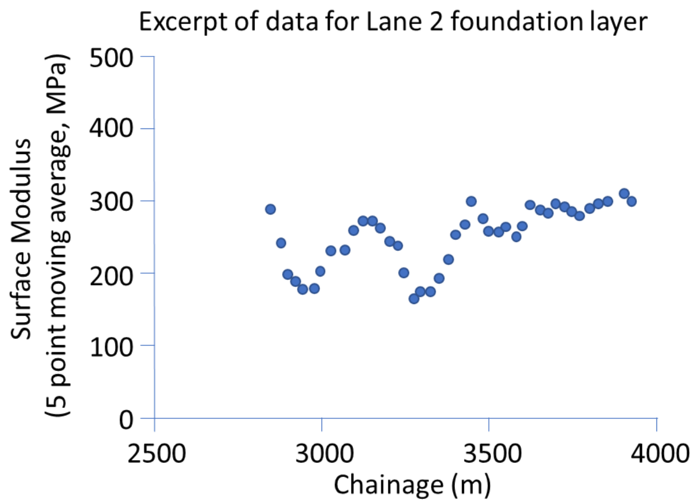

Figure 24. Structural condition achieved for case study project (reproduced from[312])

The optimised design allowed for an average saving of 30 mm in constructed depth compared with the empirical design model. On a 11 km scheme with a 14 m wide

[312] https://www.youtube.com/watch?v=y5eOAbx-LVE

carriageway this translated to a saving of over 11,000 tonnes of material, €834,000 in cost and 600,000 kgCO_2. The analysis did not consider the additional savings in cost and carbon that would occur due to the reduced transport of materials.

The ambition is to continue to develop the IAPDM, gaining confidence in acquired results, with the aim to progress to a full mechanistic analysis of all pavement layers. It will be used within an overall framework for circular economy that considers the lifecycle financial value, lifecycle environmental value and societal value delivered by a planned scheme.

9.3 USE OF LOW CARBON CONCRETE

A key choice for construction of new road pavements is that of asphalt or concrete construction. Historically, concrete pavements have been associated with a high carbon cost for construction associated with the production of cement. Feedback during the interviews with various roads authorities indicated that to achieve the long lifetimes that are possible with a concrete pavement, a high-quality installation is critical. If this is not achieved, the result can instead be premature maintenance that is expensive both in terms of financial and carbon cost.

The Global Cement and Concrete Association (GCCA) recently published a Net Zero Road map for 2050 and a report on progress one year on[313]. The Association's member companies operate worldwide and their affiliated organisations include a high proportion of LMICs. The road map targets a 20% reduction of CO_2 per tonne of cement produced and a 25% reduction in CO_2 per m^3 of concrete used by 2030, compared with a 2020 baseline. A Net Zero target is set for 2050. These targets are in the context of a background of increasing demand and are expected to be achieved through the following measures:

- Efficiencies in design and construction (22%), i.e., optimised structural design, construction site efficiencies and re-use / lifetime extension
- Efficiency in concrete production (11%), i.e., optimised mix design and improvements to the manufacturing process and quality control
- Savings in cement and binders (9%), from substitution of Portland cement with alternatives
- Savings in clinker production (11%), from thermal efficiency and use of alternative fuels
- Carbon capture and utilisation or storage, CCUS (36%), with a goal of 10 fully operational CCUS plants by 2030. Significant activity is reported, with over 35 pilot projects exploring a range of different technologies across the world. (In the UK, the current cost of carbon capture and storage is reported to be in the range US$50-70/t$CO_2$ for a cement kiln, which would increase cement production costs by about 30-60%[314].)
- Decarbonisation of electricity at cement plants and in concrete production (5%)
- CO_2 sink (6%) through the natural process of recarbonation (atmospheric CO_2 taken up by the surface of concrete particles)

[313] https://gccassociation.org/wp-content/uploads/2022/10/7286_GCCA_RoadmapOneYearOn_Artwork_Screen_v3_lr.pdf
[314] https://www.ice.org.uk/media/q12jkljj/low-car303bon-concrete-routemap.pdf

The most recent data, from 2020, shows a 22% reduction in net CO_2 emissions per tonne of cementitious material produced, compared with a 1990 baseline. The progress report describes 25 carbon reducing projects that are provided by GCCA members. They represent diverse technical approaches and appear promising at a pilot scale. However, little usable data is provided to judge their progress or potential for scale up.

The Low Carbon Concrete Group of the Institute of Civil Engineers (UK) has recommended a labelling scheme so that 'low carbon concrete' can be identified for each strength class[314]. Data from more than 600 recent UK mixes were collated and compared with data from four large producers to derive rating bands representative of the embodied carbon per m^3 for lifecycle stages A1-A3 (cradle to batching plant for ready mix concrete, or cradle to mould for precast concrete). Taking C35/40 concrete as an example, interpolating the presented curves suggests approximate benchmark ratings shown in Table 10.

Table 10. Estimated ranges for C32/40 concrete (reproduced from [314])

Embodied carbon (kg CO_2 / m^3)	Rating	Corresponds to (percentile of benchmarked concretes in this strength class)
0-77	A++	Lower than benchmarked concretes
77-137	A+	0-5%
137-190	A	5-20%
190-230	B	20-40%
230-263	C	40-60%
263-303	D	60-80%
303-356	E	80-95%
356-416	F	90-100%
>416	G	Higher than benchmarked concretes

Loijos makes a comprehensive assessment of the carbon emissions for the full lifecycle of a concrete pavement, for 12 typical pavement structures in the US[315]. The necessity to consider all stages of the lifecycle is highlighted to get an accurate perspective, whereas many studies published in the literature omit one or more stages. In this study, the author examines a 40-year lifecycle analysis that includes construction, rehabilitation carried out

[315] Loijos A (2011) Life cycle assessment of concrete pavements: impacts and opportunities. Massachusetts Institute of Technology. https://dspace.mit.edu/handle/1721.1/65431

at year 20 and 30, and disposal and recycling at year 40. The following elements are quantified:

- Materials extraction and production (cement production, aggregate crushing, mix water processing, steel reinforcement production, fly ash production)
- Pavement construction (concrete mixing, onsite equipment operation)
- Pavement rehabilitation (diamond grinding, slab replacement)
- Use (albedo, carbonation, fuel consumed due to roughness, lane closure, lighting)
- End of life recycling and disposal (steel recycling, pavement demolition, jaw crushing for recycling concrete, landfilling)

Since the results may be influenced significantly by the type of pavement structure, Loijos analysed the designs for 12 representative pavement structures, which were determined from the typical traffic flow, road width, and required level of performance for different road types. Table shows the calculated lifecycle carbon emissions per km of new concrete pavement, which suggests there is an order of magnitude difference between the carbon intensity of the most and least demanding applications. (For this reason, to assess the efficiency of resource use, indicators should consider the intensity of use that is supported by the resources committed to each application, e.g. the traffic carried during a pavement's lifetime.)

Table 11. Lifecycle GHG emissions per km of new concrete pavement (using data from[315])

Rural road types	t CO_2e*	Urban road types	t CO_2e*
Interstates	3,690	Interstates	6,190
Other principal arterials	1,280	Other freeways / expressways	3,980
Minor arterials	1,140	Other principal arterials	2,360
Major collectors	730	Minor arterials	1,290
Minor collectors	510	Collectors	940
Local roads	320	Local roads	520

**From data given in Appendix 4 of the reference cited*

The contributions to totals above are given in Figure 25. In the figure, the carbonation contribution is shown as negative (this refers to the effect of atmospheric carbon dioxide becoming bound to the concrete surface and is affected by maintenance strategies and how the concrete is disposed of at the end of life). The single largest contribution, for all road types, is from cement production, which ranges from 51% of the total emissions on urban interstates to 85% on rural local roads. The results are most sensitive to variation in the width and depth of the concrete pavement, and by the carbonation rate and % cement used in the mix.

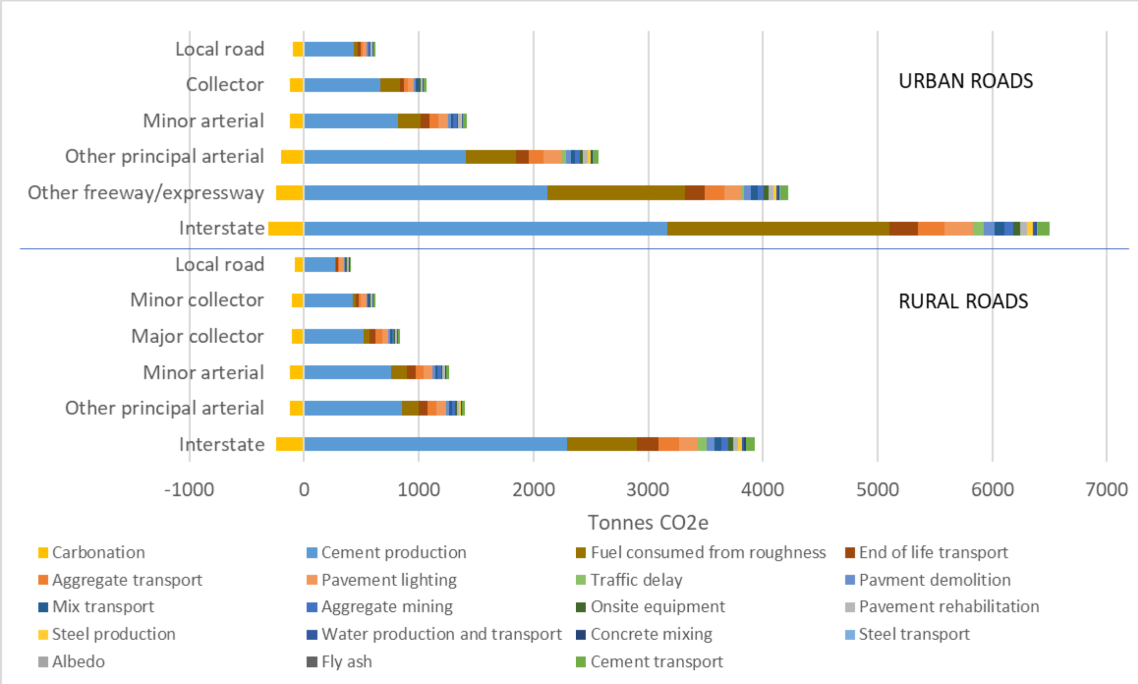

Figure 25. Lifecycle CO_2e per 1 km, by road type and component (using data provided in[315])

The impact of four carbon reduction strategies were examined:

- Reducing cement content by substitution with up to 30% fly ash. This is also believed to increase the rate of carbonation. Other strategies for reducing cement content were noted but not analysed. Furthermore, potential effects on the durability of the pavement were not considered.
- Whitening the pavement though selection of the aggregate and sand to reduce albedo. This provides benefits by increasing the reflection of sunlight back out of the Earth's atmosphere and by reducing the requirement for pavement lighting.
- Increasing carbonation through end-of-life management. If concrete is crushed at the end of life, the surface area available for carbonation increases. .
- Reducing fuel consumption due to pavement roughness. The model includes an additional rehabilitation at year 10 to improve the surface characteristics, with additional depth of pavement at construction to allow for this grinding.
- A combination of these strategies seems to offer the potential to reduce lifecycle carbon emissions by well over 50%. The most effective strategy was dependent on the road type: on interstates, the end-of-life carbonation was found to be the most effective strategy whereas fly ash substitution was found to be slightly more beneficial on roads with less than 20,000 vehicles/day. Although carbonation was reported in this paper to be the most effective strategy, the benefit will not start to be felt until many years in the future, which does not reflect the pressing need for reduction.

On rural local roads, reducing albedo is effective, since the structure is relatively thin, i.e. with a high surface area to achieve the beneficial effects, for its volume. However, additional transport distances to obtain white materials need to be factored into this benefit, and this is affected by the carbon intensity of the transport mode used. For additional pavement rehabilitation to reduce roughness, the benefits are greatest on roads carrying high traffic, with an AADT of approximately 2,500 calculated as the point at which the carbon saved outweighs the carbon cost of the additional treatment and slightly deeper construction.

9.4 USE OF RECLAIMED ASPHALT

Reuse of reclaimed asphalt has both financial and sustainability benefits. The National Asphalt Pavement Association (NAPA) in the US report a growing number of States using greater proportions of reclaimed asphalt pavement (RAP) in hot mix and warm mix asphalt pavements[316]. Asphalt mixtures containing recycled materials should meet the same requirements as mixtures with all virgin materials and perform as well or better. NAPA cite a study analysing Long-Term Pavement Performance data from 16 US states and two Canadian provinces which show that overlays with at least 30 % RAP performed equally to overlays using virgin mixtures. Similarly, test sections containing 50% RAP on a test track outperformed comparative test sections with all virgin materials, in all performance measures.

Figure 26 plots a subset of NAPA data that estimates the proportion of RAP, on average, in HMA / WMA. By 2020, it was estimated that at least 20% RAP was used, on average, in more than half of the States where data were obtained.

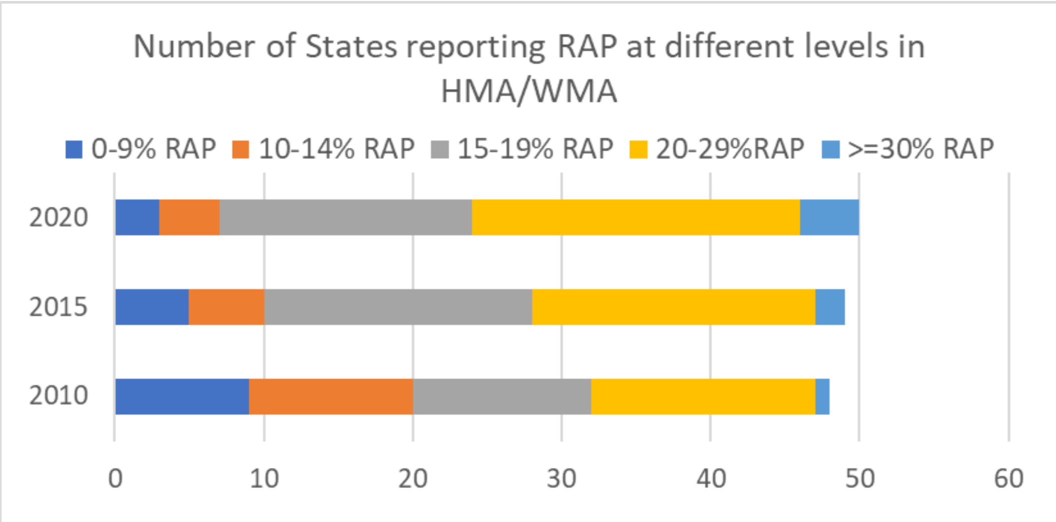

Figure 26. Number of States with Estimated RAP% in the ranges shown (reproduced from316)

NAPA estimated the GHG emissions reduction from the use of RAP, based on a national total of 87.0 million tons of RAP:

- 2.51 million tonnes CO_2e through the avoidance of virgin binder, equivalent to the 5% binder present in RAP
- 0.35 million tonnes CO_2e through the avoidance of virgin aggregate, equivalent to the 95% binder aggregate present in RAP
- 0.45 million tonnes CO_2e through the avoidance of transport, assuming average haulage distances and emissions factors for transportation via medium and heavy-duty trucks

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[316] Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage 2020. National Asphalt Pavement Association Information Series 138, www.asphaltpavement.org

- Emissions from the transport and processing of RAP were ignored as being associated with the end-of-life phase of the previous pavement
- 0.11 tonnes CO_2e additional associated with processing of RAP
- 0.88 tonnes CO_2e additional associated with transport of RAP over a 50-mile haul distance to the asphalt plant
- Emissions from the use of softer binders and recycling agents were ignored owing to a lack of data (which means that the full impacts were not quantified)

The total corresponds to a 2.32 million tonnes CO_2e avoided, for 87.0 million tons RAP utilised in asphalt mixtures, i.e. 27.1 kt CO_2e / t RAP. The corresponding cost savings were estimated as $2.955 bn in total, i.e. $34.5 M / t RAP, for savings in aggregate and binder. Further additional cost savings of $58.6 / t RAP were estimated from the avoidance of landfill fees.

While the use of RAP can produce high performing asphalt, with reduced carbon emissions, NAPA points to the need for good practice to produce high quality results[317]:

- Managing the reclaiming process to avoid contamination with dirt or other construction materials
- Managing RAP stockpiles to avoid segregation, average out variations in the materials received, avoid compaction of the stockpiles and minimise moisture content
- Control of processing to obtain a uniform material that matches the need for the mix design, while avoiding the production of excessive fines
- Using appropriate methods of sampling to accurately characterise the stockpile for testing
- Carrying out testing to determine the asphalt binder content, gradation of the aggregate, bulk specific gravity and aggregate properties
- Implementing various measures in mix production needed to accommodate RAP

Their guidance also covers management of recycled asphalt shingles and further advice is produced on mix design guidelines for mixtures incorporating RAP[318].

9.5 CASE STUDIES ON RECYCLED ASPHALT

In a 2010 case study of a 4.7 km section of State Highway in Wisconsin, USA, a lifecycle analysis compared a conventional pavement design with an alternative design incorporating recycled materials[319]. The alternative design used 305 mm recycled pavement material stabilized with fly ash as base course on top of a sub-base of 760 mm foundry sand. These layers replaced equivalent thicknesses of conventional crushed aggregate and subbase, respectively. Both designs were topped with 160 mm hot mix asphalt (HMA).

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[317] Best practices for RAP and RAS Management. National Asphalt Pavement Association Quality Improvement Series 129 www.asphaltpavement.org

[318] Designing HMA mixtures with high RAP content. National Asphalt Pavement Association Quality Improvement Series 124 www.asphaltpavement.org

[319] Lee, Jin & Edil, Tuncer & Tinjum, James & Benson, Craig. (2010). Quantitative Assessment of Environmental and Economic Benefits of Recycled Materials in Highway Construction. Transportation Research Record: Journal of the Transportation Research Board. 2158. 138-142. 10.3141/2158-17

The lifecycle analysis modelled the deterioration of IRI (International Roughness Index), with a predicted design life of 29 years for the conventional materials and 32 years for the recycled material, owing to its expected superior properties. With a 50-year analysis period, this resulted in one rehabilitation of the pavement in both cases.

The authors' analysis of material production, transportation and construction is shown in Table 12. In both cases, the HMA component is reported to be the dominant contributor to all four of the environmental indicators, so the overall benefit of using recycled materials is modest. Nevertheless, the analysis predicts an overall 20% reduction in CO_2e, most of which occurs from reduced emissions during material production. Substantial energy savings are also predicted, although the study does not provide carbon reductions associated with the reduction in energy requirements.

Table 12. LCA predictions using conventional and recycled materials (reproduced from [319])

	Conventional materials			Recycled materials			Change
	Material production	Transportation	Construction	Material Production	Transportation	Construction	(%)
CO2 (Mg*)	3,630	323	111	3,028	163	54	-20
Energy (GJ*)	66,680	4,318	1,476	58,023	2,187	723	-16
RCRA hazardous waste (Mg*)	629	31	9	611	16	4	-6
Water (L)	17,185	735	144	15,637	372	70	-11

*GJ = gigajoules ; Mg = megagrams (i.e. tonnes)

From a cost perspective, a 21% saving is predicted in both Agency cost and user cost (

Table 13), which includes the avoidance of landfill tipping fees of $40/Mg.

Table 13. Lifecycle costs for pavement designs using conventional and recycled materials (reproduced from [319])

Category	Reference	Alternative	Saving
Agency costs ($)	9,044,570	7,107,230	1,937,340 (21%)
User cost ($)	10,570	8,380	2,190 (21%)
Total cost ($)	9,055,140	7,115,610	1,939,530 (21%)

Qiao et al.[320] cite several other studies that predict cost savings as a result of using recycled asphalt pavements (RAP), including when the progression of rutting and cracking is considered in addition to roughness. Their study goes further, considering the implications of local weather conditions and future climate trends up to 2040.

The study focusses on financial cost to the road administration. Carbon savings are not considered explicitly. However, many of the savings in cost are likely to be associated with savings in carbon, as seen from the above studies, and this methodology could be adapted to quantify carbon benefits.

A 22 km length of the I-95 interstate highway in New Hampshire, USA, was selected as a case study. It has an annual average daily traffic flow of 88,000, with 10% heavy vehicles. Dynamic modulus testing from similar structures was carried out to establish the properties of HMA containing 40% RAP and HMA using virgin aggregate, over a range of temperatures. These data were used to improve the prediction of future pavement performance, depending on the temperature regime it is exposed to. Climate models were used to predict future, local trends in temperature and rainfall under a moderate scenario of global warming. For the study location, these models predicted a reduction in extreme cold conditions, increase in extreme hot condition and increase in rainfall in future years.

The 20-year lifecycle analysis modelled roughness, rutting, thermal cracking and fatigue cracking, with appropriate maintenance interventions when triggered by pre-set thresholds. All lifecycle stages were modelled: material production, transport, construction, maintenance, use (i.e. road user costs) and salvage. The following maintenance scenarios were predicted for a standard structure (150 mm asphalt concrete over 710 mm granular base and 200 mm sub-base) for the two different materials:

- For the virgin HMA, an overlay was triggered in year 6 and year 15 as a result of rutting
- For the HMA with 40% RAP, local crack sealing was triggered in year 3 as a result of thermal cracking, and an overlay was triggered in year 8 as a result of rutting

[320] Qiao Y, Dave E, Parry T, Valle O, Mi L. Ni G, Yuan Z and Zhu Y Life cycle cost analysis of reclaimed asphalt pavement (RAP) under future climate. Sustainability 2019, 11, 5414, doi:10.3390/su11195414

The difference between the maintenance scenarios results from the higher stiffness of the HMA with 40% RA, which accelerates the development of thermal cracks but reduces the progression of rutting. This translates to a significant reduction of lifecycle cost for the maintenance phase, compared with HMA with virgin materials (Figure 27), despite the additional treatment for thermal cracking. Reductions are also observed for the construction and transportation stages. Collectively these three stages make up the majority of costs to the road administration, which are predicted to be 18% lower for HMA with 40% RAP than for the virgin materials. However, when the use phase is considered, this translates to a modest 2% reduction since, for both material types, the overall cost is dominated by road user fuel consumption.

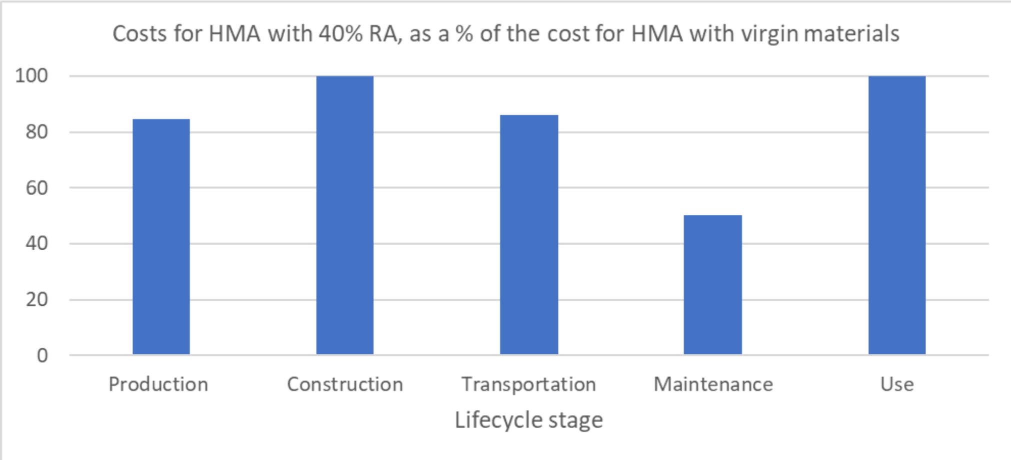

Figure 27. Relative lifecycle cost for HMA with 40% RA, compared with virgin material (reproduced from[320])

Similar findings were observed from the other, stronger pavement structures considered: in all cases the drivers for maintenance were predicted to be rutting (for the virgin HMA) and thermal cracking (for the HMA incorporating 40% RAP). In both cases, the stronger structures were predicted to be more resistant to deterioration. This reduces the difference in the cost to the road administration between the two materials and also results in an overall cost saving because the higher construction costs are more than offset by the saving in maintenance costs from the stronger structures.

9.6 USE OF OTHER SECONDARY MATERIALS IN ROAD CONSTRUCTION

A quarter of the companies responding to the NAPA survey in 2020[316] reported use of additional recycled materials in asphalt mixtures. The data are summarized in Table 14.

Table 14. Summary of the use of additional recycled materials, reported to NAPA for 2020 (reproduced from [316])

	Asphalt mixture reported to be produced with this material (tons)	Quantity of material reported to be used (tons)	Number of States in which this material is reported	Reference
Recycled Tyre Rubber	1,343,406	19,025 10	10	Table 19
Steel Slag	3,850,456	643,484	10	Table 20
Blast Furnace Slag	121,241	666,873	6	Table 20
Recycled Fibres	2,249,354	8,748	22	Table 21
Coal Combustion Products	435,492	13,883	7	Table 22
Other recycled materials*	81,000	6,005	4	Table 23

*Comprising, in 2020: blasting sand, marble production dust, plant start-up waste and recycled polyethylene; crushed concrete aggregates were also reported in previous years.

Liu et al.[321] reviewed the potential for reducing carbon emissions, stated in literature, as summarised below.

[321] Liu N, Wang Y, Bai Q, Liu Y, Wang P, Xue S, Yu Q and Li Q. Road life-cycle carbon dioxide emissions and emission reduction technologies: a review. J. Traffic and Transportation Eng. (2022); 9 (4) p532-555

Table 15. Summary of the potential for carbon reduction from use of recycled materials (from Liu et al.)

Recycled material	Location	Key finding
RAP	USA	Reduction up to 12.4% with increased RAP content in asphalt binder
	Italy	Reduction of 6.8% for RAP with HMA
	Italy	Reduction of 48.3% with RAP and lime stabilization for an embankment; 21.2% for RAP only or 11.0% for lime stabilization only
Crumb rubber	USA	Carbon emissions of asphalt rubber are higher than HMA but lower than Portland cement mixtures
	China	Reduction of 17.1% compared with styrene-butadiene-styrene modified asphalt
	Italy	Reduction of 36-44% for asphalt with 18% crumb rubber using wet technology, compared to standard mixture
Industry wastes & by products	USA	Reduction of 29.6% from partial substitution of Portland cement with fly ash
	India	Limestone and brick dust < stone dust mixes < glass powder and concrete dust
Steel	Sweden	Reduction of 5%-27% from use of recycled steel

A comprehensive review of the use of tyre rubber in asphalt pavements is provided by Presti[322]. Different production processes are possible; some are relatively complex and require specialist plant with high set-up costs. However, extensive development has taken place and asphalt incorporating tyre rubber has been widely used, including in the USA (Arizona, California, Texas and Florida), South Africa, Australia and Europe, with investment reported in Taiwan, China, Brazil and Sudan. The benefits can include improved durability, resistance to cracking and reduced temperature susceptibility. One lifecycle study reported by Presti shows a 46% reduction in maintenance costs and a 33% reduction in user costs compared with conventional asphalt, over a 25-year life. However, Presti notes other studies that suggest they are not cost effective in all situations. Furthermore, there is extensive evidence of the performance level of asphalt produced by well-established

[322] Presti D Recycled tyre rubber modified bitumen for road asphalt mixtures: a literature review. Construction and building materials **49** (2013) p 863-881

methods, whereas this is not the case for newer methods. There are some concerns over the use of tyre rubber in asphalt pavements. Production of fumes has been cited as an issue, although this is significantly reduced by adoption of warm mix methods. The recyclability of the rubberized asphalt at the end of life also needs to be considered, although there are examples where this has been achieved successfully.

9.7 CONSIDERATIONS FOR ROADS AUTHORITIES

Transparency of performance is essential for effective decision making. By baselining existing carbon emissions and identifying the major sources of emissions, an appropriate reduction strategy can be developed.

For a robust approach to assessing options, the scenarios evaluated should take account of local conditions (e.g. for transport distances and the efficiency of local plant). All phases of the lifecycle should be evaluated (many published studies omit one or more stages); a competent analysis will declare the stages considered in relation to established standards for lifecycle analysis. The system boundaries should also be studied carefully, in case an apparent reduction in emissions in one area results in displacing the burden to a different part of the process. This has been found to be key across all strategies for carbon neutrality. The analysis requires estimation and, as such, sensitivity analysis is essential to identify critical influences and the assess the uncertainties associated with them.

Existing design strategies can be challenged to allow for greater resource efficiency. This can take account of site conditions, properties of locally available materials, site-specific traffic, etc., as well as the predicted environmental conditions considering climate projections over the life of the pavement.

Engagement with industry stakeholders early in the project development stage can allow ways to reduce carbon to be investigated, and drive motivation for further innovation. Numerous different approaches to carbon reduction are being employed. In some cases, e.g. use of reclaimed asphalt or cold-mix or warm-mix asphalt in place of hot-mix, the technical and financial cases have already been established. In other cases, or to achieve greater reductions, further innovation will be needed and here road authorities have an important role in establishing pilot projects and sharing lessons learned.

Irrespective of the design option selected, requiring suppliers to produce information on the carbon (and other) impacts will drive a focus on reduction. Environmental product declarations, rating systems or other standardised approaches should be adopted to provide a consistent means to rank proposals.

PART D – Conclusions and Recommendations

10 GAP ANALYSIS

The number of examples reported relating to different strategies adopted by NRAs are shown in Figure 28. The largest segment is for low carbon design and construction, partly reflecting the deeper analysis of road construction in Part C of this report. This topic includes sources on the use of recycled asphalt, use of other secondary materials, warm mix asphalt and reducing the carbon intensity of concrete through the use of alternative cement binders. For this topic, as well as for road maintenance and life extension, the quality of the evidence on the degree of carbon reduction is relatively high, with around 40% of sources rated as providing reliable, quantitative information.

The second largest segment is for influencing choices of road users, with 16 examples, split between transfer to active travel and public transport. 15 examples were identified of operations on the road network, primarily the opportunities for LED lighting, and 13 for decarbonising vehicles and fuels.

A smaller number of examples was found for low carbon options for construction plant, procurement and carbon offsetting, reflecting the early stages of development for strategies in these areas. Only three examples were identified of the carbon impacts of road maintenance and life extension, probably reflecting that there is insufficient awareness of the carbon impact of traditional asset management decisions.

For topic areas other than low carbon design and construction, and road maintenance and life extension, the percentage of sources rated as providing reliable, quantitative information was lower, always below 20% and, on average only 10%. As it stands, this makes it difficult for road authorities to assess the best strategies to achieve their goals. Furthermore, it should be noted that, even where they are quantified, the benefits achieved in one situation may not match those achieved elsewhere, with different circumstances (so it will be important for road authorities to either conduct their own analyses or assess the parallels of any study with their own situation).

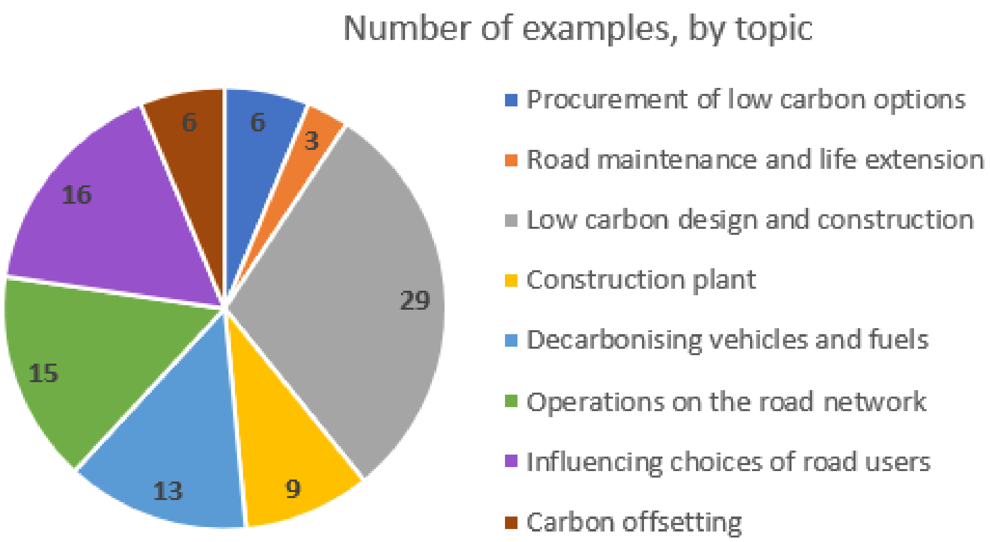

Figure 28. Summary of the strategies reviewed

The strategies reviewed were classified depending on how far they have progressed to full implementation, and this is summarised by topic in Figure 29. Extent to which the strategies reviewed have been adopted. For decarbonisation of vehicles and fuels, the examples show that they have largely progressed beyond ambition, to trial and progressive rollout. This is also the case for operations on the road network (dominated by LED lighting), whereas the examples for influencing road users are less well advanced, mainly at the level of research and ambition.

Surprisingly, for low carbon design and construction, for which the quality of evidence is high, few sources provided data relating to extensive rollout; the quantification of carbon benefits seems largely to remain at a research or theoretical stage. This was also the case for road maintenance and life extension. This suggests that better quantification of the carbon impacts of construction and maintenance is needed, as a matter of routine, to allow these assessments to be made.

There are examples of low carbon construction plant progressing to limited rollout, but this has yet to progress into widespread use. Initiatives in procurement, by their nature, are unlikely to involve a research stage. Finally, for carbon offsetting, there are several initiatives underway but the quality of evidence of outcomes achieved from these schemes was particularly low, with none of the sources rated as providing reliable, quantified evidence of the carbon benefits.

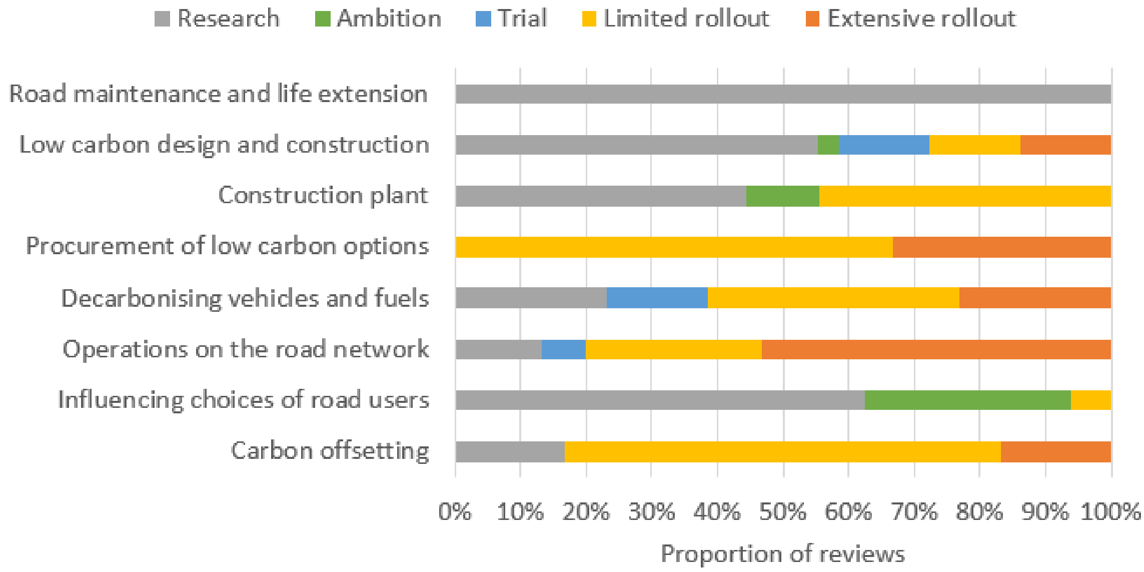

Figure 29. Extent to which the strategies reviewed have been adopted

A breakdown of the origin of the examples reviewed is given in

Table 16, for geographical region and in Table 17 for the country type. The responses are dominated by Europe and Central Asia, specifically by the European Union and United Kingdom, followed by East Asia and Pacific, which includes a broad range of countries: Australia, China, Hong Kong, Indonesia, Japan, Republic of Korea and Vietnam. 30% of examples are from LMIC countries.

Table 16. Number of examples by region

Region	Number of examples
East Asia and Pacific	10
Europe and Central Asia	33
Latin America and the Caribbean	2
Middle East and North Africa	2
North America	18
South Asia	2
Sub-Saharan Africa	5
Not stated / various	25
Total	97

Table 17. Number of examples by country type

LMIC?	Number of examples
Yes	16
No	56
Not stated / various	25
Total	97

11 SUMMARY OF TECHNICAL SOLUTIONS AND POTENTIAL CARBON SAVINGS

It is very difficult, if not impossible to determine the potential carbon savings that could be made globally, as the situation of each NRA and options available will be different, for example, budget, ambition, technical capability, not to mention areas beyond the remit of NRAs, such as wider governmental targets on achieving net zero and the mix of fuels used to power the electricity grid (for the powering of electric vehicles and/or production of green hydrogen).

Nonetheless, a summary of technical solutions identified and estimates of the levels of savings by adopting various options is presented below.

11.1 Construction and Maintenance of Road Infrastructure

Need for road construction

A pause and review approach such as that set out by the Welsh Government can allow different priorities to be established for road investment, with greater emphasis on reduction of carbon emissions, and shift to active travel and public transport.

Road maintenance and life extension

A pavement that is well maintained, smooth and in good condition will also lead to lower emissions from vehicles using the road. Regular maintenance and life extension of road infrastructure can form part of CO_2 saving strategies.

- Road maintenance practices and policies vary throughout the world, so it is difficult to determine the global CO_2 savings from more efficient road maintenance or life extension. To make a crude approximation, given the length of paved roads worldwide is approximately 12.7 million km and an assumption that 10% of roads are maintained annually, extrapolating figures presented in Section 3.2 indicates a potential saving of between 25-28 $MtCO_2$ annually from choosing maintenance practices such as chip seal and crack seal over thin overlay. These figures are purely indicative in the absence of full Life Cycle Analysis but give a very tentative estimation of the scale of saving that could potentially be achieved from using less carbon intensive methods.

Low carbon construction

- Advances are being made in carbon neutral construction and operation practices, as follows:
- The A590 project in the UK demonstrated how significant carbon reduction can be achieved across three main areas of carriageway construction; materials reduction and reuse, energy reduction and transportation efficiencies
- Early consultant and early contractor engagement is critical
- Various case studies highlighted the importance of both optimising the design life and setting targets for environmental performance early in the project
- Structural Health Monitoring can be used to determine the condition of bridges reaching the end of their design life, potentially avoiding unnecessary repair/replacement and associated CO_2 emissions

- The production of cement is very carbon intensive, with 0.59 tCO_2 generated for each tonne of cement produced in 2021. The International Energy Agency (IAE) published a roadmap to reach net zero by 2050, outlining methods to reduce carbon emissions associated with cement production[323]. The IAE also reports an earlier target to reduce emissions to 0.43 tCO_2 generated for each tonne of cement produced by 2030[324]. It is expected that carbon reduction can be achieved using biothermal and renewable energy to produce cement and by reducing clinker to cement ratio using clinker substitutes. If global targets are met, assuming a linear progression each year between 2022 and 2030, an ongoing increased reduction of about 7.5 $MtCO_2$ could be achieved annually in the road construction sector (assuming 10% of cement is used in the road construction sector). It is noted that these targets are not currently being met, so it is unlikely savings on this magnitude will be achieved.
- Regarding concrete design and Secondary Cementitious Materials (SCM), assuming that 5% of new roads constructed annually will be concrete (taking account of pavements and highway structures etc.), using an additional 10% SCM in the concrete mixes could result in global reductions of between 0.8 $MtCO_2$ and 3.8 $MtCO_2$ annually.

Low rolling resistance pavements

Construction of smooth and stiff pavements can reduce transport emissions, by improving fuel efficiency of the vehicles driving on them. When compared to conventional pavement construction, the CO_2 savings associated with low rolling resistance pavements could be between 6,000 and 12,000 tonnes, per 1 km of high traffic, 4-lane carriageway during a 15-year life.

Circular economy and resource efficiency

By transforming how materials are used and by optimising utility, circular economy approaches have the potential to make a significant contribution to completing the decarbonisation of the transport sector.

- Learning from previous projects that have adopted circular approaches, it is essential to consider circularity in the early stages of the scheme
- Ongoing monitoring and evaluation is important to achieve long term goals and to influence future work
- A collaborative approach between procurers and suppliers is essential

Potential carbon savings are difficult to estimate as it has not been implemented widely, so savings are very scheme specific currently. It also depends on the nature of the solution being developed, the construction material and method and other scheme objectives such as net biodiversity gain. On an 11km scheme in Ireland, savings of over €800,000 and 600t CO_2 were achieved.

Low carbon materials

[323] Net Zero by 2050 - A Roadmap for the Global Energy Sector (windows.net)
[324] Cement – Analysis - IEA

Advances in material technology now offer the potential to use low (or lower) carbon alternatives to conventional construction materials.

- Warm mix or cold mix asphalt materials are tried and tested alternatives to hot mix and are also, in some cases, more suitable to local conditions. Carbon savings could be in the order of 8 to 16 tonnes from using warm mix asphalt in place of hot mix asphalt per 1 km of 4 lane carriageway
- Secondary cementitious materials can be used as clinker/cement alternatives to reduce the CO_2 emissions associated with the production of concrete.
- Optimization of concrete mix design can lead to lower cement content in concrete paving mixes and reduced CO_2 emissions
- Recycled concrete can be used as coarse aggregate in concrete mix designs to reduce environmental impacts
- Using high performance concrete can have the effect of reducing net cement quantity required in construction of concrete structures as well as having the potential to increase durability and reduce CO_2 emissions associated with maintenance and rehabilitation over the lifespan of the structure

Decarbonisation of construction plant and construction operations

- Road maintenance activities alone may emit 8 million tonnes of CO_2 per year. There is the potential to save a significant proportion (potentially up to 50% for some sites and operations) through job site optimisation, machine optimisation and machine control. There is the potential for the remainder to be powered by electricity or hydrogen.

There are various options to reduce fuel use from construction plant, including machine control to improve efficiency of operation, use of GPS to ensure, e.g. correct compaction through to fully automated plant in some use cases (e.g. mines and quarries) operating with optimum efficiency. In terms of alternative power for construction plant to replace diesel, the size and use cases of machines influences the choices available.

- Many smaller items of plant, such as mini diggers, access platforms and small dump trucks are now offered in battery electric variants, with an 8+ hour operating window and overnight charging
- Whilst there are some examples of very large battery vehicles, in general it is considered that hydrogen is the way forward with both direct burn of hydrogen trialled and hydrogen fuel cell operation for large plant. There have been some concerns about the robustness of hydrogen fuel cells in challenging construction environments
- Biodiesel is another potential option, though there are concerns regarding the use of agricultural land to grow fuel crops, whilst there remain exhaust emissions. There are demonstrations of advanced biofuels manufactured from non-edible sources such as woody crops, wood chips and agricultural waste such as husks and stems. This does not compete with food production but has not yet been operated on an industrial scale
- The use of solar powered lighting solutions is now becoming more common to replace diesel generators. Apart from the benefit of zero carbon operation, there are no exhaust emissions, zero noise and operational improvements through avoiding the requirement for refuelling with diesel. Some claim to be able to operate year-round, even when there are 16 hours of darkness, whilst there are solar hybrid options with a diesel back up

- Depending on the level of use and exact size of the lighting tower, it could be possible to save 5 tonnes of CO_2 per year, per unit by switching to either solar power, or green hydrogen.
- Estimating the potential savings achievable by replacing diesel generators with solar power or green hydrogen is far more difficult due to the large variations in the size and applications. However, based on reasonable assumptions of mid-size generators, the potential savings could be in the order of millions of tonnes per year
- The use of hydrogen fuel cell powered lighting and site power has also been trialled on construction projects and are increasingly in use in other sectors (e.g. film and tv).
- NRAs should investigate what lighting towers and generators are used in their organisation and by their supply chain and look to a rolling programme of replacement where possible. Efforts to stimulate the market for green hydrogen production would need to be made to replace diesel in large generators.

11.2 Decarbonisation of Road User Vehicles

- Road vehicles emitted around 5.6 Gt of carbon in 2020, the largest of all carbon sources in roads. Theoretically, all of this could be provided by carbon neutral means, through electric vehicles being charged with electricity produced by renewables, or green hydrogen produced by electrolysis of water, powered by renewable energy. There may be roles for biofuels that don't compete with food production or niche applications for synthetic fuels.
- Emissions generated from vehicles using the road, represent the largest source of carbon, but also the one on which national road administrations have the least control.

Road administrations can support low emission vehicles, through for example, the provision of electric vehicle charging points, but other government bodies have the control over fuel standards, public transport and energy policy.

- Most fuels sold in Europe and other regions have a small percentage of biofuel bended within them.
- For light vehicles such as cars and vans, battery power has taken the significant market share, with 3 million vehicles sold in 2020, compared to only 26,000 hydrogen vehicles, with only two production models available.

There are also significant numbers of electric buses in use, the majority of which are in China. Hydrogen could be a viable option for buses too, especially in cities with many hills and either cold or hot temperature extremes, which makes battery power less efficient.

- For heavy goods vehicles, whilst there have been trials of battery powered units, which could potentially have sufficient range, hydrogen or direct electric power seem to be the frontrunners at this stage. One reason that hydrogen has not taken off for light vehicles is lack of fuelling infrastructure. This should be less of an issue for heavy goods vehicles as fuelling facilities can be installed at depots. For electric power, for example through catenary wires, this would require road administration involvement at some level.
- To achieve this would require vision, intra- and inter-governmental cooperation, research and development and finance. A challenge will be to generate the additional green electricity to achieve this vision. Better use of existing roads through a modal shift to public transport or infrastructure designed for walking and cycling could decrease carbon emissions in the short to medium term and reduce the requirement for additional electricity generation.

11.3 Operations on the Road Network

Vehicles operated by road administrations

All road administrations have vehicle fleets ranging from cars and vans to heavy equipment such as snow ploughs and gritters. The use cases and issues regarding fuels are as for other vehicles described above.

Road administrations may have a role in testing and demonstrating the use cases of alternate fuel vehicles, whilst helping develop the fuelling infrastructure as a single depot can service many vehicles.

LED lighting

Many countries are striving to move to more efficient lighting technology, for environmental reasons, and for economic and safety reasons.

In countries where solar gain is abundant, solar lighting solutions can provide drivers with a greater sense of security at night, and greatly improve safety for all road users.

Additional recommendations and considerations for roads authorities when planning a lighting scheme are presented in Table 9.

The carbon savings from switching to LED lighting depends greatly on type of system being replaced, the sophistication of the system being installed and the source of power to operate the lighting (e.g., fossil fuels or renewable). Globally, the world has approximately 363 million streetlights. It is estimated that by replacing an additional 10% with LED technology, global annual reductions of between 2.5 – 16.5 $MtCO_2$ could be achieved.

Carbon Offsetting

Carbon offsetting is seen as a potential means of achieving carbon neutrality for difficult to decarbonise sectors or for residual emissions.

- There are various technologies used to achieve this, including planting, improving soils, mangrove and sea grass restoration, production of biofuels and direct air capture.
- Some approaches are associated with additional benefits, such as supporting biodiversity or improving air quality
- However, the scale of emissions associated with road transport means that carbon offsetting is unlikely to be a successful route to achieving carbon neutrality, without also achieving substantial reductions in carbon emissions
- There are concerns regarding offsetting in part because some schemes are not well managed, so the true amount of carbon removed is not known. There is also considerable uncertainty over the time period for which the carbon will remain locked away. For example, whilst tree planting is seen as a positive in general, there are concerns around tree planting for carbon offsetting, as trees die or can get burnt down, they might compete with agricultural land and creating or protecting in one location may result in logging in another as the demand remains the same

- There are concerns about how many, even certified schemes, result in genuinely additional carbon removal, whilst there is an overarching concern that the potential to offset emissions may result in a lack of action in reducing emissions
- Generally, carbon offsetting should be the last resort in a strategy, with emissions reduction, the key action

Lessons from rail sector

- As with highways, the rail sector also has targets for decarbonisation and there is potential good practice that can be shared.
- There are good examples of measuring carbon across their network and using carbon management systems to reduce emissions, including the use of science-based targets for carbon reduction
- There has been progress in the production of renewable energy on estates, certification of electricity being of green origin and power purchase agreements to fund for zero carbon power solutions
- Operations are being decarbonised, for example replacing natural gas for point heating with electric alternatives and diesel trains being replaced by green electric, hydrogen or battery alternatives
- Operators also often have large road fleets and are transitioning this to ultra-low emissions alternatives

11.4 Road User Choices

- Non-Motorised Transport (NMT) not only has the impact of reducing carbon emissions, but can also have significant economic, social and health benefits. However, it is crucial that the schemes are designed with NMT as a priority from inception rather than an add on to motorised schemes.
- NMT services should be provided as a network rather than as a standalone scheme.
- To improve user participation, users should be involved in all aspects in the development and implementation of NMT projects
- Public bicycle sharing initiatives can be an effective means of reducing car journeys in cities.
- To promote a modal shift towards public transport, a passenger centred approach is required to provide a reliable, affordable, and efficient service that is a viable alternative to private vehicles
- Incentives such as reduced public transport cost, reimbursements, tax deductions and subsidies can also increase public transport use. Parking fees, congestion taxes and high fuel cost can be effective to discourage private vehicle use in urban areas

Transfer to active transport

The Netherlands has a very high cycling uptake, and it is estimated that this saves 1.3 $MtCO_2$ per year. Figures from the UK indicate that if 10% of the public moved entirely from private car use to cycling, and annual reduction of 13.6 $MtCO_2$ could be expected. However, this level of active transport is probably unlikely in many countries. In England, it is expected that there will be between 1 and 6 MtCO2 reduction between 2022 and 2030 due to a reduction in car emissions by promoting public transport, cycling or walking the natural first choice for those capable. If these figures for the England were extrapolated globally, an estimated additional reduction between 2-13 $MtCO_2$ could potentially be achieved annually.

Transfer to public transport

In the USA it was estimated that in a single year, a reduction of 6.9 $MtCO_2$ could be attributed to the use of public transport due to the reduction in emissions from private cars and from reduced congestion. A rough extrapolation on a global level would result in a potential reduction of 20 $MtCO_2$ annually, given there are 4,304,715 km of paved roads in the US, and 12,717,850 km globally (34% in US). Figures from the UK indicate that a modal shift from private car to bus transport for 10% of the public would result in a reduction in the range of 5.8 $MtCO_2$ annually. With the UK making up 3.1% of paved roads globally, extrapolation of the figures from the UK to a global scale would lead to a reduction of potentially up to 190 MtCO2 annually. These figures are just indicative and the level of CO_2 reduction would depend on many factors, including the availability of integrated public transport services which are reliable and attractive to road users.

Table 18, below provides a summary of the potential carbon savings of the various technologies described in this report in terms of low, medium, high and very high (L, M, H and VH). These are further categorised as to whether the solution would be most applicable to LMICs or HMICs or both, the technical ease for implementing this on a A to C scale, as follows: A, has no significant technical obstacles; B, some technology available but requires maturity; C, early-stage technology at least for mass adoption. Finally, the table indicates on an A to C scale the level of NRA influence as follows: NRA Scope: A, entirely within their scope; B strong influence (e.g. requesting contractors to use warm mix); C, beyond their control, but could support wider government initiatives.

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Table 18. Summary of solutions in achieving carbon savings

Solution	WIDESPREAD ACHIEVABILITY		POTENTIAL TO REDUCE CARBON	TECHNICAL EASE*	NRA SCOPE*
	LMIC	HIC			
Strategy					
Purchasing of green power	P	P	M	A	A
Road maintenance and life extension					
Maintaining roads in good condition (IRI ~ 1)	P		L/H**	A/B***	A
Structural health monitoring of bridges to extend life		P	M	B	A
Use of chip seal or crack seal in place of thin overlays	P	P	L	A	B
Use of cement replacements in concrete roads	P	P	M	A	B
Implement circular economy	P	P	M	B	A
Low carbon materials					
Use of cold mix or warm mix in place of hot mix asphalt		P	L	A	B

Solution	WIDESPREAD ACHIEVABILITY		POTENTIAL TO REDUCE CARBON	TECHNICAL EASE*	NRA SCOPE*
	LMIC	HIC			
Low carbon cement production	P	P	H	B	B
Use of additives in concrete and cement production	P	P	M	B	B
Concrete recycling	P	P	H	B	B
Use of innovative high-performance concrete	P	P	M	B	B
Low rolling resistance pavements		P	L	B	A
Decarbonisation of construction plant and construction operations		P			
Construction plant efficiency	P	P	M	B	B
Alternative fuels for construction plant		P	M	B	C
Alternatives to diesel powered lighting towers	P	P	L	A	B
Alternative fuels for diesel powered generators		P	L	B	C
Decarbonisation of road user vehicles					
Alternative fuels		P	M	A	C

Solution	WIDESPREAD ACHIEVABILITY		POTENTIAL TO REDUCE CARBON	TECHNICAL EASE*	NRA SCOPE*
	LMIC	HIC			
Electrification		P	VH	B	C
Hydrogen		P	VH	C	C
Buses	P	P	VH	A	C
HGVs		P	VH	C	C
Operations on the road network					
Vehicles operated by road administrations		P	L	B	A
LED lighting	P	P	L	A	A
Road user choices					
Transfer to active transport	P	P	H	A	B
Transfer to public transport	P	P	H	A	C
Carbon Offsetting		P	N/A	A	A

*   A = relatively high; C = relatively low.

**   Improvements to already good roads do not significantly improve efficiency, but emissions increase significantly where roads are in poor or very poor condition (IRI values >3). Here the potential for fuel savings is high.

***   Scale of impact depends on the improvement in road roughness that is achieved.

12 RECOMMENDATIONS

Much progress has been made, in LMICs and HICs, on establishing policies and pledges to decarbonise road transport, as seen from Part A of this report. At the time of writing, there are large numbers of examples of NRAs across the world, demonstrating progress in reducing carbon emissions in specific schemes and projects (with some even achieving net-zero). However, it is also clear that long-term strategies for delivering the transformation needed to become carbon-neutral or reach net-zero across all their networks are either in the early stages of development or yet to start. Parts B and C of this report set out the approaches available to road authorities. These examples are from many countries around the world, both LMICs and HICs and the knowledge and experience are highly transferrable. During this research the following themes have emerged as important enablers:

Strategy

For each road administration, it is necessary to develop long-term-strategy as soon as possible, setting out a roadmap with intermediate target dates for reducing carbon emissions. As planned and appropriately funded strategies will take time to develop and implement, and published target dates for net-zero for most countries are within a 30-year horizon, it is necessary to begin this process urgently. Strategies should be based on an understanding of where the NRA is at in terms of the carbon footprint of all its activities and should consider all potential areas for carbon reduction: construction, maintenance and operations as well as providing lower carbon options for road users that are practical and affordable.

Offsetting residual emissions is viable only as a part of the solution. There are considerable uncertainties over the quantification of carbon removal and the timescale over which it remains locked away with existing offsetting schemes and it is becoming increasingly clear that the role of off-setting is as an addition to carbon reduction strategies.

The appropriate solutions for individual NRAs will be driven by a combination of prevailing circumstances, e.g., transition to EVs is developing into the stated ambition of most countries but the feasibility and degree of benefit may be limited by the availability not only of the funding but also of electricity from sustainable sources.

Establishing a baseline of the sources of current emissions is an essential early step to identify the areas for focus and to measure progress in achieving reductions.

Personnel

The knowledge, skills, mindsets and behaviours of the entire workforce (e.g. policy makers, delivery teams, supply chain), all play a significant role in achieving decarbonisation as they are collectively responsible for identifying and evaluating options, managing procurement and delivering the solutions identified. Basic carbon literacy and an awareness of the carbon activities of their activities is a minimum requirement for all personnel. There is also a need for technical knowledge to be developed further and shared widely. This will enable road administrations to identify optimal options and ensure that the expected benefits are realised in practice.

Road administrations should invest in the skills and knowledge of their personnel and ensure that their supply chains do likewise.

Collaboration

Some initiatives for decarbonisation will be outside the influence of individual NRAs, e.g. incentivising uptake of EVs. In such cases NRAs can play an important enabling role, in this case by supporting the installation of EV charge points at accessible and convenient locations. However, similar challenges are shared by different agencies and finding common solutions can reduce costs and accelerate progress and there are several examples of collaboration and knowledge sharing between NRAs. An important area that would benefit from increased collaboration is in the development and use of, and reporting from, carbon measurement tools.

Road administrations should adopt a proactive role in engaging with other agencies and leading cooperation throughout the supply chain to facilitate change.

Procurement

The approach adopted by NRAs in procurement greatly influences the response of the supply chain. To achieve decarbonisation, Standards (e.g. construction, maintenance, materials, safety), must actively encourage innovation and enable the development and adoption of new materials, ways of working, etc., that have lower carbon impacts. Business models driving procurement must also include the evaluation of carbon and other environmental impacts in addition to standard whole life cost. Consistent feedback was obtained from the interviews carried out during this project that carbon prices, at current levels, are not high enough to drive the procurement of lower carbon solutions.

Road administrations should review their Standards and tender evaluation criteria so that appropriate attention and weight is given to decarbonisation.

Whole lifecycle analysis of carbon emissions

For road construction and maintenance, whole life analysis of carbon impacts is critical to understanding the most carbon efficient solution for specific situations. This is clear from the analysis of, for example, asphalt vs. concrete construction and implementation of LED lighting schemes. For a robust approach, it is essential for all phases of the lifecycle to be included (many published studies omit one or more stages); a competent analysis will declare the stages considered in relation to established standards for lifecycle analysis. The system boundaries should also be studied carefully, in case an apparent reduction in emissions in one area results in displacing the burden to a different part of the process. The analysis requires estimation and so sensitivity analysis is essential so that critical influences can be identified and the uncertainties associated with them acknowledged.

Road administrations should develop the assessment of carbon impacts within whole life cycle analysis and make this a routine part of options appraisal.

Data

A striking finding from the gap analysis is the limited rigour of the evidence presented on the actual or potential reductions in carbon emissions due to adopting particular strategies when implementing projects. As it stands, this makes it difficult for road administrations to learn from the experience of others and assess how best to pursue their own goals of carbon neutrality. Furthermore, transparency over the performance of goods and services is needed for road administrations to be able to identify genuinely low carbon approaches. Data (as well as skills and tools) are needed to make the quantification of carbon impacts a routine part of decision making.

Road administrations should support evidence gathering, data collection, identification of success factors and sharing knowledge of lessons learned.

13 GLOSSARY

Abbreviation	*Full*
BCR	Benefit cost ratio
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
Carbon offsetting	Accounting for carbon emissions generated by one process by reducing an equivalent amount elsewhere
Carbon sequestration	Removal of carbon from the atmosphere and 'locking' it away either temporarily (e.g. in trees) or permanently (e.g. in rocks)
Decarbonisation	Reducing the carbon intensity of a technology or process (not necessarily to zero)
Embodied carbon	Carbon emissions generated from the manufacture of a built asset, e.g. concrete, asphalt and steel
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
Gt	Giga tonne – 1 billion metric tonnes
HIC	High income countries
LCA	Life cycle analysis
LCC	Life cycle cost
LIC	Low-income countries
LMIC	Low and/or middle income countries. Also, lower middle-income countries
Mt	Mega tonne – 1 million metric tonnes
Net Zero Carbon	Reduction of the carbon emissions of a technology or process to zero overall
NMT	Non-motorised transport

Tailpipe emissions	Emissions generated from exhaust from burning fuel in an internal combustion engine
Ton	US – 2,000 lbs
Tonne	Metric - 1,000 kg
UMIC	Upper middle-income countries
UNEP	United Nations Environment Programme
WLA	Whole life analysis
Zero tailpipe emissions	Vehicle with no emissions from tailpipe (e.g. electric vehicle). Depending on the source of the electricity, there could be emissions generated elsewhere (e.g. coal, oil or gas fired power station)

14 ACKNOWLEDGEMENTS

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14.1 QUESTIONNAIRE

Organisation	Country
Dirección Nacional de Vialidad	Argentina
Austroads	Australia and New Zealand
Transport for New South Wales (TFNSW)	Australia
Department of Infrastructure and Transport, South Australia	Australia
Federal ministry for climate action, Environment, Energy, Mobility, Innovation and Technology	Austria
Agentschap Wegen en Verkeer (Flemish gov't – Ministry of Public Works)	Belgium – Flanders
Service Public de Wallonie Mobilité et Infrastructures	Belgium – Wallonia
Ministère des Transports du Québec (MTQ)	Canada-Quebec
Transport Canada	Canada
Transport Planning and Research Institute, Ministry of Transport	China
Instituto Nacional de Vías - Invias	Colombia
Ministerio de Obras Públicas y Transporte (MOPT) Secretaría Planificación Sectorial	Costa Rica
Department of Morbihan	France
Development Durable	France
Vegagerðin (Icelandic road and coastal authorities)	Iceland

Ministry of Public Works and Housing, Directorate General of Highways	Indonesia
Roads Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT)	Japan
Rijkswaterstaat	Netherlands
Federal Roads Maintenance Agency	Nigeria
Norwegian Public Roads Administration (NPRA)	Norway
General Directorate for National Roads and Motorways	Poland
Institute for Mobility and Transport	Portugal
National Company for Roads Infrastructure Administration	Romania
Dirección General de Carreteras. Ministerio de Transportes, Movilidad y Agenda Urbana de España	Spain
Trafikverket, Swedish Transport Administration	Sweden
Federal Office for Roads (FEDRO)	Switzerland
National Highways, England	United Kingdom-England
Transport for the North	United Kingdom-England Region
Transport for Wales	United Kingdom-Wales
Transport for the South East	United Kingdom-England Region
UK Department for Transport	United Kingdom-all. England only for roads
Minnesota Department of Transportation	USA
Directorate for Roads of Viet Nam, Ministry of Transport	Vietnam

14.2 Follow-On Discussions

Organisation	***Name***
Department for Infrastructure and Transport, South Australia	Bruno Castellucci and Jennifer Slocombe
Department for Transport, UK	James Henry
Federal Highways Administration, USA	Gina Ahlstrom
Federal Office for Roads, Switzerland	Laure Gauthiez
Ministère des Transport de Québec, Canada-Quebec	François Marchand and Luc Vescovi
Ministry of Public Works and Transportation, Costa Rica	Alvaro Bermudez Pena
National Highways, UK	Mark Emmett and Colin Holm
Transport for New South Wales, Australia	Chris Royal
TU Delft, Netherlands	Avishreshth Singh
Welsh Government, UK	Tim Barnes, Gareth Day and David Denner

World Road Association (PIARC)

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