Wayne Evans
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Submission on Coffs Harbour Bypass SSI_7666

I object to this project in its current form as it fails Ecologically Sustainable Development (ESD) Principles under the N.S.W. E.P. & A. Act,1979 relating to climate change, and is therefore not in the public interest.

This project must be carbon neutral. Offsets should include a swifter transition to affordable electric cars, electric bicycles, buses, and trains as well as the immediate introduction of safer emission standards.

Euro 6/VI vehicle emission standards must be adopted at a Federal level before any major infrastructure works are commenced.

Australia has failed to live up to its obligations to the global community to address the climate emergency that we and all sentient beings face.

"Total CO_2 emissions from road transport increased by 31% between 2000 and 2017, rising from 16% of total emissions in 2000 to 22% in 2017. With no action, transport emissions are projected to reach 111 million tonnes of CO_2 by 2030."(Appendix D The Conversation)

The Federal Government still embraces old vehicle emission standards (Euro 5) and as such we have become a dumping ground for defective and polluting vehicles. A ministerial forum set up in 2015 has failed to progress Australia's emissions levels.

According to the Climate Council of Australia:

"***Australia is one of just a handful of OECD countries without greenhouse gas emissions standards for vehicles, and lacks credible national policy to tackle transport emissions. In order to seriously address climate change, Australia needs to rapidly roll out a fleet of sustainable transport solutions like high quality public transport, cycling and walking infrastructure as well as renewable powered vehicles in the form of electric bicycles, cars, trains, trams and buses."***

This project fails Ecologically Sustainable Development (ESD) Principles under the N.S.W. E.P. & A. Act. The Chief Judge of the Land and Environment Court has stated:

"***..that the principles of ESD particularly intergenerational equity and the precautionary principle are themselves ample enough to enable consideration of the impacts a development might have on climate change or the impacts climate change might have on the development."***

The Precautionary Principle :

"If there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation."

Intergenerational Equity:

" The present generation should ensure that the health, diversity and productivity of the environment is maintained or enhanced for the benefit of future generations."

One of the greatest advocates of ecologically sustainable development as a means to address the impacts of climate change was Justice Peter Biscoe (late) of N.S.W. Land & Environment Court. He said:

"Climate change presents a risk to the human race and other species. Consequently, it is a deadly serious issue. It has been increasingly under public scrutiny for some years. No doubt that is because of global scientific support for the existence and risks of climate change and its anthropogenic causes.."

The United Nations Intergovernmental Panel on Climate Change (IPCC) states:

"Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (high confidence)."

The carbon footprint that this proposal will leave at a time when we face a climate emergency is unsustainable and unacceptable. During construction alone tens of millions of litres of diesel will be used.

Atmospheric inversions, which occur in Coffs Harbour will trap pollutants in the lower atmosphere, exacerbating the impact of these hazardous emissions.

According to the Roads & Maritime Services the volumes of traffic on the Coffs Harbour Inner Bypass and the current highway through the CBD will be the same.

Dr Vicki Kotsirilos from Doctors for the Environment states:

"There is "no safe level" for diesel pollutants, and any cars expelling higher than normal emissions are of major concern. Diesel emissions are particularly toxic chemicals that are released into the air. When we inhale these chemicals, they can irritate the nasal passages, cause allergies and irritations, they can cause lung disease, trigger asthma in people who have asthma."

Monitoring of air quality on the highway near the CBD should commence as soon as possible, in the interests of public health. Testing should cover particulate matter (PM10 and PM2.5), carbon monoxide, sulfur dioxide, nitrogen dioxide, and Lead.

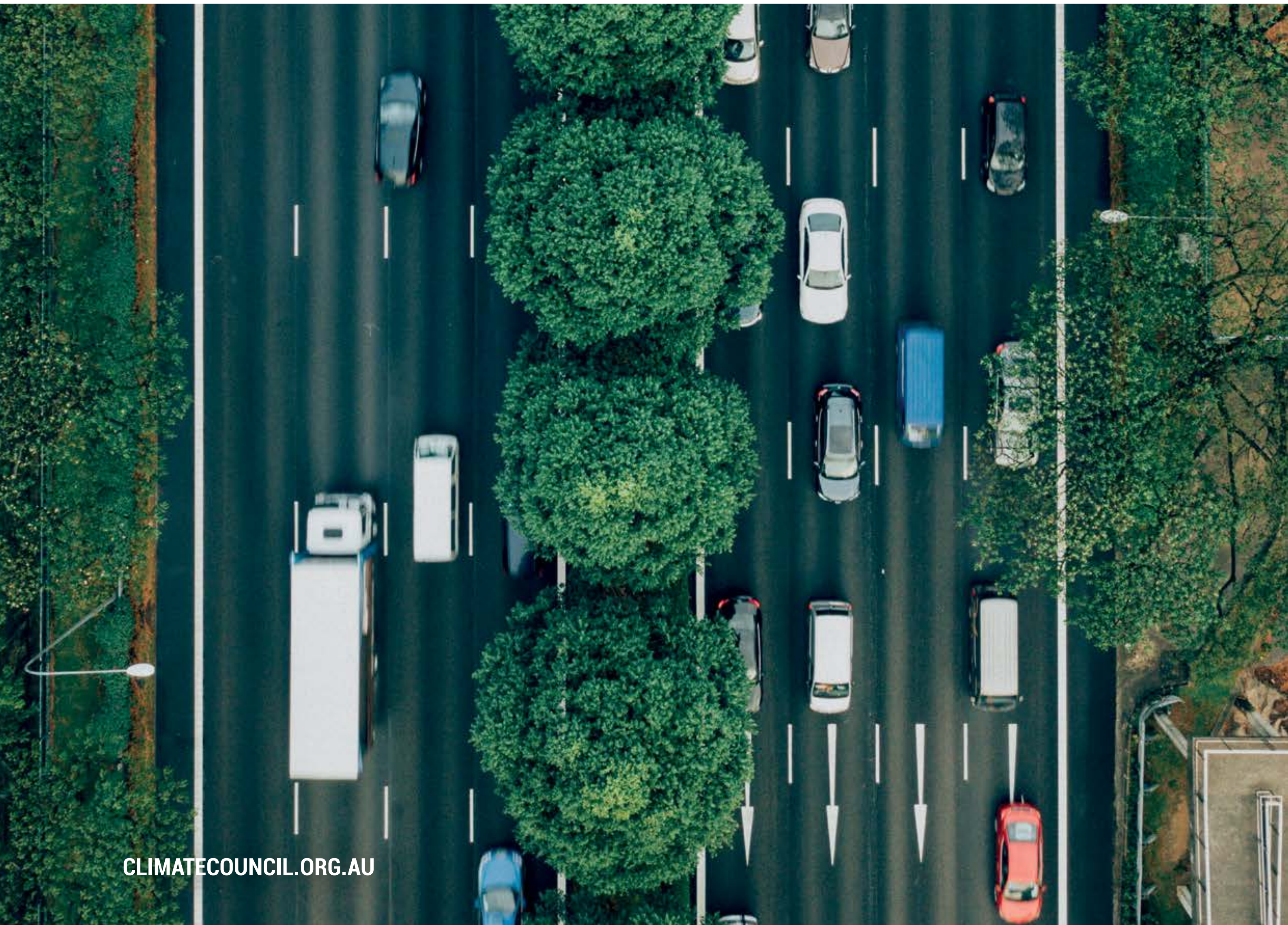
APPENDIX A:
Waiting for the Green Light: Transport Solutions to Climate Change
Climate Council of Australia Ltd

APPENDIX B:
A technical summary of Euro 6/VI vehicle emission standards
ICCT The International Council on Clean Transportation

APPENDIX C:
Global warming of 1.5°C A Special Report
United Nations Intergovernmental Panel on Climate Change (IPCC)

APPENDIX D:
The Conversation
We thought Australian cars were using less fuel. New research shows we were wrong

WAITING FOR THE GREEN LIGHT: TRANSPORT SOLUTIONS TO CLIMATE CHANGE



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Preface

This report marks the beginning of a new flagship project for the Climate Council aimed at cutting greenhouse gas pollution levels from the transport sector - Australia's second largest source of greenhouse gas pollution.

Australia's greenhouse gas emissions are rising and are projected to continue increasing in the absence of credible and comprehensive climate and energy policy tackling all key sectors: electricity, transport, stationary energy, agriculture, fugitive emissions, industrial processes, waste and land use.

There has been considerable public discussion in Australia surrounding the need to transition the electricity sector away from polluting, ageing and inefficient coal and gas generation to clean, affordable and reliable renewable power and storage. There are now many policies and programs at the federal, state and local levels designed to drive greater uptake of renewable energy. While more still needs to be done to continue cutting greenhouse gas pollution levels in the electricity sector, there is an urgent need to start addressing pollution from other sectors, particularly transport, the nation's next largest polluter.

Australia's transport emissions or transport greenhouse gas pollution levels have been steadily rising and are projected to continue going up. Factors such as population growth have led to a higher number of cars on the road, while increased demand for freight is also driving up truck emissions. Domestic air travel continues to increase, leading to an increase in aviation emissions (Australian Government 2017).

Solutions are readily available to cut rising greenhouse gas pollution levels from the transport sector. These include introducing vehicle emissions standards, planning for and investing in infrastructure to enable more people to walk, cycle and use public transport, powering cars, buses and rail with renewable energy, along with increasing the uptake of electric vehicles. However, Australia needs federal, state and local policies and investment to set us on the right path to do so.

We would like to thank Dr John Stone, Prof Peter Newman, Dr Graham Sinden (EY), Marion Terrill (Grattan Institute) and Tony Morton (President of the Public Transport Users Association) for kindly reviewing the report.

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Key Findings

1

Transport is Australia's second largest source of greenhouse gas pollution (after electricity).

- Australia's transport related greenhouse gas pollution levels increased 3.4% in the year to December 2017.
- Road based transport accounts for an even greater share of transport pollution in Australia than the global average, at around 85%.
- Cars and light commercial vehicles alone make up over 60% of Australia's transport pollution levels.
- Greenhouse gas pollution levels from transport are projected to continue rising to 2030 and beyond, reaching 112 $MtCO_2e$ in 2030, a further 12% above current levels.

2

Global transport pollution levels are rising by around 2.5% each year. Without action they are expected to double by 2050.

- The transport sector contributes 14% of total global greenhouse gas pollution annually.
- Road related transport - motorcycles, cars, trucks and buses - make up about three quarters of global transport greenhouse gas pollution levels.
- An international scorecard for transport energy efficiency ranked Australia third highest for car distance travelled per capita on an annual basis (8,853 kilometres per person), after the United States (highest, 14,724 kilometres per person) and Canada (second highest, 8,864 kilometres per person). Australia lags behind Russia, Mexico and Indonesia on transport efficiency.

3

Congestion is a $16 billion dollar handbrake on the productivity of Australian cities.

- Congestion in Australia costs the economy more than $16 billion per year - measured in lost private and business time, vehicle costs and air pollution. This figure is expected to rise.
- Demand and congestion on Australian roads will continue to soar as city populations rise. Investing in better public transport infrastructure is a proven means of alleviating congestion.
- Population growth in Australian cities is driving increased demand for public transport. Infrastructure Australia forecasts an 89% increase in demand for public transport between 2011 and 2031.
- Federal and state governments can play a major role in encouraging more people to use public transport through both investing in infrastructure as well as running more frequent public transport services on existing routes.

4

Nearly 8 out of 10 Australians travel to work, school or university by car.

- On average, one in three cars on the road during the morning peak are people making their way to work.
- The majority (79%) of Australian commuters travel to work by car with a much smaller proportion taking public transport (14%), walking (4%) and riding a bicycle (1%).
- The average Australian household spends seven times more on transport (over $11,000 per year) than electricity (around $1,500 per year).
- A study of Sydney transport costs to the taxpayer found cars to be the most expensive mode of travel costing society 86c for every passenger kilometre, compared with rail (the cheapest) at 47c and buses at 57c.

5

Australia is one of just a handful of Organisation for Economic Co-operation and Development (OECD) countries without greenhouse gas emissions standards for vehicles, and lacks credible national policy to tackle transport emissions.

- Mandatory vehicle emissions standards need to be introduced soon to enable Australia to prevent emissions of up to 65 MtCO_2 by 2030 (significantly more greenhouse gas pollution than what New South Wales' entire coal fleet produces in a year).
- To tackle climate change, Australia needs to rapidly roll out a fleet of sustainable transport solutions like high quality public transport, cycling and walking infrastructure as well as renewable powered vehicles in the form of electric bicycles, cars, trains, trams and buses.
- By 2025, an electric car is anticipated to be similar in terms of upfront cost compared to a conventional (petrol or diesel) vehicle.
- In Australia, the adoption of electric vehicles is being held back by the lack of policy support or incentives, higher upfront cost, lack of choice of available electric vehicles for sale in Australia, and the availability of public vehicle charging infrastructure.

Recommendations for policy makers

1

Federal, State and Territory governments to set targets for zero emissions, fossil fuel free transport well before 2050. Develop a climate and transport policy and implementation plan to achieve these targets.

2

Ensure cost benefit analyses for all transport project business cases account for the additional greenhouse gas pollution that projects will lock in over their lifetime, or pollution avoided (e.g. from public transport improvements).

3

Establish mode shift targets for public transport, cycling and walking.

4

Ensure that at least 50% of all Federal, State and Territory Government transport infrastructure spending is directed to public and active (e.g. walking and cycling) transport.

5

Federal, State and Territory governments to introduce targets to drive uptake of electric buses, trucks, cars and bicycles powered by renewables. Electric vehicle targets can be established for specific sectors and government operations, including:

- State and territory public transport systems.
- Federal, state and territory government vehicle fleet purchases.

6

State and Territory Governments to contract additional 100% renewable energy to power public transport systems (trains, light rail and buses).

7

Federal Government to introduce strong vehicle greenhouse gas emissions standards. State and Territory Governments to advocate for vehicle emissions standards through the Council of Australian Government's Transport and Infrastructure Council.

8

Federal, State and Territory governments to encourage the rollout of 100% renewable powered electric vehicle charging, particularly in regional areas and interstate routes.

9

Put a price on pollution. Consider policies or pricing which better reflects the cost of greenhouse gas pollution, so that road or public transport users bear the cost, or reap economic benefits based on emissions associated with their chosen travel mode. End government subsidies, incentives and support for fossil fuel use in the transport sector.

Contents

1. Introduction

Road and public transport systems in Australia are under increasing strain due to growing populations, the layout of our cities and suburbs, our heavy reliance on cars to get around, and in many cases the lack of suitable public transport alternatives. As the transport systems in our major cities come under pressure, some commuters and communities are experiencing negative effects such as high transport costs and travel times, congestion, overcrowding, noise, air pollution, and reduced physical activity.

Australia is failing to tackle greenhouse gas pollution from transport; our second highest emitter.

Crucially, our transport systems are failing when it comes to tackling climate change. Transport is now Australia's second largest source of greenhouse gas pollution (after electricity) and the sector has seen the largest percentage growth (62.9%) since 1990 (Department of Environment and Energy 2018a). Without action, transport emissions will continue rising (Department of Environment and Energy 2017).

Australia can do much more to reduce greenhouse gas pollution from the transport sector. Compared with other countries, Australia consistently ranks at the back of the pack when it comes to tackling its transport emissions (ACEEE 2018). In fact, Australia's cars are more polluting; our relative investment in and use of public and active transport options is lower than comparable countries; and we lack credible targets, policies, or plans to reduce greenhouse gas pollution from transport.

Action on climate change is urgent. The world experienced its hottest five-year period on record between 2013 and 2017, continuing a strong, long-term upswing in global temperatures (Climate Council 2018; NOAA 2018). Increasing global heat, driven primarily by the burning of fossil fuels like coal, oil and gas, is exacerbating extreme weather events around the globe and in Australia.

Greenhouse gas pollution from air travel is also significant and rising.

Transport systems are vulnerable to disruptions and damage from more frequent and intense extreme weather events such as heatwaves, storms and bushfires. For example, on 7 January 2018, the Sydney suburb of Penrith was recorded as the hottest place on earth over a 24-hour period (with temperatures reaching 47.3°C). This extreme heat led to cancellations and delays across the city's public transport system (News.com.au 2018; SMH 2018a).

Transport plans, policies and investments made today have long-term implications decades into the future. These impacts include concerns over how efficiently we will be able to move around our major cities, how rapidly we can cut greenhouse gas pollution, and how well our transport systems are able to withstand the impacts of extreme weather.

To tackle climate change, Australia must rapidly roll out a fleet of sustainable transport solutions. These include improving the quality, efficiency and accessibility of public transport, cycling and walking alternatives as well as shifting to renewable powered vehicles in the form of electric bicycles, cars, trains, trams and buses. Australian governments need to develop coherent transport and climate change policies with the aim of lowering greenhouse gas pollution across the sector.

Transport policies need to consider the many factors that influence people's transport choices - family, work and household circumstances, housing choices, comparative costs, how long it takes to get from A to B and whether the route is direct or meandering. Fortunately, there are many transport solutions available that can both drive down greenhouse gas pollution levels, while also bringing significant environmental, health and economic benefits.

This report focuses on climate solutions to road-based transport, as cars, commercial vehicles, trucks and buses make up the vast majority (85%) of Australia's transport-related greenhouse gas emissions. It is important to note emissions from domestic and international air travel are also significant and rising, with domestic air travel alone making up 9% of Australia's transport emissions.

Section two of this report provides an overview of the transport sector's contribution to greenhouse gas pollution globally and in Australia. Section three considers how Australia's transport sector emissions measure up compared with other nations. Section four provides background to some of the pressures facing Australian cities and their transport systems. Section five describes key climate solutions to drive down transport emissions in Australia. Section six highlights a range of local and international case studies of transport climate solutions.

2. Transport and climate change

Greenhouse gas pollution from transport represents a significant share of emissions both globally and in Australia, with pollution increasing year on year.

Australia's transport sector adds 100 million tonnes of greenhouse gas pollution to the atmosphere every year.

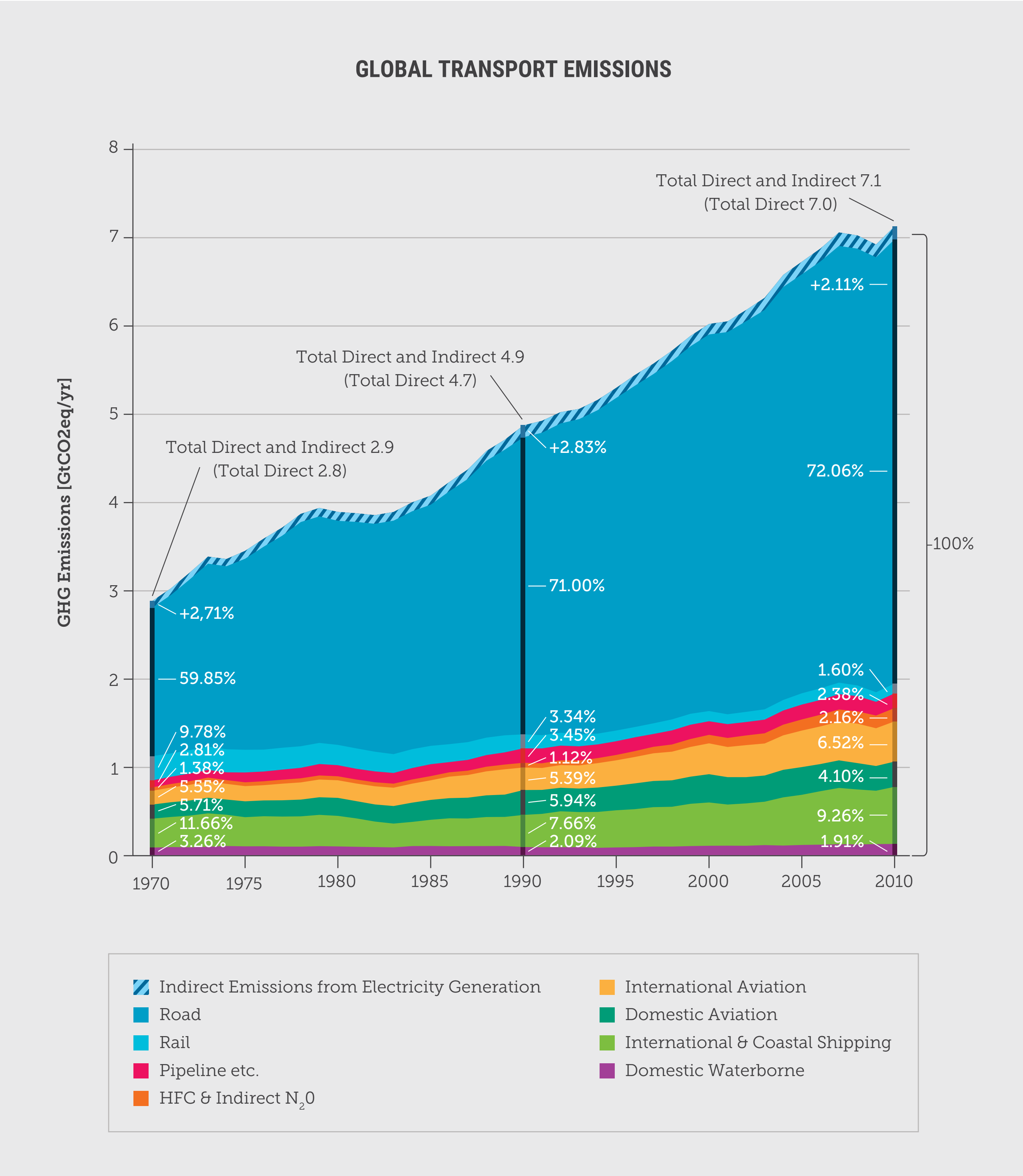
Globally, the transport sector contributes nearly a quarter of energy-related carbon dioxide pollution. The transport sector contributes 14% of total global greenhouse gas pollution annually (7.0 $GtCO_2$ in 2010) (IPCC 2014). Road related transport - motorcycles, cars, trucks and buses - make up about three quarters of global transport emissions (The ICCT 2017).

Transport emissions are rising (Figure 1). Worldwide transport-related emissions are increasing by around 2.5% every year (IEA 2017b; The ICCT 2017). Without action, transport emissions are expected to double by 2050 (IPCC 2014; Figure 1).

In Australia, transport (18%, 100 $MtCO_2e$) is the second largest source of greenhouse gas pollution after electricity (33%, 184.5 $MtCO_2e$). Australia's transport related emissions increased 3.4% in the year to December 2017 (Department of the Environment and Energy 2018a).

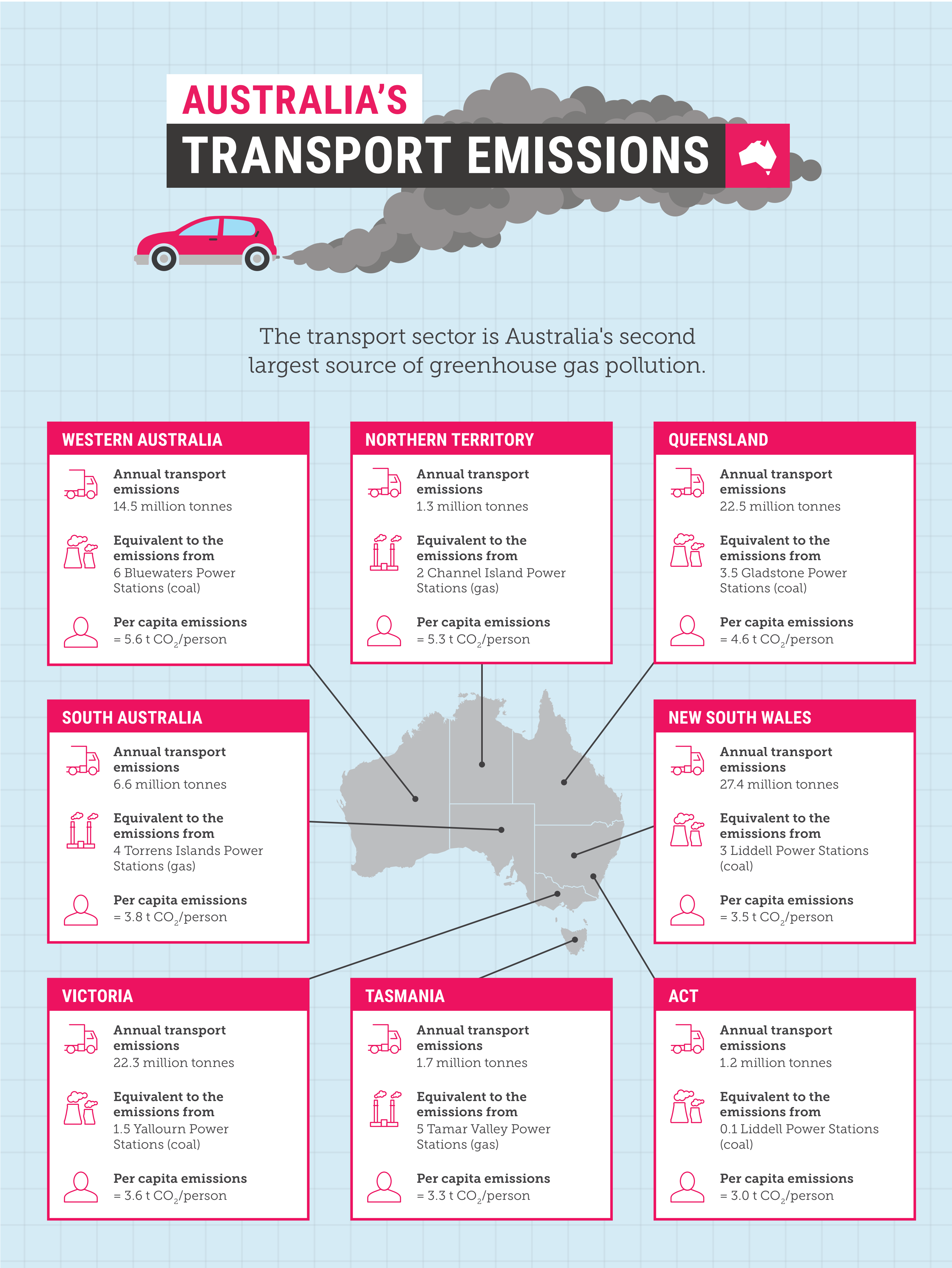
Road based transport accounts for an even greater share of transport emissions in Australia than the global average, at around 85% (Department of the Environment and Energy 2017). Cars and light commercial vehicles alone make up over 60% of Australia's transport emissions. New South Wales has the highest total transport emissions of any state or territory, whereas Western Australia has the highest transport emissions on a per capita basis.

Figure 1: Global transport emissions are rapidly rising.



Source: IPCC 2014.

Figure 2: State and territory transport emissions.

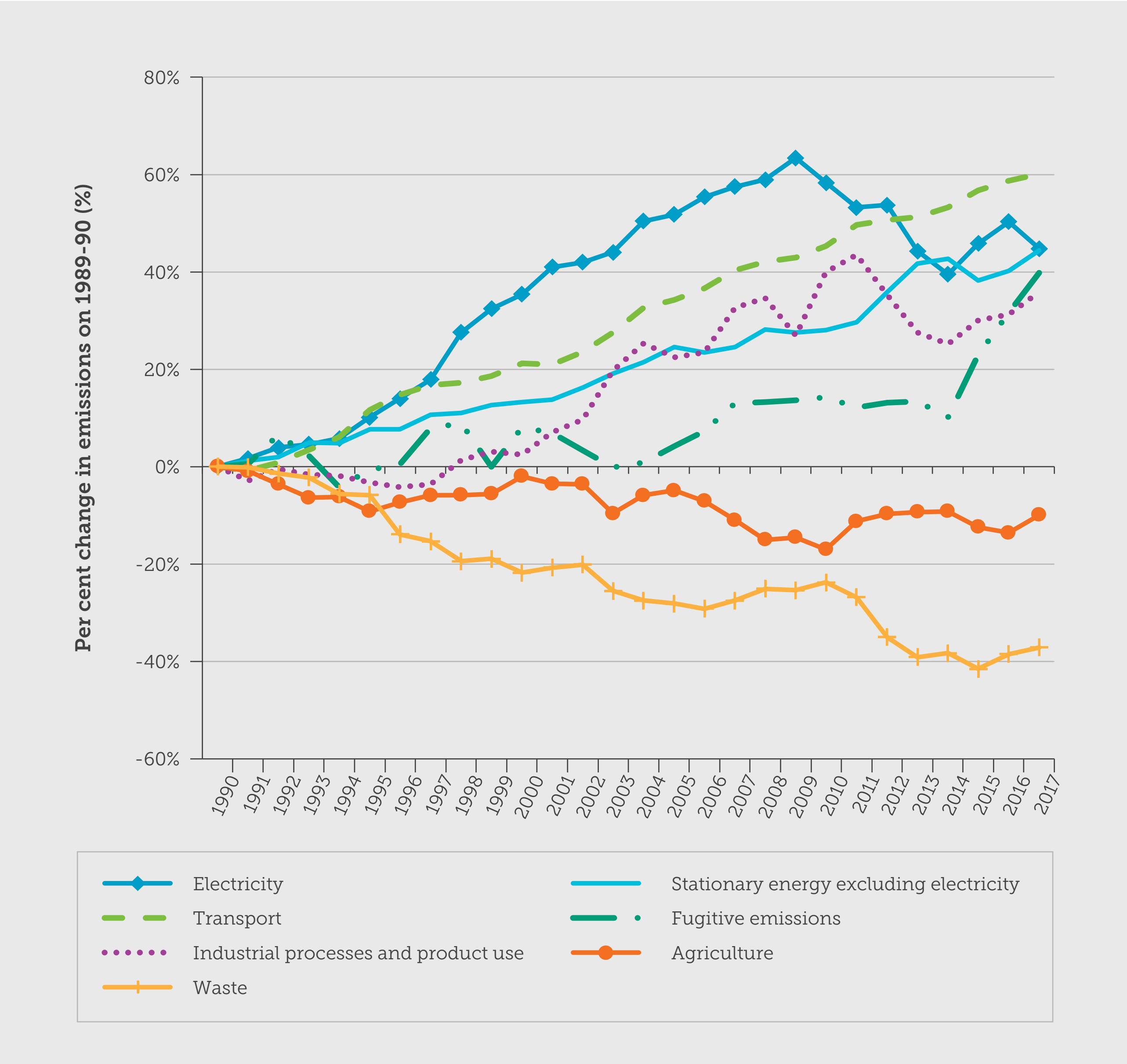


Sources: ABS 2017a; Clean Energy Regulator 2018; Department of the Environment and Energy 2018b.

Greenhouse gas pollution from cars, trucks and buses is on the rise both globally and in Australia.

In Australia, greenhouse gas emissions from transport have increased dramatically since 1990 (62.9%), experiencing higher growth than any other sector. Pollution levels from transport are projected to continue rising to 2030 and beyond, reaching 112 $MtCO_2e$ in 2030, a further 12% above current levels (Department of the Environment and Energy 2017; Figure 3).

Figure 3: Transport emissions increased the most as a percentage of any sector since 1990.



Source: Department of the Environment and Energy 2018a.

Emissions from the transport sector must be rapidly reduced in order to tackle climate change (IEA 2017b).

Transport solutions - improving city planning; investing in public transport; encouraging people to shift out of cars and on to public and active transport modes; and adopting technological developments such as renewable powered electric cars, buses, light rail and trains - are together capable of reducing greenhouse gas pollution levels globally by 15 - 40% from business as usual by 2050 (IPCC 2014).

BOX 1: THE CLIMATE BENEFITS OF CANBERRA'S LIGHT RAIL PROJECT

Commencing construction in 2016, the Australian Capital Territory's Capital Metro Light Rail (CMLR) system will be a transformative project for the Canberra-Queanbeyan urban area, bringing a wide range of economic, health, social and environmental benefits. Climate benefits are an important component of that list.

The first stage of the CMLR system – a 12 kilometre line from the northern town centre of Gungahlin to Canberra's city centre – will be fully operational in 2019. It will achieve a reduction in greenhouse gas emissions along the transit corridor of up to 30% compared to the business-as-usual case with no light rail, based on the number of passengers who shift from private cars to light rail.

Even more impressive are the reductions on a per-passenger basis. For every passenger who switches from a car to the light rail, emissions will be reduced by 100%, that is, a complete decarbonisation of the trip.

The reason for this massive reduction in per-passenger emissions is two-fold. First, moving from a car to the light rail system reduces emissions to only a sixth of what it would have been had the passenger stayed in the car. Second, the CMLR trains will be powered by electricity, not by liquid fuels such as petrol that directly emit CO_2 on combustion.

By 2020 the ACT has contracted enough wind and solar power to ensure the Territory is powered by 100% renewable electricity. So the electricity powering the trains will be entirely free of greenhouse gas emissions.

The other way that the CMLR system will reduce greenhouse gas pollution is by the land use change it will enhance. As people will want to live and work near the fast, high quality rail service, land development will be attracted closer in to the city rather than in highly car dependent suburbs on the urban fringe. Such changes in land use not only make the economics of urban rail much more attractive, they also reduce greenhouse gas pollution on the train and on all the travel done by those living closer to the city.

These very large emission reductions show the potential of quality public transport such as light rail, running on renewable energy, to drastically reduce greenhouse gas emissions on a per passenger basis and cut greenhouse gas pollution for the transport sector. In the longer term, the light rail network will become the backbone of a transformed transit system – integrated with bus routes, cycleways, walking corridors and electric vehicle charging stations – delivering an efficient, resilient, carbon-free transit system, powered by renewable energy.

Source: Steffen et al 2015.

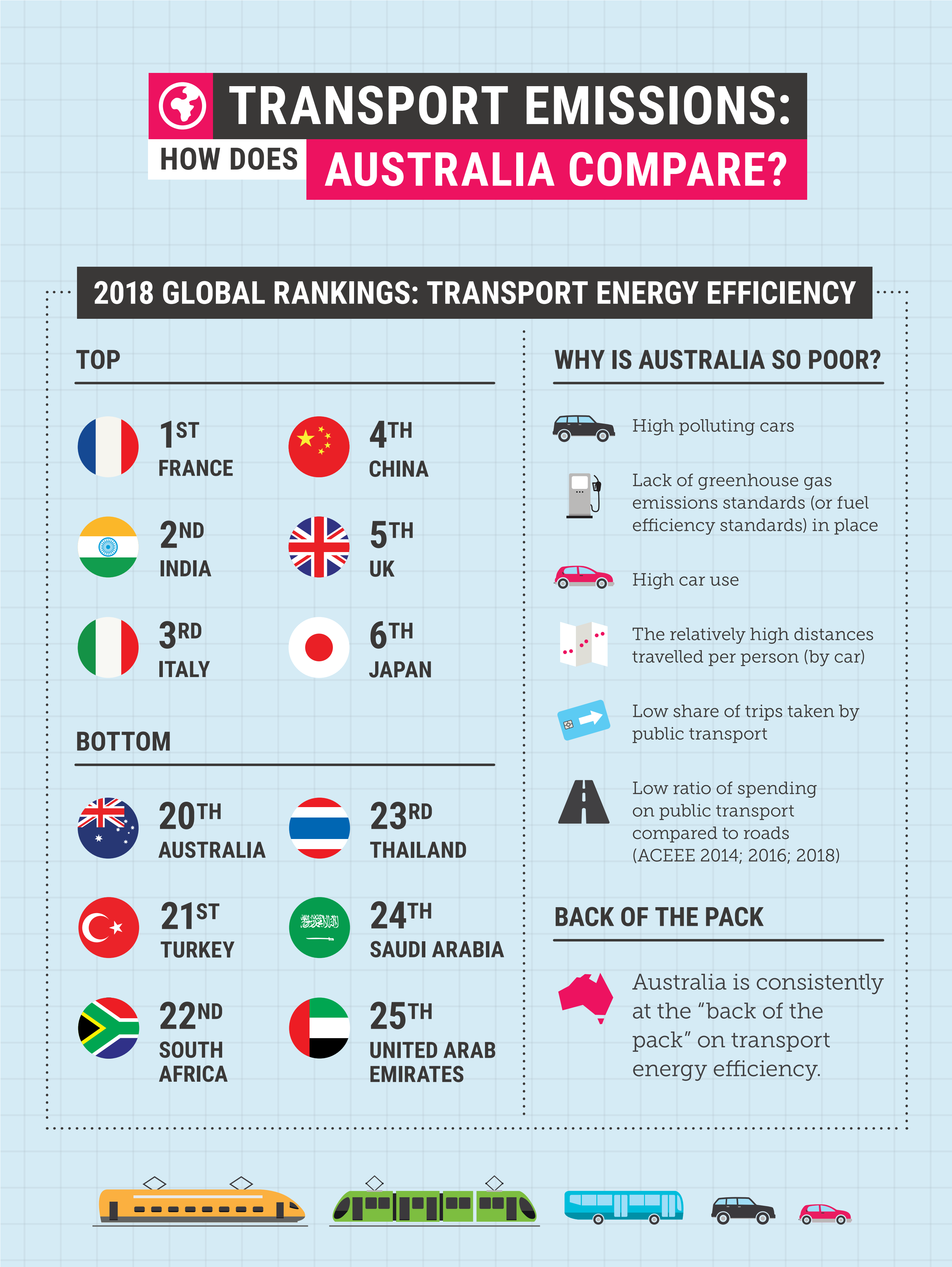
3. Transport emissions: How does Australia compare?

An international scorecard comparing the energy efficiency of the world's top energy consuming countries consistently places Australia at the "back of the pack" on transport energy efficiency due to:

- High polluting cars
- Lack of greenhouse gas emissions standards (or fuel efficiency standards) in place
- High car use
- The relatively high distances travelled per person (by car)
- Low share of trips taken by public transport
- Low ratio of capital spending on public transport compared to roads (ACEEE 2014; 2016; 2018)

Australia lags behind Russia, Mexico and Indonesia on transport efficiency.

Figure 4: 2018 International Energy Efficiency Score Card - Transport.

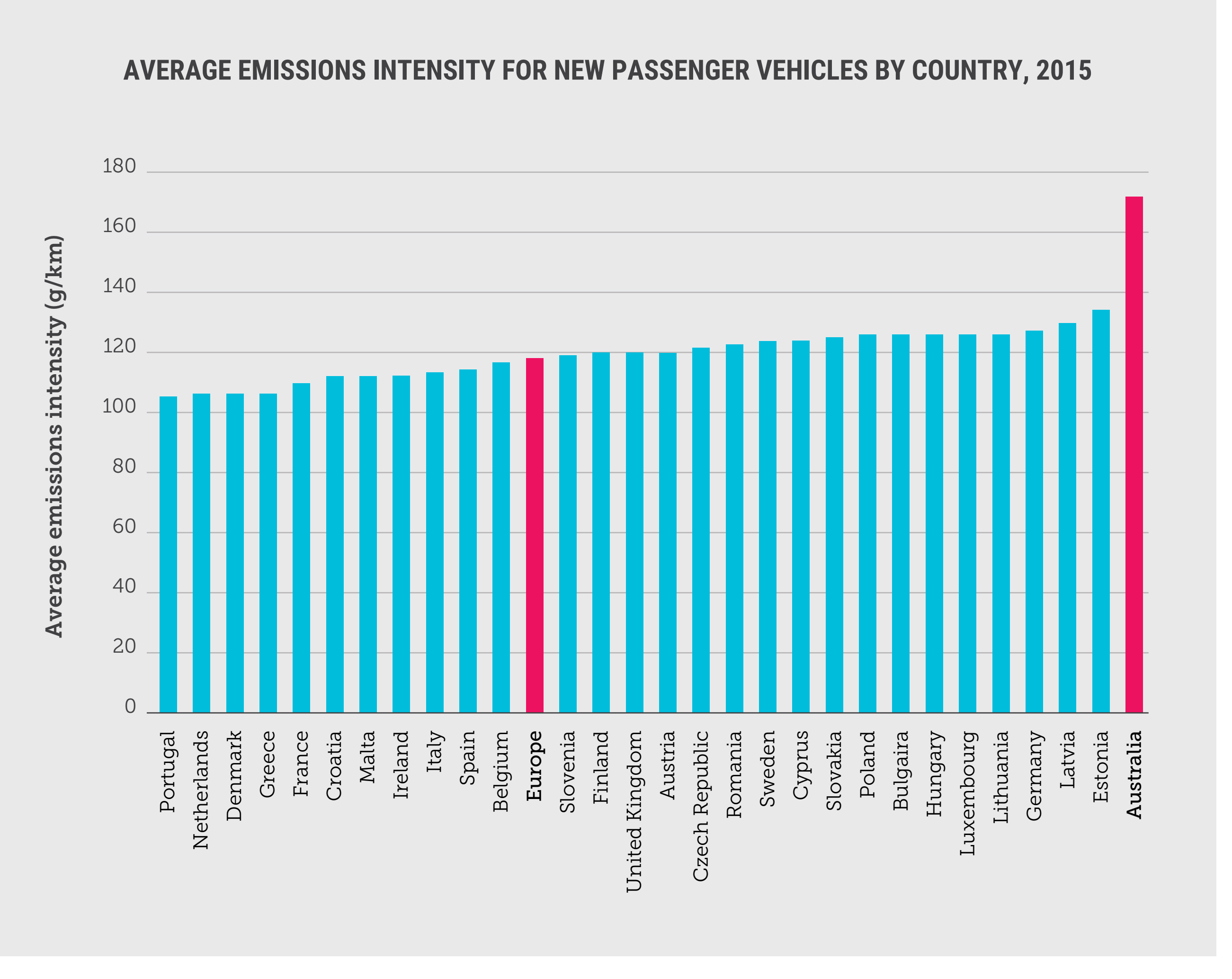


Sources: ACEEE 2018.

3.1 Australian cars pollute more

Australian vehicles emit more greenhouse gas pollution per kilometre than comparable countries. The average car purchased in Australia emits 182g of carbon dioxide per kilometre (g/km) (NTC 2017). This is much higher than comparable countries. For example, the emissions intensity of Australian vehicles is 46% higher than vehicles in European countries (NTC 2017; Figure 5).

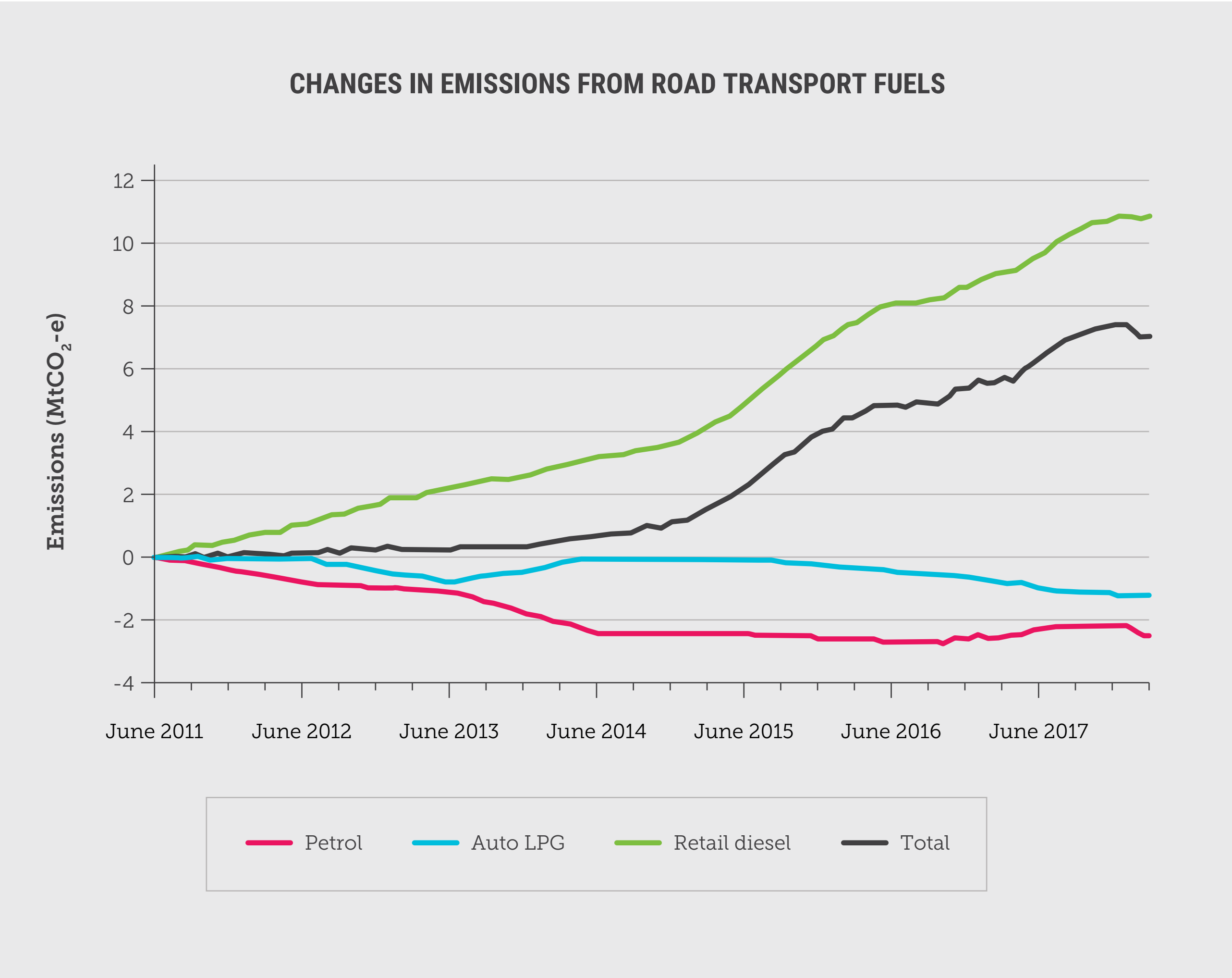
Figure 5: Emissions intensity for new passenger vehicles - Australia compared with European countries.



Source: NTC 2017.

Australian cars pollute more per kilometre than other comparable countries due to a range of factors, including vehicle size, the lack of mandatory greenhouse gas emissions standards for cars, as well as purchasing decisions made by individuals, business and government fleet buyers (NTC 2017). Since 2011, diesel emissions have gone up significantly as more people choose diesel vehicles (TAI 2018; Figure 6).

Figure 6: Diesel emissions have risen as more people choose diesel cars.



Source: TAI 2018.

3.2 Australians depend heavily on cars to get around

Australians rely heavily on their cars to get around, particularly when travelling to work, school or university. A greater proportion of people drive in Australian cities (rather than using public transport) compared to overseas (ACOLA 2015). For example, the majority (79%) of Australian commuters travel to work by car with a much smaller proportion taking public transport (14%), walking (4%) or riding a bicycle (1%) (BITRE 2017).

An international scorecard for transport energy efficiency ranked Australia third highest for car distance travelled per capita on an annual basis (8,853 kilometres per person), after the United States (highest, 14,724 kilometres per person) and Canada (second highest, 8,864 kilometres per person) compared with 25 high energy consuming nations (ACEEE 2018).

Sydney, Melbourne and Brisbane are Australia's most populous cities and have higher car ownership than other global cities (UITP 2015). Global research comparing transport trends in more than 60 cities worldwide found Australian cities (Brisbane, Melbourne and Sydney) were amongst the top third of cities in terms of car ownership per capita. Of the cities compared, Brisbane had the fourth highest car ownership per capita overall after Portland (US), Turin and Rome (Italy) (UITP 2015).

There are some signs of a cultural shift away from private car ownership. Younger Australians (born after 1982) are less likely to obtain a drivers license, less likely to own their own vehicle and more likely to prefer walking and public transport. Technological developments such as autonomous vehicles, electric vehicles, car sharing and ride sharing are expected to change car ownership patterns, but not necessarily reduce car use (NRMA 2017).

Nearly 8 out of 10 Australians travel to work, school or university by car.

3.3 Low use and limited access to public transport in Australian cities

Australia's most populous cities - Sydney, Melbourne and Brisbane - have lower supply of and use of public transport compared with other global cities (UITP 2015).

A study of 39 countries placed Australia among the lowest for levels of public transport use in terms of journeys per capita (UITP 2017).

Research comparing transport trends in more than 60 cities worldwide found Australian cities (Brisbane, Melbourne and Sydney) were among the lowest 25% based on supply of public transport (measured in total public transport vehicle kilometres per capita) and demand for public transport (measured in passenger kilometres per capita) (UITP 2015). However, demand for public transport is growing in Australia, linked to inner city population growth and investment in new lines and services (UITP 2017).

Solutions to reduce Australia's greenhouse gas pollution from the transport sector are outlined in Section 4.

Table 1: Public transport use.

Higher use (More than 10% larger than average)	**Medium use** (Within 10% of average)	**Lower use** (More than 10% smaller use than average)
Singapore, Czech Republic, Hungary, Austria, Luxembourg, Japan, Republic of Korea, Estonia, Switzerland, Lithuania, Germany, Sweden, Poland, Latvia, Romania, Croatia, Ukraine, France, Slovakia, UK, Norway	Italy, Turkey, Belgium, Bulgaria, Russia, Finland, Brazil, China	Denmark, Portugal, Canada, Spain, Malta, Australia, Ireland, Slovenia, US, New Zealand

Source: UITP 2017.

4. Pressures on and impacts from transport in Australian cities

Population growth in Australian cities is placing increased pressure on both road and public transport networks, leading to issues such as overcrowding and congestion. The approach to transport in our cities has a number of social, economic and environmental implications.

Population growth in Australian cities is putting pressure on transport networks.

4.1 Population growth placing pressure on transport systems

Australia's major cities are facing record levels of demand on road and public transport systems as urban populations surge (Commonwealth of Australia 2016a). Melbourne and Sydney both added more than 100,000 people over the past year, Brisbane added around 48,000 people and Perth an additional 21,000 (ABS 2018a; Table 2).

Table 2: Population growth in Australian capital cities.

Capital city	Population 2017	Population change 2016 - 2017	Growth 2016 - 2017
Melbourne	4,850,740	125,424	2.7%
Sydney	5,131,326	101,558	2.0%
Brisbane	2,408,223	47,982	2.0%
Canberra	410,301	6,833	1.7%
Hobart	226,884	2,422	1.1%
Perth	2,043,138	21,094	1.0%
Adelaide	1,333,927	9,648	0.7%
Darwin	146,612	696	0.5%

Source: ABS 2018a.

4.2 Congested roads

Many Australian roads are congested at peak times. The average car trip to the city in Sydney or Melbourne takes 50-70% longer during the morning peak than it would at night (Terrill M 2017). Travel times in all four big Australian cities have grown beyond the 30-minute average travel time, a period considered to be an acceptable journey time from home to work (Newman and Kenworthy 2015; Figure 7).

On average, one in three cars on the road during the morning peak are people making their way to work. Approximately one in five are travelling to school or university (BITRE 2016a). More than 60% of children are now driven to and from school (ACOLA 2015), with some parents reportedly travelling up to 100 kilometres to drive children to their school of choice (SMH 2018a; The Age 2018a).

Figure 7: Average commuting times for full time workers in Sydney, Melbourne, Brisbane and Perth.

Source: BITRE 2016b.

Congestion represents a cost to the economy and a handbrake on the productivity of our cities. In Australia, the annual economic cost of congestion - measured in lost private and business time, vehicle costs and air pollution - is estimated at over $16 billion per year and is expected to rise (BITRE 2016b). While congestion represents a cost to the economy, it is important to note that reducing congestion is not without cost, often requiring new investment in public transport or funds for administering road pricing policies (Terrill 2017). Eliminating congestion entirely from major city roads is an unrealistic goal, given a certain amount of congestion reflects an efficient use of road space (Whitehead 2015).

Reducing congestion requires investing in public and active transport alternatives together with congestion charges or disincentives discouraging people from driving at peak times (Aftabuzzaman et al 2010; Glover 2013; Whitehead 2015). On the other hand, building more roads often contributes to increased traffic, as more people decide to drive, in turn increasing road congestion (Glover 2013; Beck and Bliemer 2015; Whitehead 2015).

New roads are often sold to the public as "congestion busters"; however, research consistently shows that increasing road capacity can actually increase congestion by encouraging additional car trips as traffic increases to fill the available road space (Litman 2015). While counter-intuitive, removing roads may over-time result in improved traffic conditions (Beck and Bliemer 2015).

Congestion is a $16 billion dollar handbrake on the productivity of Australian cities.

Where public transport provides an alternative service to driving that is efficient, affordable, and meets people's travel needs, this can lead to more and more people using public transport and less tolerance for driving and road congestion, ultimately creating a lasting improvement in road traffic conditions. Importantly though, this will only happen if planners resist the temptation to undermine the mode shift to public transport (and away from private cars) by adding more road capacity.

For example, Beijing has successfully reduced congestion by 50% year-on-year from 2010 by prioritizing public transport in planning and investment, expanding the rail network by three new subway lines (totalling 36 kilometres of rail) and limiting increases in car ownership. Public transport now accounts for over 40% of all trips, and peak hour travel speeds have improved by more than 10% (International Transport Forum 2013).

4.3 Increasing demand for public transport systems

Most Australian capital cities offer a range of public transport services: rail (in the form of trains and light rail), buses and in some cases ferries. In 2016, public transport users in Sydney, Melbourne (e.g. Figure 8), Brisbane, Adelaide and Perth took 680 million trips by rail (trains) and 230 million trips on light rail (BITRE 2017).

Population growth in Australian cities is driving increased demand for public transport. Infrastructure Australia forecasts an 89% increase in demand for public transport between 2011 and 2031 (Infrastructure Australia 2016).

The capacity of public transport to move more people in Australian cities and towns depends on diverse factors including infrastructure, technology measures (e.g. signalling), fleet size, staffing, and even the design of stations and interchanges.

Light rail and urban trains generally tend to service inner city suburbs, or extend like spokes of a wheel, connecting the central city to outer suburbs. Trams (street-based light rail) generally operate up to around 10 kilometres from the central city (Victorian Auditor General 2014), whereas light rail can extend further into suburbs and hinterlands. In recent years most Australian cities have been building fast

Figure 8: Melbourne's Flinders Street Station.

rail into the outer suburbs to ease the travel times of people living a long way from work and these have been highly successful in drawing people out of cars (Glazebrook and Newman 2018). The Western Australian Government's MetroNet program has major rail connections into five corridors of Perth costing over $5 billion. Other significant rail investments include Adelaide's rail extension to Noarlunga, Sydney's North West and South West rail projects, Melbourne's new South West line and Melbourne Metro, the Canberra and Gold Coast Light Rail projects and Sunshine Coast rail projects. Pressure on existing transport systems and communities experiencing long travel times to work and other major services have been strong drivers for these rail investments. The change in priorities from spending on roads and buses to building fast rail services has happened mostly over this century and is paralleled by changes across the world (Newman, Glazebrook and Kenworthy 2012; Glazebrook and Newman 2018).

The trend to build urban rail in recent decades across the globe has been documented by Newman and Kenworthy (2015) who show that urban or metro rail is now faster than traffic in most cities (including Australia) as traffic has slowed from congestion and new fast rail systems are being built that go over, around or under the traffic. Table 3 shows this trend and the opportunity through rail to enable large shifts in modal split away from cars.

Buses have provided the backbone of public transport in Australian cities, particularly for those living in the outer suburbs, for the past 50 years. A study of Melbourne public transport found nearly 90% of homes are located within walking distance (400 metres) to one or more modes of public transport - over 80% lived near a local bus, around 30% near a train, and 20% near a tram (Victorian Auditor General 2014).

Figure 9: Canberra Bus.

Table 3: Ratio of overall average transit system and rail speed to general road traffic speed in cities, 1960 to 2005.

Comparative speeds in global ciites	1960	1970	1980	1990	1995	2005
Ratio of overall public transport system						
American Cities	0.46	0.48	0.55	0.50	0.55	0.54
Canadian Cities	0.54	0.54	0.52	0.58	0.56	0.55
Australian Cities	0.56	0.56	0.63	0.64	0.75	0.75
European Cities	0.72	0.70	0.82	0.91	0.81	0.90
Asian Cities	-	0.77	0.84	0.79	0.86	0.86
Global average for all cities	**0.55**	**0.58**	**0.66**	**0.66**	**0.71**	**0.70**
Ratio of metro/suburban rail speed to road speed						
American Cities	-	0.93	0.99	0.89	0.96	0.95
Canadian Cities	-	-	0.73	0.92	0.85	0.89
Australian Cities	0.72	0.68	0.89	0.81	1.06	1.08
European Cities	1.07	0.80	1.22	1.25	1.15	1.28
Asian Cities	-	1.40	1.53	1.60	1.54	1.52
Global average for all cities	**0.88**	**1.05**	**1.07**	**1.11**	**1.12**	**1.13**

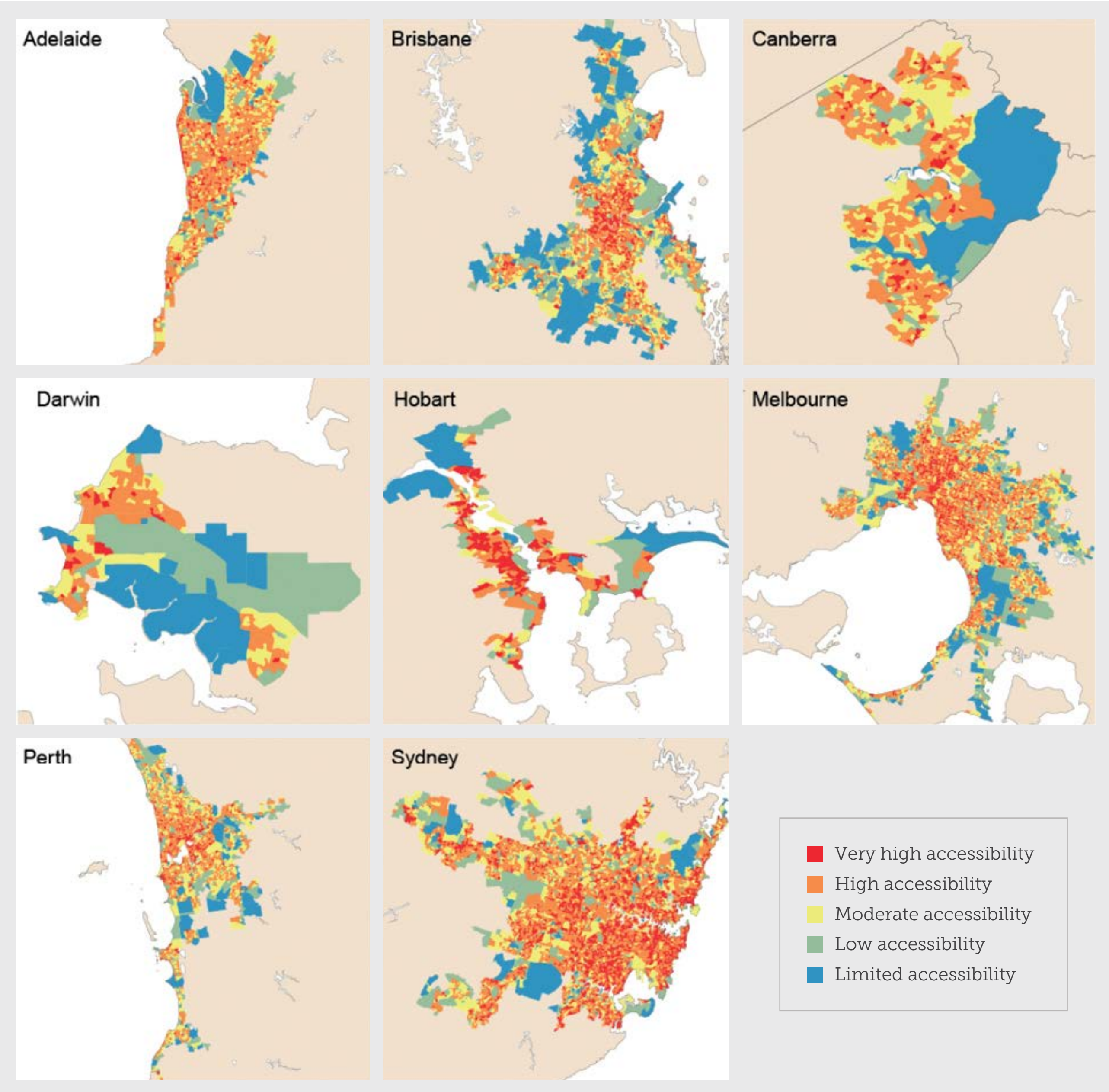
Source: Newman and Kenworthy (2015).

Accessibility of public transport services is critical.

Accessibility of public transport is critical to encouraging more people to take the bus, light rail or train instead of driving. Hobart and Sydney ranked the highest in terms of the percentage of residents with high or very high accessibility (of nearby public transport stops). However, this does not matter if the speed and quality of the public transport option is not better than that provided by cars[1]. Out of the capital cities, Brisbane had the largest proportion of residents having low or limited access to public transport (Commonwealth of Australia 2016b; Figure 10).

1 Accessibility is defined geographically and does not take into account the quality or how frequent the service is.

Figure 10: Accessibility of public transport in Australian cities.



Source: Commonwealth of Australia 2016b.

Light rail and trains in Australian cities are bursting at the seams.

Many public transport systems in our major cities, particularly light rail and train services, are bursting at the seams. Many public transport services are already at or beyond capacity during peak periods, leading to crowding, delays and worsening quality of service. Ongoing rapid growth and investment in new high quality public transport systems is needed to tackle climate change and make our cities responsive and resilient.

In contrast, many bus services are characterised by low use and low levels of satisfaction. Issues affecting bus services and levels of use include indirect routes, infrequent services, limited hours of operation and poor coordination with trains and light rail (Victorian Auditor General 2014).

Buses can be very slow in the transport system. In recent decades our streets have become more congested and unfortunately buses are also stuck in the traffic. This drawback for efficient bus systems has partly contributed to the preference in Australian cities for a faster rail connection to the outer suburbs.

In general, the service level of buses and light rail in our major cities (like Sydney and Melbourne) are poor compared to other global cities in terms of provision, frequency, average speeds and unplanned disruptions. Investment in and increases in public transport service have not kept pace with population growth (Currie 2016).

Rapid growth and investment in public transport systems is needed to tackle climate change.

4.4 Health and wellbeing impacts from transport choices

People living in Australian cities are spending a large proportion of time travelling to and from work, school or university. Those living in Sydney (5:42 hours per week), and Brisbane (5:00 hours) are spending a large amount of time each week in the car, train, light rail, tram or bus (AMP 2011, e.g. Figure 11). However those living in the Northern Territory are spending less than three hours a week commuting to work.

Time spent commuting impacts on people's work and leisure time. Long commutes also negatively affect people's wellbeing, stress levels, and their relationships with families, communities and workplaces (TAI 2005).

The way people travel - by car or public transport - can have ramifications for their health. Public transport use is linked to lower weight and higher levels of physical activity compared to driving. This is due to incidental physical activity such as walking to or from the train station or bus stops (Rissel et al 2012). Compared with driving, public transport users:

› are 3.5 times more likely to meet recommended levels of physical activity (30 minutes a day)

› walk an extra 8 to 33 additional minutes each day

› are less likely to be sedentary or obese (Rissel et al 2012).

People living in Australia's major cities are spending between four and six hours a week in the car, train, light rail, tram or bus.

Public transport users are more likely to meet recommended levels of exercise.

A study of incidental physical activity associated with public transport use in Melbourne found car drivers average 10 minutes of daily physical activity, whereas public transport users achieve 35 minutes, and walkers and cyclists 38 minutes (Beavis and Moodie 2014).

One of the healthiest forms of travel is walking. The rebuilding of cities to make them more walkable has been the life work of Danish urban designer Jan Gehl (Matan and Newman 2016). Gehl's work in Melbourne, Sydney, Adelaide and Perth has been critical to their becoming far more walkable in their central cities, regenerating the original walking urban fabric (Newman et al 2016). This has been the basis of strong economic performance, higher liveability, greater health and reduced car use. Such activities have demonstrated the importance of co-benefits in achieving reductions in transport greenhouse gas pollution.

Figure 11: Traffic congestion in Sydney.

4.5 Urban air pollution and noise

In Australia, an estimated 1,700 deaths occur every year as a result air pollution from cars, trucks and buses - larger than the national road toll (Schofield et al 2017; Department of Infrastructure, Regional Development and Cities 2018).

Diesel cars, trucks and buses are key sources of urban air pollution. Diesel is becoming an increasing source of air pollution in Australian cities (Commonwealth of Australia 2016a). Diesel-fuelled vehicles emit air pollutants such as nitrogen oxides and particulate matter, which can cause cancer and respiratory problems (Nieuwenhuis 2017).

The use of diesel is increasing across Australia both for road transport and other activities (agriculture, mining, construction) (TAI 2018). Sales of diesel cars are growing in Australia, increasing 8.5% between 2015 and 2016 (NTC 2017). Bus routes in Australia are predominantly serviced by diesel buses. Out of 97,000 buses on Australian roads, four out of every five are diesel (ABS 2017c).

Across the world many cities are banning diesel for health reasons and because electric vehicle alternatives of all kinds are now the rapidly growing new market. Electric vehicles can reduce urban air pollution and noise.

Simple measures such as discouraging the practice of idling (when a vehicle's engine is left running unnecessarily) near schools and childcare centres can reduce children's exposure to noxious chemicals as well as reducing greenhouse gas pollution (Schofield et al 2017; The Age 2017).

Diesel buses, trucks and cars are a key source of air pollution.

4.6 The cost of transport

Despite the recent focus on energy bills, the average Australian household spends seven times more on transport (over $11,000 per year) than electricity (around $1,500 per year) (ABS 2017b; ACCC 2017).

Compared to driving, public transport is cheaper for individuals, households, and society, particularly when all external costs are factored in (for example, public expenditure, accidents, congestion, air pollution, and noise costs).

At a household or individual level, deciding to take public transport instead of the car can save between $5,500 (if a car is kept at home and not used) and $9,400 (if using public transport avoids the purchase of a car, or second car) per year (Wang 2013).

A study of Sydney transport costs to the taxpayer found cars to be the most expensive mode of travel costing society 86c/passenger kilometre, compared with rail (the cheapest) at 47c and buses at 57c (Glazebrook 2009).

The external costs of road-based transport are significant. Globally, around 1.3 million people are killed every year by motor vehicles, and an additional 20-50 million people are seriously injured (Sims et al 2014). In Australia, the annual road toll results in around 1,200 lives lost due to car accidents (Department of Infrastructure, Regional Development and Cities 2018).

Households spend seven times more on transport than what they spend on electricity.

5. Transport climate solutions

While the transport sector is Australia's second largest source of greenhouse gas pollution, there are significant opportunities to reduce emissions through a shift to public and active transport alternatives, and to renewable-powered electric vehicles (ClimateWorks 2014; Hawken 2017).

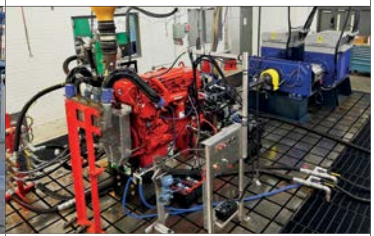
Key climate solutions to drive down transport emissions involve:

› providing viable alternatives to driving, such as expanding access to reliable, comfortable public transport, cycling and walking alternatives.

› electrifying and powering cars, buses, trains and light rail with 100% renewable energy (eg. Canberra's light rail).

› adopting policies and incentives to encourage lower emitting vehicles, such as mandatory greenhouse gas emissions standards and electric vehicle targets (Table 4).

Table 4: Transport solutions to reduce greenhouse gas pollution.

Solution	Mode shift to public and active transport alternatives	Renewable energy powered electric vehicles	Policies and incentives for more fuel efficient vehicles
			
What is it?	Increasing public and active transport use by providing viable alternatives to driving, such as high quality, efficient and accessible public transport, cycling and walking alternatives.	Electrifying bicycles, cars, buses, light rail and trains and powering them with 100% renewable energy.	Mandatory fuel emissions standards set targets for new cars to meet lower emissions (per kilometre travelled) over time. The overall emissions intensity of the car fleet is reduced over time as new, more efficient vehicles are purchased to replace older ones. Targets and incentives to drive the uptake of electric bicycles, cars and buses.
Benefits (in addition to reduced greenhouse gas pollution)	Reduced congestion Safer (reduced car accidents) More physical activity More inclusive (transport access for people without access to a car or unable to drive) Improved air quality Lower transport costs (compared to driving) Reduced public space dedicated to cars	Reduced urban air pollution and noise Electric vehicles can be powered by renewable energy Lower running costs	Covers a broad range of vehicles, driving down emissions across the entire car fleet Lower running costs
Barriers	Car oriented planning, urban design and infrastructure budgets Lack of investment in public and active transport infrastructure Requires behaviour change	Lack of charging infrastructure Lack of policy and incentives to drive take up (emissions standards/ targets) Upfront cost (offset by lower running costs) Perceptions, e.g. concerns about distance per charge	Government inaction

Sources: ESAA 2013; CCA 2014; Hawken 2017.

Globally transport solutions have the potential to significantly reduce greenhouse gas emissions by 2050 (Table 5).

Table 5: Emissions reduction potential from transport solutions.

Solution	Global emissions reduction potential to 2050 (gigatonnes CO_2e)
Mode shift	
Mass transit	6.57
Walkable cities	2.92
Bike infrastructure	2.31
Digital communications (as an alternative to travel)	1.99
High speed rail	1.42
Ride-sharing	0.32
Total	**15.53**
Renewable powered electric vehicles	
Electric vehicles	10.8
Electric trains	0.52
Electric bikes	0.96
Total	**12.28**
Greenhouse gas standards	
Cars	4.0
Trucks	6.18
Total	**10.18**

Source: Hawken 2017.

5.1 Increasing public transport use to move more people with less pollution

Mode shift from car travel to public and active transport is one of the most effective measures available to reduce transport energy use and greenhouse gas pollution. Federal and state governments can play a major role in encouraging mode shift to public transport through both infrastructure provision and efficient day-to-day service planning (such as coordinated timetables and running more frequent public transport services on existing routes).

Figure 12: Adelaide Tram.

European cities have led the shift from car travel to public transport, with Vienna, Paris, London, Oslo, Prague and Geneva increasing the share of journeys by public transport by 20% or more by increasing public transport supply and discouraging car travel (for example through parking restrictions and congestion charging). In Vienna, Austria - which recently overtook Melbourne as the "world's most liveable city" - more trips (54%) are now made by public transport than by private vehicle (UITP 2015; The Guardian 2018).

Even cities famous for their car dependent, sprawling suburban development such as Houston and Dallas in Texas, United States have been taking steps - rolling out new light rail and train systems and investing in improving bus services - to increase the use and availability of public transport (Case Study 9). The number of light rail systems in American cities has doubled since 1995. Use of public transport is growing in the United States, particularly on light rail and trains (Newman et al 2012).

Almost every capital city in Australia is now planning, building or extending new light rail or train services (The Age 2018b, e.g. Figure 12).

5.1.1 CREATING A PUBLIC TRANSPORT "NETWORK EFFECT"

An effective public transport service recognises that not all journeys - for work, education, or social activities - involve travelling to and from the city. Providing a seamless public transport service that enables people to travel from any part of the city or suburbs, to any destination in a direct, efficient and low cost way is critical to encouraging higher levels of public transport use. The key to encouraging a shift to public transport is by creating a "network effect", resembling a grid or web pattern criss-crossing the city.

Key elements required for an efficient, high quality public transport network include implementing:

- Regular, reliable and frequent services.
- A network or grid of high speed, high capacity cross-city public transport links and local feeder bus services.
- A series of well-designed interchanges, or connection points, and simple, coordinated timetables enabling commuters to quickly and easily switch from one route or mode to another.
- Integrated ticketing.
- Information, including public transport maps which are comprehensive and easy to use as well as effective signage at rail and bus stations.

(Victorian Auditor General 2014; Stone and Kirk 2017).

Real world data on cities (such as Vancouver, Canada, Zurich, Switzerland and Vienna, Austria) that have implemented this kind of public transport network, have recorded higher levels of public transport use, compared to similar cities where public transport follows a radial pattern (focused on travel to and from the city) (Stone and Kirk 2017).

This public transport "network effect" can even be retrofitted onto existing transport systems by re-designing bus routes in a way that provides efficient and direct cross-city services, to integrate with existing high capacity routes (such as rail lines) to and from the city. A number of cities around the world, and in Australia are now seeking to apply the principles of the "network effect" in redesigning their public transport systems in order to achieve higher rates of use such as Houston, Texas (Case Study 9).

5.1.2 LAND USE PLANNING AND PUBLIC TRANSPORT

The Australian Government's Smart Cities Plan promotes the concept of a "30 minute city", or one where in each part of the city it is possible to reach a major centre for work and services within 30 minutes (Commonwealth of Australia 2016c). The idea is for land use planning to design cities and their transport systems so that residents can access jobs, education, shops and recreational facilities within 30 minutes from their home. The new Sydney strategic plan *A Plan for Growing Sydney* sets out this as its basic strategic idea, and the Victorian Government's *Plan Melbourne* aims to achieve a 20 minute city (Commonwealth of Australia 2016c). Many other Australian cities have similar plans and objectives, often supported by local government planning.

However, delivering on the concept, where people have much less need for a car and many more local and cross-city transport options, is not straightforward or easy. Much of the land use in inner cities is rapidly redeveloping at higher densities due to large demand by people to live nearer urban amenities and jobs, but middle and outer suburbs are struggling to redevelop with the kind of densities needed in suburban centres that can make them viable (Thomson et al 2016).

If land use planning is conducted in isolation from transit planning then problems follow. For example, parts of Australian inner cities have been developing in the absence of additional public transport investment contributing to overcrowding on public transport. Many cities are encouraging infill development of new high and medium rise developments along existing public transport corridors in the inner city. Where such development and population growth occurs without a corresponding increase in the frequency and provision of public transport, this can further exacerbate pressures on transport systems.

A number of Australian cities are also expanding outer suburban boundaries and opening up new areas for development. This can result in the creation of outer suburbs beyond the reach of existing public transport networks. As a result, people living in outer suburbs of Australian cities often have access to fewer public transport options than inner city areas or no public transport options at all. Where public transport services do exist in these outer areas, they are often less direct, meaning longer travel times (Infrastructure Australia 2016).

When urban development (such as new apartments, shops and offices) is planned around rail stations then not only do more people have easy access to the train but they have much less need to travel in general, have shorter distances to travel by car and easier walking and cycling distance to shops and services. Such integrated developments dramatically improve the value for money for public transport projects (Newman and Kenworthy 2015).

Integrating transport planning and land development can be combined into train and land packages, and can help finance the development of public transport. This approach called the Entrepreneur Rail Model (Newman et al 2017) is how tram and train lines were first built and has been rediscovered in Japan and Hong Kong with increasing numbers of projects now attempting such partnerships in America and Australia (Newman et al 2017). This integration of transit, land development and finance is being pursued as part of City Deals with the Federal Government and suggests that some structural reform of transport systems may be underway.

5.1.3 CAPTURING "LOW HANGING FRUIT" WITH SERVICE PLANNING AND NEW TECHNOLOGY

In addition to investing in upgrading existing and building new public transport infrastructure, network planning and improved services are critical to encouraging more people to use public transport.

Australian governments have a history of investing in large public transport infrastructure projects but then failing to enact service plans to make full use of the added capacity. For example, the Melbourne City Loop was planned in the early 1970s as a measure to increase peak hour central-area train capacity, yet from the time it opened in 1981 until 2008, the number of train arrivals at Flinders Street station in the busiest hour remained below the 95 arrivals in the 1960 timetable (excluding the St Kilda and Port Melbourne lines). Following the completion of the Regional Rail Link in 2015, the number of train arrivals at Flinders Street via Newport between 8am and 9am has increased by just 1, from 11 to 12.

There are many opportunities in Australian cities to capture 'low hanging fruit' by providing additional services (more frequent buses, or rail services) on existing routes without costly infrastructure investment. For example in Melbourne, many suburban train lines have the capacity to provide service every 10 minutes all day, 7 days a week, following the example set by the Frankston and Dandenong lines. This is possible because main train lines already provide service better than every 10 minutes during peak times. For bus routes, providing additional services requires nothing more than an expanded fleet, additional depot space and drivers.

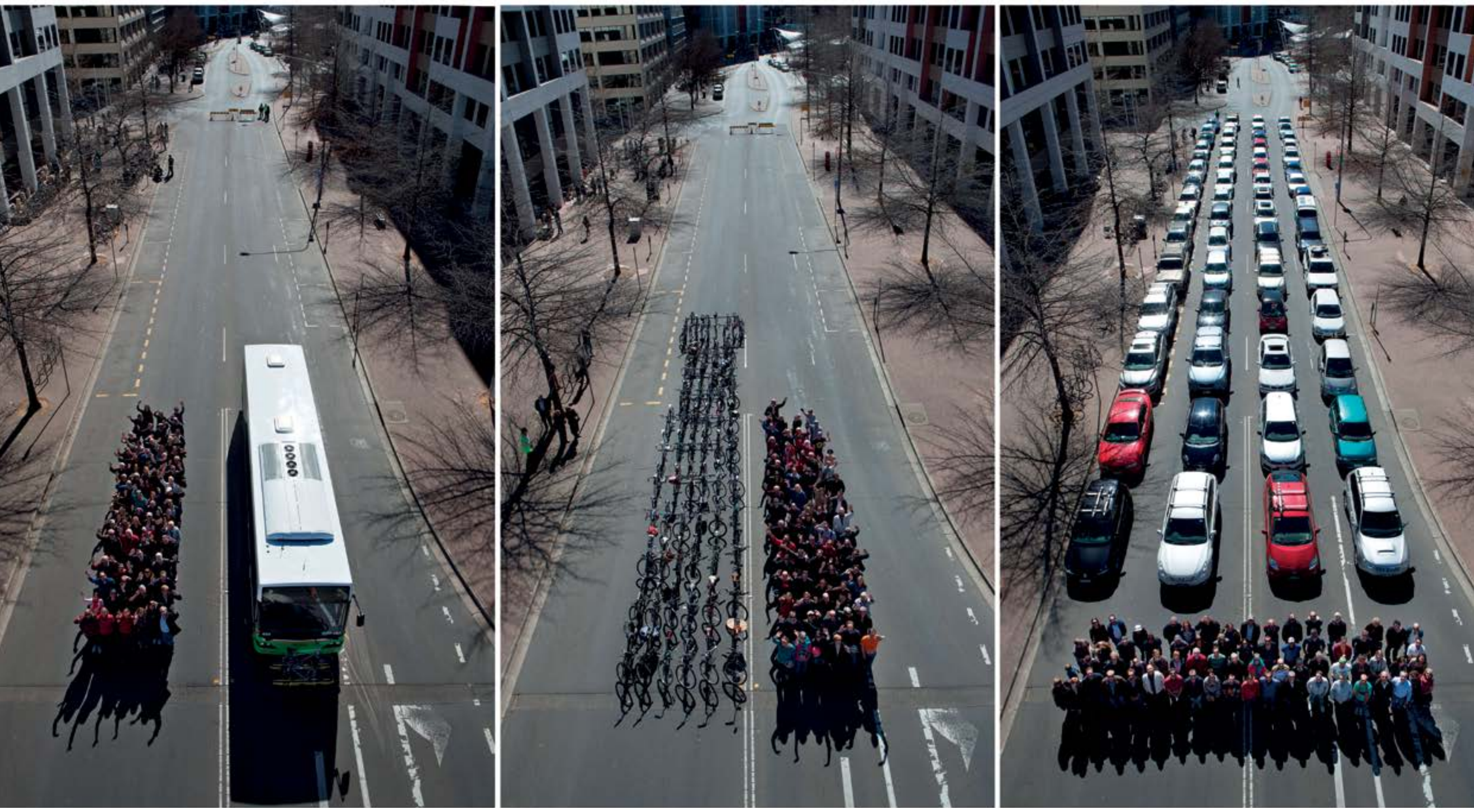
There are also a number of ways to increase the speed of buses by making their routes more direct and giving them right of way. New technology like the Trackless Tram offers ways of significantly increasing speed, ride quality and patronage without significant cost (Glazebrook and Newman 2018).

5.1.4 BENEFITS OF PUBLIC TRANSPORT

Compared to building new roads, investment in public transport is a more efficient (e.g. transporting more people, requiring less land use) way of meeting the transport needs of growing populations in Australian cities. Roads and car travel use a disproportionately large amount of land compared to public transport, especially in the inner city (e.g. Figure 13). For example, in the City of Melbourne, more than 60% of street space is dedicated to roads and car parking, even though driving only accounts for around a third of trips to the city (City of Melbourne 2018a).

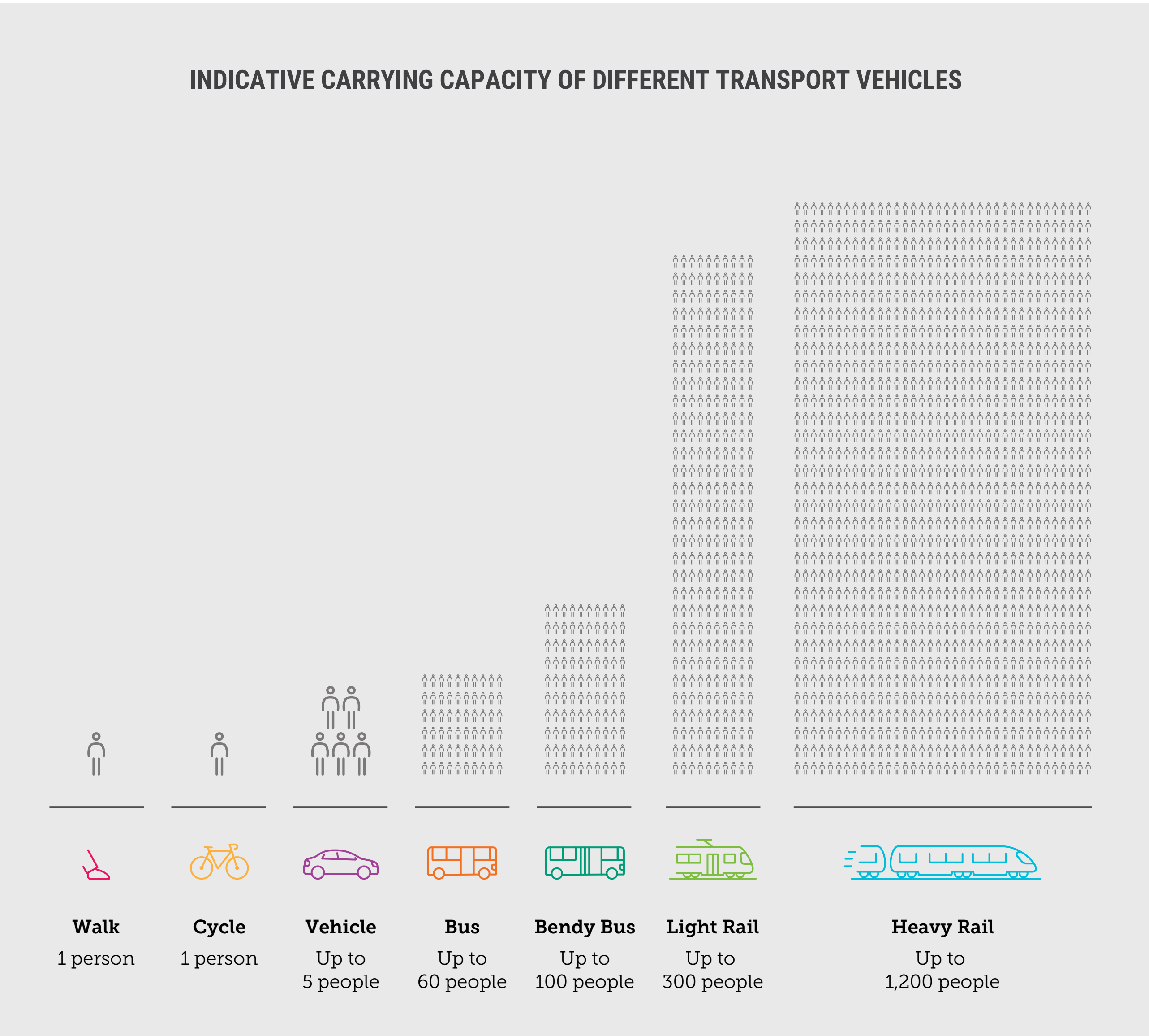
Public transport options can carry more people and require less land use compared to roads with cars carrying one or two people (Infrastructure Australia 2016; Figure 13). For example, in Melbourne, trams along Swanston Street carry more people to and from the city each day than the West Gate Bridge (City of Melbourne 2018b).

Figure 13: Cars use a disproportionately large amount of land compared to public and active transport.



Expanding access to and use of high quality public transport is a proven way to reduce car use and associated greenhouse gas pollution. People who live in communities with accessible public transport tend to own fewer vehicles, drive less and rely more on public transport than other areas (Litman 2010).

Figure 14: Carrying capacity of different transport modes.



Source: Transport for NSW.

5.2 Walkable, cyclable cities

Cities which cater for pedestrians and bike riders enable residents and visitors to minimise their need to rely on cars to get around. Australian cities have much lower walking and cycling rates than European cities (Pojani et al 2018), although much has begun to happen following the ideas of Jan Gehl (see Section 3.5).

Figure 15: Adelaide Riverbank Pedestrian Bridge.

Improving walkability and cyclability in cities requires:

- Making footpaths and bicycle lanes a standard component of transport planning (e.g. Figure 15)
- Positive messaging and political support:
  - highlighting the benefits to businesses and households from high quality walking and cycling infrastructure (and removing road and parking space to accommodate pedestrian and cycling paths).
  - encouraging people to take up active travel options
- Greater funding for active transport in infrastructure budgets. For example, in 2016 the combined national investment in cycling totalled $122 million, equivalent to less than 1% of funding for roads (Pojani et al 2018).

5.3 Renewable powered electric vehicles

While there has been significant media and public focus on electric cars, there are significant benefits of shifting to battery electric buses, bicycles and trucks as well as cars.

The source of electricity for electric car charging is critical to reducing emissions. As electric vehicle uptake grows, this must be accompanied by new, additional investments in renewable energy. As electric vehicles are an additional source of electricity demand, it is important that new renewable electricity sources for charging electric cars are additional to those that would otherwise be provided, so as not to undermine pollution reductions being made in the electricity sector.

5.3.1 RENEWABLE POWERED PUBLIC TRANSPORT

Some Australian states and cities are taking steps towards renewable powered public transport. In 2013, Adelaide led the way as the first city in the world to introduce a solar-charged electric bus operating on the city's free connector service (City of Adelaide 2013), while Flinders University is trialling an autonomous solar-powered electric bus to shuttle students from its nearby train station. A similar trial is underway at Curtin University. Canberra, a city on track for 100 per cent renewable energy by 2020, is trialling two electric buses, and is ultimately planning to transition its ageing bus fleet to electric (ACT 2018). Melbourne's tram network will soon get their electricity from large-scale solar plants in the north of Victoria (Case Study 10). New South Wales' 87MW Beryl solar project has been contracted to power Sydney's new north-west rail line (Renew Economy 2018a).

5.3.2 ELECTRIC BUSES

Electric buses offer significant benefits over their diesel and gas counterparts, which dominate inner city bus fleets in Australian cities today. While diesel buses are noisy and their exhaust is bad for health and climate change, electric buses are modern, quiet, and clean people movers. Electric buses are more expensive upfront, but with lower fuel, maintenance and running costs.

Switching from gas or diesel to battery electric buses significantly reduces greenhouse gas emissions (Dallman et al 2017). Battery electric buses produce less greenhouse gas pollution per kilometre than buses running on compressed natural gas or diesel. This is the case, even in countries like Australia where fossil fuels like coal and gas make up a relatively high proportion of electricity generation (Dallman et al 2017). As the percentage of renewable energy in the electricity mix increases, the climate benefits associated with switching to electric buses also increases.

A shift away from diesel buses can also dramatically reduce 'black carbon' emissions from diesel exhaust. Black carbon is a sooty black material that is both harmful to human health, and a potent greenhouse gas. In the atmosphere, black carbon contributes to over 3,000 times the warming over 20 years compared to carbon dioxide.

Shifting from diesel to electric buses would improve air quality, particularly in inner urban areas where there is a concentration of bus services.

Buses operating in cities are particularly well suited to switching to electric, as they have known routes and timetables. Charging infrastructure (as well as solar panels) can be readily installed on bus terminals and interchanges. Electric bus models are now available which can drive up to 1,700 kilometres on a single charge - meaning buses can operate throughout the day without needing charging (Quartz 2017)

While in some cases today, electric buses have a higher upfront cost than their diesel equivalents; electric buses are already cost-competitive with diesel over their operating life, when the substantially lower operating and maintenance costs of electric buses are taken into consideration (BNEF 2018a; WRI 2018). Furthermore, the cost of electric buses is coming down rapidly as global uptake increases. Electric buses are expected to be the same or cheaper than diesel buses by 2030 or earlier. Bloomberg New Energy Finance projects electric buses will make up nearly half of the global fleet of buses by 2025 (BNEF 2018b).

In 2017, the city of Shenzhen in China became the first major city in the world to switch its entire bus fleet to electric. Numerous other cities and towns are following suit. Fourteen major cities - London, Copenhagen, Auckland, Paris, Milan, Los Angeles, Barcelona, Vancouver, Mexico City, Rome, Heidelberg, Quito, Seattle and Cape Town have pledged to buy only electric buses from 2025 to reduce pollution (C40 2017). Many of these cities are already investing in electric buses, with Los Angeles ordering 100 electric buses while London introduced long-distance electric double decker buses (Elektrek 2017). San Francisco's transport agency will only purchase electric buses from 2025 and aims to switch its entire bus fleet to electric by 2035 (SFMTA 2018).

5.3.3 ELECTRIC CARS

Compared to petrol and diesel counterparts, electric cars bring benefits through reduced greenhouse gas pollution, reduced reliance on imported fuels, cleaner air and the potential to attract investment and jobs in vehicle manufacturing.

The source of electricity for electric car charging is critical to reducing emissions. As electric cars are an additional source of electricity demand, it is important that new renewable electricity sources for charging electric cars are additional to those that would otherwise be provided, so as not to undermine pollution reductions being made in the electricity sector. Public provision of electric vehicle charging infrastructure can ensure that these charge-points are powered by 100% renewable energy.

Electric vehicles powered entirely on renewable energy have negligible emissions, compared to an average new car (182gCO_2/km) (The ICCT 2015; National Transport Commission 2017). Charging an electric vehicle with renewable energy - be it rooftop solar panels or 100% GreenPower purchased from an electricity retailer - is substantially cheaper than the cost of fuel for an equivalent petrol car (AECOM 2015).

In most cases, charging an electric vehicle from the electricity grid results in less greenhouse gas pollution than a conventional vehicle. Even without 100% Greenpower or solar panels, charging an electric vehicle from the electricity grid results in less greenhouse gas pollution compared to a conventional vehicle, in every state except Victoria (ClimateWorks 2018).

Solar powered electric cars would seem to be a good fit for Australia, with its world-leading uptake of household solar (Australian Energy Council 2016), and high dependence on cars to get around. As more Australians put solar on their rooftops, and the proportion of renewable electricity in the grid grows, emissions associated with electric vehicles will fall further.

Shifting from diesel and petrol to electric vehicles would improve air quality, particularly in inner urban areas.

Today an electric car often costs more upfront than a conventional car. However, as global production increases, costs are coming down rapidly. By 2025, an electric car is anticipated to be similar in terms of upfront cost compared to a conventional (petrol or diesel) vehicle.

Falling costs together with supportive government policies are driving global growth in electric vehicles. Worldwide electric vehicle sales reached 1.2 million in 2017, increasing rapidly from hundreds in 2010. There are now over 3.2 million electric cars on the road worldwide (Lutsey et al 2018).

Car manufacturers are investing more than $150 billion to increase the production of electric vehicles (Lutsey et al 2018) and are aiming to achieve annual sales of 13 million electric cars by 2025 (from 1.2 million in 2017). Over 90% of global vehicle sales and production occurs in China, Europe, Japan and the United States (Lutsey et al 2018).

Governments around the world at national, state and local levels are seeking to accelerate the shift to electric vehicles. Mandatory greenhouse gas standards operating in 80% of the global car market are one factor driving the adoption of electric vehicles. In addition, specific targets to drive electric vehicle uptake have been put in place in China, California (United States), and Quebec (Canada) and are under consideration in Europe (Lutsey et al 2018).

In Australia, the adoption of electric vehicles is being held back by the lack of policy support or incentives, higher upfront cost, limited choice of available electric vehicles for sale in Australia, and the availability of public vehicle charging infrastructure (Business Insider 2017).

According to ClimateWorks, 2,284 electric vehicles were sold in Australia in 2017, around 0.2% of new cars sold that year (ClimateWorks 2018; NTC 2017). Contrast this to Norway, where 39% of all new cars sold are electric (Reuters 2018a).

In New Zealand, which has a target to reach 64,000 electric cars by 2021, new electric car sales, outstripped sales here in Australia (Table 6).

A number of countries have signaled they will move to ban fossil fuelled (petrol, gas and diesel) cars, including:

- Norway by 2025
- India by 2030
- The Netherlands by 2030
- United Kingdom by 2040
- France by 2040 (CNN 2017; ACT Government 2018).

Table 6: Australia and New Zealand electric car uptake compared.

Australia	New Zealand
2,284 new electric cars sold in 2017 Proportion of new car sales - 0.2%	3,659 new electric cars sold in 2017 Proportion of new car sales - 3.4%
7,341 total electric cars by end 2017 Proportion of total registered vehicles - 0.04%	6,209 total electric cars by end 2017 Proportion of total registered vehicles - 0.12%
No national electric vehicle target	Target: 64,000 electric vehicles on the road by 2021

Sources: ABS 2018b; ClimateWorks 2018; FCAI 2018; Motor Industry Association 2018; NZ Transport Agency 2018; Transport NZ 2018.

New Zealand's electric car sales surpasses Australia's.

BOX 2: WHAT ABOUT EMERGING TRANSPORT TECHNOLOGIES?

New transport technologies are rapidly emerging on the scene, variously referred to as 'disruptive technologies', the 'gig economy', or the 'sharing economy'. These new transportation technologies range from autonomous (driverless) vehicles, ride sourcing applications to public transport applications and bicycle share schemes. Each of these new technology driven transport options can have complex interactions with existing transport services and potentially significant positive or negative implications on greenhouse gas pollution levels.

Examples of emerging transport technologies include car-sharing services (where users can access shared vehicles rather than owning their own e.g. Flexicar), ride sourcing applications (e.g. Uber), public transport journey planning and payment applications, autonomous or driverless vehicles, bike sharing schemes (e.g. obikes) and drones.

Policy makers should consider the potential implications for individual technologies, particularly any environmental, social and economic impacts and whether proactive policy or regulation is necessary to avoid adverse or unintended outcomes.

For example, considerations may include whether individual technologies will:

- improve or worsen associated greenhouse gas pollution
- reduce or increase demand for private or public transport
- improve or worsen car dependency and congestion levels
- increase or decrease the cost of transport to individual users and society
- cannibalise existing services (e.g. traditional taxi services) or substitute for car use or for other modes such as public transport, cycling or walking
- change car ownership
- increase or decrease competition
- support or undermine public transport services
- impacts on physical activity levels
- impacts on land use allocated to private vehicles and parking
- impacts on pedestrians and bike riders
- provide transport access to vulnerable groups
- create other impacts or trade-offs, for example accessing user data, associated advertising, flow on impacts for other services and businesses, changing nature of employment conditions.

Sources: Institute for Sensible Transport 2016; Kleinman and Rohr (2018).

5.4 Policies, standards and targets

Mandatory greenhouse gas standards are government policies or regulations that require car manufacturers to reduce the emissions from new cars over time.

Mandatory greenhouse gas standards (or vehicle efficiency standards) apply to over 80% of the world's car market (including the United States, Europe, Japan, Korea, China, India, Canada and Mexico) (CCA 2014; Lutsey et al 2018). Australia is one of only a handful of OECD countries without mandatory greenhouse gas standards for vehicles (ACEEE 2018).

Australia is one of only a handful of OECD countries without greenhouse gas standards for vehicles.

The sooner mandatory emissions standards are introduced, and rapidly strengthened, the greater the impact. If strict standards are introduced, Australia can prevent up to 65 $MtCO_2$ of emissions by 2030 (Australian Government 2017). This is equivalent to the annual emissions from seven Liddell Power Stations (Clean Energy Regulator 2018). Urgency is key. Mandatory emissions standards have wider benefits, reducing fuel bills for car owners, saving an estimated $8,500 over a vehicle's lifetime (CCA 2014).

Since 2015, the Federal Government has considered in detail the introduction of emissions standards for cars and light vehicles, but the Federal Government has yet to implement any such policy.

The success of mandatory emissions standards in cutting greenhouse gas emissions relies on new lower emissions vehicles replacing existing higher emissions vehicles over time. Even with the introduction of strong mandatory emissions standards, it will be important to ensure that higher emissions vehicles are retired, or taken off the road, over time so that new vehicles (whether they be lower emissions, or electric) don't simply add to the total number of vehicles on the road, and the total vehicle-kilometres travelled.

6. Case studies

6.1 Australia

CASE STUDY 1:

Gold Coast Light Rail

The first stage of the new Gold Coast Light Rail project opened in 2014, connecting 16 stations along 13 kilometres of track. Services run at least every 15 minutes on weekdays. Already the light rail project has carried 21,000 passengers on average every day, and contributed to 23% growth in public transport use between 2015 and 2016.

The project has also reduced vehicle traffic on the Gold Coast Highway at Broadbeach by 21% (City of Gold Coast 2017). Stage 2 of the light rail opened in December 2017, extending the line by a further 7.3km (Gold Coast Light Rail 2017).

This is just the first of several stages, as part of the Gold Coast City's Transport Strategy 2031.

Figure 16: The Gold Coast light rail has reduced vehicle traffic on the highway at Broadbeach by 21%.

CASE STUDY 2:

Electric Buses Driving New Manufacturing Jobs in Adelaide

In July 2017, the first Australian designed, engineered and manufactured electric bus rolled off the production line and onto Adelaide's streets, becoming part of Adelaide's public transport network. The success of this project has seen the manufacturers Precision Buses contracted to produce 50 more low carbon buses for New South Wales, Queensland and Victoria. This will increase the number of employees at the organisation from 29 to 79 (Business Insider 2017).

CASE STUDY 3:

ACT Zero Emission Vehicle Action Plan

The ACT Government is on track to achieve 100% renewable electricity by 2020, and has a target to reach net zero emissions before 2050. With transport a key source of greenhouse gas pollution in the ACT, the Government has released an action plan to dramatically reduce greenhouse gas pollution from vehicles as well as encouraging people to walk, cycle and use public transport instead of driving.

The ACT Government has already undertaken a number of actions including:

- Transitioning the ACT Government fleet to zero emissions vehicles. The ACT Government now has 17 electric vehicles, 7 plug-in hybrid vehicles, 62 hybrid vehicles and 8 electric bikes
- Trialling battery electric buses on a number of routes throughout Canberra
- Investigating hydrogen vehicles
- Encouraging the rollout of public charging infrastructure

Future actions include:

- All newly leased ACT Government vehicles will be zero emissions from 2020-21
- Investigating covered car parks with solar powered vehicle charging stations
- Creating incentives for zero emissions vehicles such as parking priority and ability to drive in transit lanes (ACT Government 2018)

CASE STUDY 4:

Queensland Electric Vehicle Superhighway

The Queensland Government have recently rolled out stage one of what they claim to be the world's longest electric vehicle highway in a single state. The project came online in January 2018 and connects Coolangatta in the south east of the state to Cairns in the far North. All of these chargers are superfast DC chargers and most of them have been installed by Brisbane-based company Tritium. Tritium's DC chargers can charge an EV battery in as little as 10 minutes (Reneweconomy 2018b).

This project enables long distance trips to be undertaken in electric vehicles across Queensland. Further charging stations will come online later this year (Reneweconomy 2018b).

CASE STUDY 5:

Melbourne's Solar Powered Tram Network

Victoria's tram network is one of the largest in the world, with 200 million boardings every year (Yarra Trams 2018). The entire tram network will soon be powered by 100% renewable energy, with the construction of 138MW of solar capacity by the end of 2018. The Bannerton and Numurkah solar farms in northern Victoria are being built after winning a Victoria government tender in 2017 (Premier of Victoria 2017).

Figure 17: Melbourne's trams will soon get all their electricity from solar plants.

CASE STUDY 6:

Adelaide's World First Solar Electric Bus and electric vehicle charging stations

Adelaide is home to the world's only pure electric bus powered entirely by solar energy. Unlike other solar powered transport, the "Tindo" bus does not have solar panels on its roof. Instead it is recharged by energy from solar panels on the roof of the Adelaide Central Bus Station. The bus runs on Adelaide's free connector bus service every day (City of Adelaide 2013).

The City of Adelaide installed 19 fast-charging stations in the Central Market precinct in 2017. These charging stations are DC chargers. This means they can fully charge an electric vehicle with a range of 52 km (eg. Mitsubishi Outlander) in just 30 minutes. Tesla Superchargers have also been installed, which can charge a Tesla Model S and Model X with a range of 270 km - in just 30 minutes. The Tesla Superchargers will eventually be rolled out across South Australia and enable a Tesla car to travel from Adelaide up to Brisbane (Premier of South Australia 2017).

A further 25 charging stations will be installed throughout the city by mid-2018 (Premier of South Australia 2017).

Figure 18: Adelaide's world-leading solar electric bus.

CASE STUDY 7:

Sustainable Transport Moreland, Victoria - integrated transport strategy

The city of Moreland in inner urban Melbourne has developed an integrated strategy for transport which aims to achieve a shift to more environmentally sustainable travel behaviour; support transport access for all parts of the community; and improve safety and support development around transport hubs (with access to trains, trams, bicycle and walking paths) in Moreland.

Moreland supports car sharing services for residents who don't own a car. In 2012, the council installed Victoria's first electric vehicle charging station, it now has three charging points throughout the city, and is integrating electric cars into its council fleet (Figure 19). The council has strategies to encourage walking, cycling and public transport in Moreland (City of Moreland 2017).

City of Moreland installed Victoria's first electric vehicle charging station.

Figure 19: One of Moreland City Council's electric vehicle charging points.

6.2 International

CASE STUDY 8:

Sustainable transport Washington, D.C. - transport targets and actions

In 2012, Washington DC (population 643,000), embarked on an ambitious and comprehensive plan "Sustainable DC", to tackle the city's key sustainability challenges of jobs and economic growth; health and wellness; equity and diversity; and climate and environment (Sustainable DC 2016). The plan includes a target for 50% of city's power use (both council operations and the community) to come from renewable energy sources by 2032.

Transportation was identified as one of the Sustainable DC plan's seven key areas. Specific targets were set for trips within the city by 2032 - with car travel to decrease to less than 25% of trips, public transport trips to increase to 50%, and biking and walking to increase to 25%. The goals and targets were underpinned by a detailed action plan (Table 7).

As a result of its actions, 2016 saw Washington DC become the equal first out of 50 US cities (tied with Boston) for the proportion of commuters walking or cycling, and second best (after New York) when public transport was included (Alliance for Biking and Walking 2016). The city was one of two major cities (with Portland, Oregon) to make a significant gain in the share of commuters biking and walking (Alliance for Biking and Walking 2016).

Nearly 39% of Washington DC residents now commute by public transport, nearly 13% walk and 4% ride (Alliance for Biking and Walking 2016). These shares are significantly higher than the average mode shares for Australian cities - 14% by public transport, 3.8% walk and 1.3% ride on average (Australian Government 2013).

Figure 20: Washington DC Capital bike share scheme.

Table 7: Sustainable DCs Transportation Goals, Targets and Actions.

Goals	Targets	Actions
Improve connectivity and accessibility through efficient, integrated, and affordable transit systems	Increase use of public transit to 50% of all commuter trips	› Complete 60 kilometres of tram networks › Improve transit connections to employment and activity centers from underserved areas › Define and secure permanent funding for transit planning and improvements › Design transit systems for resilience to extreme weather events
Expand provision of safe, secure infrastructure for cyclists and pedestrians	Increase biking and walking to 25% of all commuter trips	› Develop a citywide, 100-mile bicycle lane network › Expand the Capital Bikeshare program by 200 stations › Partner with community organizations to deliver bike and pedestrian safety education › Collect data to improve understanding of cyclist and pedestrian travel patterns › Program crosswalks and traffic lights for improved safety and convenience of pedestrians and cyclists
Reduce traffic congestion to improve mobility	Reduce commuter trips made by car or taxi to 25%	› Implement an expanded Performance-Based Parking program › Expand car-sharing programs to low-income residents using financial tools › Encourage private businesses to offer incentives for employee travel by transit, walking, or biking › Encourage and promote telecommuting and alternative work schedules for employees › Study the feasibility of a regional congestion fee for travel during peak hours
Improve air quality along major transportation routes	Eliminate all "unhealthy" air quality index days, including "unhealthy for sensitive groups"	› Strictly limit idling engines. › Require District Government, and encourage private businesses, to purchase clean fuel, low-emission fleet vehicles. › Expand electric vehicle charging infrastructure throughout the city › Offer incentives to avoid driving and other emission-generating activities on predicted Code Red and Orange air quality days › Track and report mileage data from clean fuel, low-emission, and electric vehicles

Source: Sustainable DC 2016.

CASE STUDY 9:

Houston bus network re-design

Houston is often regarded as one of the world's most car-dependent cities. Three years ago Houston made dramatic changes to the design of its bus network in order to encourage more commuters out of their cars and onto public transport.

In 2015, the Houston Metro completely redesigned the city's bus network, routes and timetables. The transformation involved shifting away from a system where most routes ran to and from the city, to a grid network of bus routes cutting across the city, with more frequent services.

Key elements of the redesign included:

- More frequent buses running at least every 15 minutes along major routes
- Routes and timetables that enable commuters to easily transfer from one route to another
- More predictable buses run on the same schedules on weekdays and weekends
- New routes following a grid pattern enabling people to more easily and directly travel to and from a greater range of locations across Houston (not just the city centre) (Mobility Lab 2018).

Prior to the re-design, the bus service had experienced a 20% decline in patronage between 2007 and 2011 (Mobility Lab 2018).

The bus network overhaul is widely judged to have been a success with local bus and light-rail systems recording a gain of 4.5 million boardings – an increase of 6.8% - between September 2015 and July 2016 (City Lab 2016). Bus ridership on Saturdays and Sundays has increased even more, with 13% and 34% increases respectively (City Lab 2016). Houston is one of only two United States cities (along with Seattle) to increase bus patronage in the last three years.

Figure 21: Houston Metro Re-design - before and after.

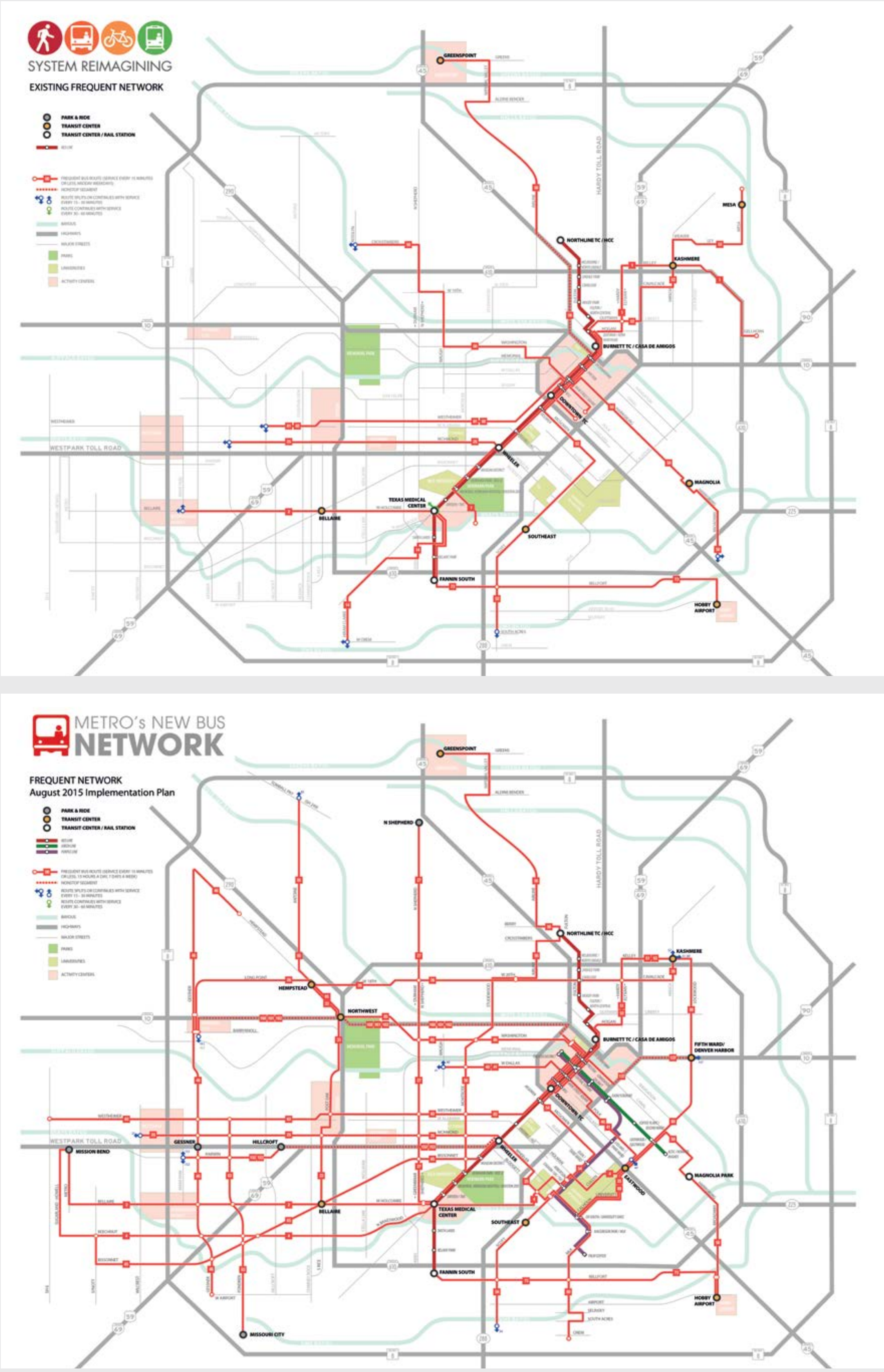


Figure 22: Aucklands Nelson Street cycleway.

CASE STUDY 10:

New Zealand Urban Cycleways Programme

The New Zealand Government is investing NZ$333 million on cycling infrastructure through its Urban Cycleways Programme. The program is funding over 50 new cycleways, with 36 of the projects completed or under construction.

The completed cycleway projects are already encouraging an increase in cycling, for example in Christchurch there has been a 21% annual increase in people riding their bikes into the city (New Zealand Government 2017).

Figure 23: Inside a train in the Shanghai metro.

CASE STUDY 11:

China's Train Metro Network

Since 1995, the number of Chinese cities with metro lines has increased from 1 to 25 and that number is still rising. Across the country, there are now more than 5,000 kilometres of metro lines (not including commuter services between cities and the country's extensive high speed rail network) (The Transport Politic 2018).

This investment has led to massive increases in public transport use. Ridership on Beijing and Shanghai's metro systems alone has doubled since 2010 (The Transport Politic 2018).

A recent study by Gao and Newman (2018) has shown that Shanghai and Beijing have both peaked in private car use per capita as both Metros have grown so popular. The result has been a decoupling of economic growth from car use, showing how it is feasible to enable the transition to low carbon options without losing jobs and economic opportunities.

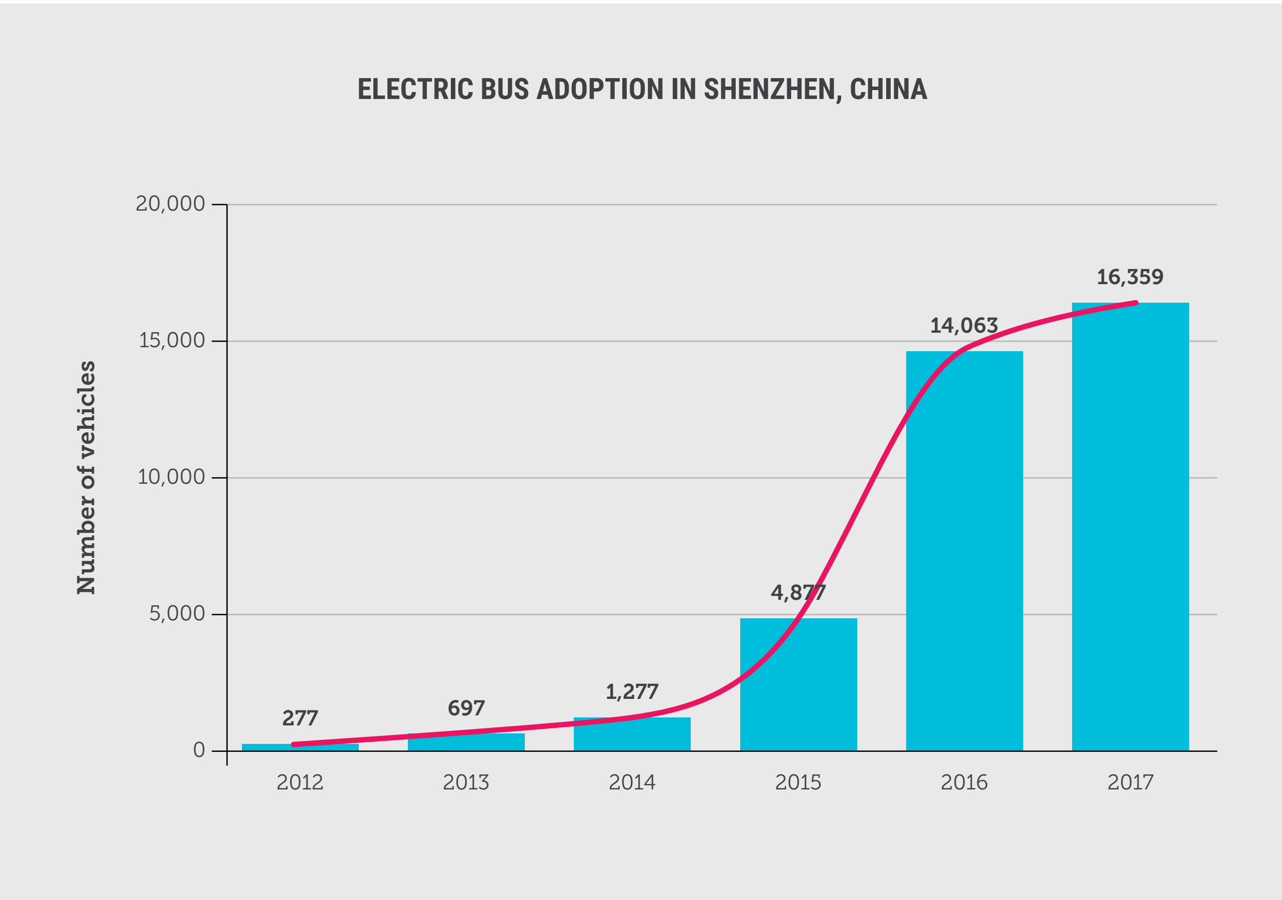
CASE STUDY 12:

Shenzhen, China - world's first fully electric bus fleet

China is leading the global rollout of electric buses, with over 300,000 on the road at the end of 2017. In the Chinese city of Shenzhen, the city's entire 16,000-strong bus fleet was converted to electric vehicles by the end of last year. The replacement of the city's diesel bus fleet began with a pilot in 2011 – just 7 years ago. Now, the city of 11.9 million people – half the size of Australia – is entirely serviced by electric buses (CleanTechnica 2017).

Figure 25: One of Shenzhen's electric buses being charged.

Figure 24: Electric bus adoption in Shenzhen, China.



Source: WRI 2018.

CASE STUDY 13:

Santiago's Public Transport Powered by Solar

The public transport system in Santiago, the capital of Chile in South America, will be run almost entirely on solar energy, after a power purchase agreement was signed to supply the system with solar power. The agreement will support the construction of a 100MW solar farm that will begin operating in 2018. This will massively reduce pollution from Chile's public transport system, which currently transports 2.2 million passengers a day (CleanTechnica 2016).

CASE STUDY 14:

One Third of New Zealand Government Cars to be EV's

The New Zealand Government has pledged that one-third of the government car fleet will be hybrid or electric by 2021. The Government currently has 15,500 vehicles, so by 2021, it will have 5,000 hybrid or electric vehicles. This will contribute to New Zealand's plan to have 64,000 electric vehicles by 2021 (National 2017).

Currently New Zealand has just 4,200 electric vehicles, although this is significantly higher than in May 2016, when just 1,300 vehicles were electric (National 2017).

Figure 26: A view of Santiago's metro train line, which will soon be powered by solar.

CASE STUDY 15:

California Aims for Five Million Electric Vehicles

California has ambitious plans for electric vehicles, with a target for 1.5 million by 2025 and 5 million by 2030 (Reuters 2018b). The state is already on its way to meeting the 2025 target, with the second largest EV market in the world consisting of over 300,000 fully electric and hybrid vehicles (Forbes 2017). Importantly the EV target is accompanied by other policies, such as the addition of 250,000 vehicle charging stations and 200 hydrogen fuelling stations by 2025 - at a cost of $2.5 billion (Reuters 2018b).

Strong, clear policies like California's EV targets have motivated car makers to build dozens of new EV models (Reuters 2018b).

CASE STUDY 16:

India Plans for EV Future by 2030

In order to deal with poor air quality and pollution, India plan to phase out the sale of all diesel cars by 2030. This ambitious target would require around 10 million electric cars to be sold in 2030 - dwarfing the global total of electric cars in 2015 (which stood at just 1.3 million). In 2016, there were just 5,000 EV's on Indian roads (Bloomberg 2017).

Along with significantly reducing toxic pollution and CO_2 emissions, the plan would also significantly cut India's oil imports (Bloomberg 2017).

Figure 27: Electric Vehicles in India.

CASE STUDY 17:

Electric Car Targets in Europe and beyond

There is a range of countries in Europe that have set up electric vehicle targets including Germany, France, the United Kingdom, Spain, Denmark, Ireland, Austria, Portugal and the Netherlands. These targets vary from the partial uptake of electric cars to the complete replacement of petrol and diesel cars (IEA 2017a).

Eight states in the United States have also introduced electric car targets, as have China, Japan, South Korea and India (see above). Combining all these targets, the International Energy Agency estimates that 13 million electric cars will be deployed amongst these countries by 2020 (IEA 2017a).

CASE STUDY 18:

Car Companies Building a European Charging Network

Volkswagen, BMW, Ford and Daimler (part of Mercedes) are starting construction on a $50 billion fast charging network along highways across Europe. The companies plan to have 100 fast charging stations in place by the end of 2018 and 400 by 2020. This project will enable owners of electric cars to make transcontinental journeys without having to worry about where to charge their cars (Automotive News Europe 2018).

This project builds upon the leadership shown by a range of European countries. Germany has already developed a comprehensive charging network that includes 8,515 charging outlets. This is one third higher than the 2016 total (Automotive News Europe 2018).

7. Conclusion

Now is Australia's opportunity to cut greenhouse gas pollution from transport while moving people in our cities more efficiently, reducing urban air pollution and noise and saving commuters money.

Australia's growing cities are starting to see breakdowns in the performance of the current transport systems. Stress, congestion, air pollution, noise, ever increasing public space dedicated to roads, and the high cost of private transport are all exacerbated by our current reliance on roads and high polluting cars.

Cities around the world are fast-tracking transport solutions to climate change with three key strategies for reducing pollution from the transport sector:

1. Avoiding or reducing the need to travel. This can be achieved through improved telecommunications and urban planning.

2. Providing viable alternatives to driving, such as expanding access to reliable, comfortable public transport, cycling and walking alternatives.

3. Reducing pollution across transport modes and vehicles. This can be achieved by electrifying and powering cars, buses, trains and light rail with 100% renewable energy. In addition, policies supporting stringent, mandatory greenhouse gas emissions standards for cars and other vehicles (and strengthening these over time) could be adopted.

It's time for Australia to get on board with transport solutions to climate change.

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BRIEFING

JUNE 2016

A technical summary of Euro 6/VI vehicle emission standards

This briefing is a comprehensive technical overview of the Euro 6/VI vehicle emissions standards, which tighten limits on air pollutant emissions set in previous European standards and require the best technology currently available for vehicle emissions control.

Countries outside of Europe, the United States and Japan have largely patterned their emissions policies on European regulations and the associated mandates for clean, low-sulfur fuels. By adopting the Euro 6/VI vehicle emission standards, these countries can achieve up to a 99 percent reduction in the emission of pollutants like fine particulate matter (PM2.5), reducing the risk of ischemic heart disease, lung cancer, stroke, and asthma.

In this briefing, we look at the historical context of European regulations, summarize the core technical elements, review the control strategies available to achieve the pollutant limits, and conclude by considering what is likely to come next in the European regulatory pathway.

BACKGROUND

The G-20 countries account for 90 percent of global vehicle sales, and 17 out of the 20 members have chosen to follow the European regulatory pathway for vehicle emissions control. The European pathway consists of six stages of increasingly stringent emission control requirements, starting with Euro 1/I in 1992, and progressing through to Euro 6/

Prepared by Martin Williams and Ray Minjares.

VI in 2015.[1] A number of Asian and Latin American countries currently have Euro 2/II, 3/III, and 4/IV standards in force.

The European Commission's Thematic Strategy on Air Pollution, adopted in 2005, sought to reduce transportation emissions as part of an overall air-quality-improvement strategy. The Euro 6/VI emission standards specifically noted that a "considerable reduction in NO_x [oxides of nitrogen] emissions from diesel vehicles is necessary to improve air quality and comply with limit values for air pollution."[2] It was clear in 2005 that member states would face difficulties achieving ambient NO_2 limit values by 2010, and that adoption of Euro 6/VI emission standards would be a determining factor. The proposal further noted that meeting the NO_x emission standards "requires reaching ambitious limit values at the Euro 6 stage without foregoing the advantages of diesel engines in terms of fuel consumption and emissions of hydrocarbons and carbon monoxide."[3] The Commission recognized that setting more ambitious emission standards for NO_x at an early stage would provide long-term planning security for vehicle manufacturers who wish to continue pursuing diesel technology.

Euro VI limits for heavy-duty vehicles were introduced in Regulation 595/2009, and were amended by Regulations 582/2011 and 133/2014. The Euro 6 limits for light-duty vehicles came earlier and were introduced along with Euro 5 limits under Regulation 715/2007, promulgated in 2007. The simultaneous release of the Euro 5 and 6 light-duty vehicle standards provided the automotive industry with a longer timeline to develop strategies for meeting future emission limits. Other countries following the European pathway can move directly to Euro 6 for light-duty vehicles and Euro VI for heavy-duty vehicles now that the technology is available to meet the emission standards.

A fundamental prerequisite for the efficient operation of exhaust aftertreatment devices for both light- and heavy-duty vehicles is having fuel with a very low sulfur content. The sulfur content of gasoline and diesel fuels in Europe has therefore been regulated to meet very stringent fuel-quality standards. Prior to the Euro 3 and 4 standards, regulations required a minimum diesel cetane number of 51, beginning in 2000, and a maximum diesel sulfur content that year of 350 ppm. Starting in 2005, the maximum diesel sulfur content was limited to 50 ppm. Gasoline sulfur content was regulated to 150 ppm in 2000, and 50 ppm in 2005. By 2005, Europe began the phase-in of virtually sulfur-free gasoline and diesel fuels (<10 ppm sulfur), replacing 50ppm fuels, which were ultimately phased out by 2009. Without these fuel-quality improvements, the increasing stringency of the limits in European standards would not have been possible.

1 The European standards are designated by Arabic numerals for light-duty vehicles, and Roman numerals for heavy-duty vehicles.

2 Regulation (EC) No. 715/2007 of the European Parliament and of the Council, Official Journal of the European Union, L 171/1, June 29, 2007, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:171:0001:0016:EN:PDF.

3 Regulation (EC) No. 715/2007 of the European Parliament and of the Council, Official Journal of the European Union, L 171/1, June 29, 2007, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:171:0001:0016:EN:PDF.

Defeat devices that reduce the effectiveness of emission controls, along with "irrational" control strategies,[4] were prohibited in Directive 2001/27/EC for diesel vehicles. Additionally, durability and on-board diagnostic (OBD) requirements were introduced for Euro IV and V in Directive 2005/55/EC, and the technical requirements were specified in Directive 2005/78/EC. Directive 2005/55/EC also restated the emission limits for Euro IV and V with additional language on the verification of European Transient Cycle (ETC) tests. A full history of the European emission and fuel-quality standards is available at: www.transportpolicy.net.

THE EURO 6 STANDARDS FOR LIGHT-DUTY VEHICLES

EMISSION LIMIT VALUES

European emission standards regulate gasoline and diesel vehicles separately. Considering first the standards for diesel vehicles (see Table 1), Euro 6 is a significant advancement over Euro 5 with regard to NO_x limits. The NO_x limit declines from 0.18 g/km to 0.08 g/km, a reduction of 56%. Explicit NO_x limits were introduced at the Euro 3 level, and in the Euro 6 standards the NO_x limit is 84% lower than the Euro 3 level. This has significant implications for control technologies, requiring for the first time the integration of emission control aftertreatment for NO_x emissions, such as selective catalytic reduction, lean NO_x traps, or others.

The particle mass and particle number standards for diesel cars in Euro 6 are the same as those in Euro 5. Limits on particle mass emissions for diesel cars have nonetheless been reduced by large amounts since the Euro 1 standards were introduced. The Euro 6 particle mass limits for diesel cars represent a reduction of 96% from Euro 1 limits. The particle mass limits are now so low that measurement accuracy and sensitivity are an issue, which has prompted the introduction of limits on particle number, which is easier to measure. These limits were first introduced at the Euro 5 level. Particle number limits are also supported by research in Europe that has found significant health impacts from exposure to high particle number counts.

The limits for gasoline vehicles have also fallen significantly, relative to earlier European emission standards. The Euro 6 NO_x standards for gasoline cars are the same as those for Euro 5, but they are 60% lower than those for Euro 1. Mindful of attempts by car manufacturers to improve the fuel consumption of gasoline vehicles through gasoline direct injection (GDI) technology, European regulators introduced particle mass limits on GDI engines at the Euro 5 level, equal to the limits set for diesel vehicles. Limits on particle number emissions of GDI engines were introduced in Euro 6 (they were introduced at Euro 5 for conventional diesel cars), and they are numerically the same as those for diesel cars. Europe phased in the Euro 6 particle number limit on GDI engines over the first three effective years of the standards. This more lax standard is 6.0×10^{12} #/km, an order of magnitude less stringent than the diesel standard (and the ultimate Euro 6 GDI limit) of 6.0×10^{11} #/km. This three-year phase-in was intended to extend the period of research and development needed to meet the standard, and by 2017 automakers are expected to meet the more stringent

4 An "irrational emission control strategy" means any strategy or measure that, when the vehicle is operated under normal conditions of use, reduces the effectiveness of the emission control system to a level below that expected on the applicable emission test procedures.

standard. Countries adopting the Euro 6 standards after 2017 should not require a phase-in period for particle number, given that technologies needed to meet the more stringent standard will be available. These countries can directly adopt the more stringent standard of 6 x 10^{11} #/km for GDI engines.

Table 1. The light-duty Euro 5 and Euro 6 vehicle emission standards on the New European Driving Cycle (NEDC)

Pollutant	Euro 5 Light-Duty		Euro 6 Light-Duty	
	Gasoline	Diesel	Gasoline	Diesel
CO	1.0	0.5	1.0	0.5
HC	0.1[a]		0.1[e]	
$HC+NO_x$		0.23		0.17
NO_x	0.06	0.18	0.06	0.08
PM	0.005[c]	0.005	0.005[c]	0.005
PN (#/km)		6.0 x 10^{11}	6.0 x 10^{11} [d]	6.0 x 10^{11}

[a] and 0.068 g/km for NMHC; [c] applicable only to DI engines, 0.0045 g/km using the PMP measurement procedure; [d] applicable only to DI engines, 6 x 1012 #/km within the first three years of Euro 6 effective dates.

TESTING

Light-duty vehicles are tested primarily in a controlled laboratory environment on a chassis dynamometer, which functions like a treadmill for vehicles, following a pre-defined drive cycle. Emissions are reported in units of g/km. The pre-defined drive cycle for light-duty vehicles is known as the New European Driving Cycle (NEDC), and it is composed of two sections. The first section, the ECE 15 cycle, was intended to represent urban driving and has been supplemented by the second section, which, is a higher speed test intended to represent highway driving. Both sections are necessary to capture the full range of low speed and high speed urban driving for a typical vehicle in Europe. Prior to the Euro 3 standards, vehicles were allowed to run for 40 seconds from cold before emissions were measured, permitting the catalyst on gasoline vehicles (see next section) to heat up and become effective. From Euro 3 onward this allowance was removed to better reflect the effects of cold start emissions, and so measurements are now made from the beginning of the drive cycle.

Regulation 715/2007, which established the Euro 5 and 6 engine standards, states in its preambular paragraphs that the [European] Commission should "keep under review the need to revise the New European Drive Cycle," and further notes that "Revisions may be necessary to ensure that real world emissions correspond to those measured at type approval."[5] Since the agreement of Regulation 715/2007, research has shown the NEDC to be a poor representation of real-world driving, with serious implications for emissions, particularly those of NO_x from diesel cars, and for the ambient air quality in Europe. The more recently developed Worldwide Harmonized Light Vehicles Test Cycle (WLTC) contains more dynamic driving conditions than the NEDC, such as higher maximum velocity and less idling time, as it was designed using a large number of real-world drives to better reflect real-world driving conditions. The European Commission

5 Regulation (EC) No. 715/2007 of the European Parliament and of the Council, Official Journal of the European Union, L 171/1, June 29, 2007, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:171:0001:0016:EN:PDF.

is preparing to add the WLTC for type-approval testing for new vehicles beginning around 2017. A shift to WLTC for certification of new vehicles would lead to improved compliance with diesel NO_x emission limits in the real world, although by reducing the importance of cold start emissions, a shift to the WLTC may also reduce the stringency of gasoline emissions limits. The European Commission also plans to implement Real Driving Emissions (RDE), a requirement that adds a road test to laboratory-based certification of vehicle engines, with the goal of further reducing the gap between certification and real-world emissions. This may go even further toward improving real-world compliance with emission standards. This is discussed further under "Real World Emissions" below.

DURABILITY AND IN-SERVICE EMISSIONS

In terms of in-service requirements under Euro 6, Regulation 715/2007 requires manufacturers to check in-service conformity for all vehicles it certifies to the Euro 6 emission standards for a period of up to five years or 100,000 km, whichever comes first. Durability testing of pollution control devices undertaken for type approval shall cover 160,000 km, the mileage over which these devices are expected to perform. The Euro 6 standards lower the thresholds for the provision of on-board diagnostic information for NO_x and PM emissions from diesel vehicles (strictly for compression ignition vehicles) by approximately 50% from Euro 5 standards.[6] This action increases the sensitivity of the OBD system to irregularities in the performance of emission control equipment, and requires higher quality engineering of system components by the manufacturer.

EMISSION-CONTROL STRATEGIES

The increasing stringency of the Euro standards has required the deployment of increasingly effective and sophisticated technologies for emission reduction in both gasoline and diesel vehicles. The evolution of such technologies for light-duty vehicles up to and including Euro 6 is the subject of a previous ICCT report: "Estimated Cost of Emission Reduction Technologies for LDVs."[7] The broad compliance approaches for light-duty Euro 5 and Euro 6 engines are given in Table 2 below.

For light-duty gasoline vehicles, the standards for Euro 6 are largely unchanged from Euro 5, with the exception of a new particle number standard for gasoline direct injection (GDI) vehicles, a standard that in Euro 5 applied only to diesel vehicles. As CO_2 standards continue to advance, GDI engine technology has matured and is increasingly deployed. Gasoline direct injection engines produce higher particle emissions than the older port fuel injection gasoline engines, hence the introduction of a PN limit to prevent an increase in particle emissions from the gasoline fleet. This new limit may require the use of particulate filters on GDI engines, in addition to improved fuel-injection techniques.

For diesel vehicles, a lower NO_x limit will require manufacturers to utilize new aftertreatment technologies, as well as exhaust gas recirculation (EGR)

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6 Commission Regulation (EC) No. 692/2008, Official Journal of the European Union, L 199/1. July 28, 2008, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:199:0001:0136:EN:PDF.

7 Francisco Posada Sanchez, Anup Bandivadekar, and John German, "Estimated cost of emission reduction technologies for LDVs," June 11, 2012, The International Council on Clean Transportation, http://www.theicct.org/estimated-cost-emission-reduction-technologies-ldvs.

technology. Aftertreatment technologies, such as lean NO_x traps (LNT) or selective catalytic reduction (SCR), may be added alongside technologies already adopted to meet CO, HC, and PM limits, including diesel oxidation catalysts (DOC) and diesel particulate filters (DPF). The technologies necessary to meet Euro 6 NO_x limits should, in principle, counteract any increase in NO_2 emissions that would result from technologies that utilize NO_2 to oxidize particulate emissions. Since higher NO_x emissions can also result from engine calibrations designed to maximize fuel economy, new NO_x aftertreatment could allow such calibration without an increase in NO_x emissions.

Table 2. Compliance approaches for light-duty Euro 5 and 6 engines

	Euro 5	Euro 6
Gasoline	• Combustion improvements over Euro 4 • Faster oxygen sensors • Catalyst improvements- oxygen storage capacity and better coatings	• No changes required for port fuel-injected gasoline engines • Improvements to fuel injection timing or addition of a gasoline particle filter for gasoline direct injection (GDI) engines
Diesel	• Combustion improvements over Euro 4 • Variable fuel injection timing for DPF regeneration • DOC + DPF • Some engines use lean NO_x traps	• Increased fuel injection pressure • Smaller and medium-size engines (<2 liters) tend to use DOC+DPF and primarily LNT for NO_x control • Larger cars (>2L) use DOC+DPF+SCR • Some manufacturers offer EGR-only NO_x control (with no aftertreatment control), and DOC+DPF on medium and larger cars

REAL-WORLD EMISSIONS

Despite the increasing stringency of the European emission standards, serious shortcomings have emerged in the control of diesel NO_x emissions under real-world driving conditions. A series of studies, beginning in 2011, using portable emission measurement systems (PEMS) mounted onboard vehicles, as well as studies utilizing remote-sensing techniques, have quantified unexpectedly high real-world emissions of nitrogen oxides (NO_x) from European diesel passenger cars.[8] Furthermore, PEMS studies show insufficient additional reductions following the transition to Euro 6. A recent review by the ICCT summarized the results of real-world on-road

8 Martin Weiss, Pierre Bonnel, Rudolf Hummel, Urbano Manfredi, Rinaldo Colombo, Gaston Lanappe, Philippe Le Lijour, Mirco Sculati, "Analyzing on-road emissions of light-duty vehicles with Portable Emission Measurement Systems (PEMS)," European Commission, Joint Research Centre, http://ec.europa.eu/clima/policies/transport/vehicles/docs/2011_pems_jrc_62639_en.pdf2; Vicente Franco, Francisco Posada, John German, and Peter Mock, "Real-world exhaust emissions from modern diesel cars," Oct. 1, 2014, The International Council on Clean Transportation, http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars; David Carslaw, Sean Beevers, Emily Westmoreland and Martin Williams, "Trends in NO_x and NO_2 emissions and ambient measurements in the UK," July 18, 2011, Department for Environment, Food & Rural Affairs (UK), https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1108251149_110718_AQ0724_Final_report.pdf; David Carslaw and Glyn Rhys-Tyler, "New insights from comprehensive on-road measurements of NO_x, NO_2 and NH_3 from vehicle emission remote sensing in London, UK," *Atmospheric Environment* 81 (2013): 339/347, http://www.sciencedirect.com/science/article/pii/S1352231013007140.

measurements using PEMS in Europe and the United States on modern diesel cars.[9] The results (Figure 1) reflect a mean conformity factor of 7 for Euro 6 cars with a range from best to worst of between 1.0 and 25.4. These studies have shown that despite large reductions in the NO_x limit value for diesel vehicles throughout the European regulatory pathway, very little improvement in real-world NO_x emissions from diesel vehicles has occurred in Europe.

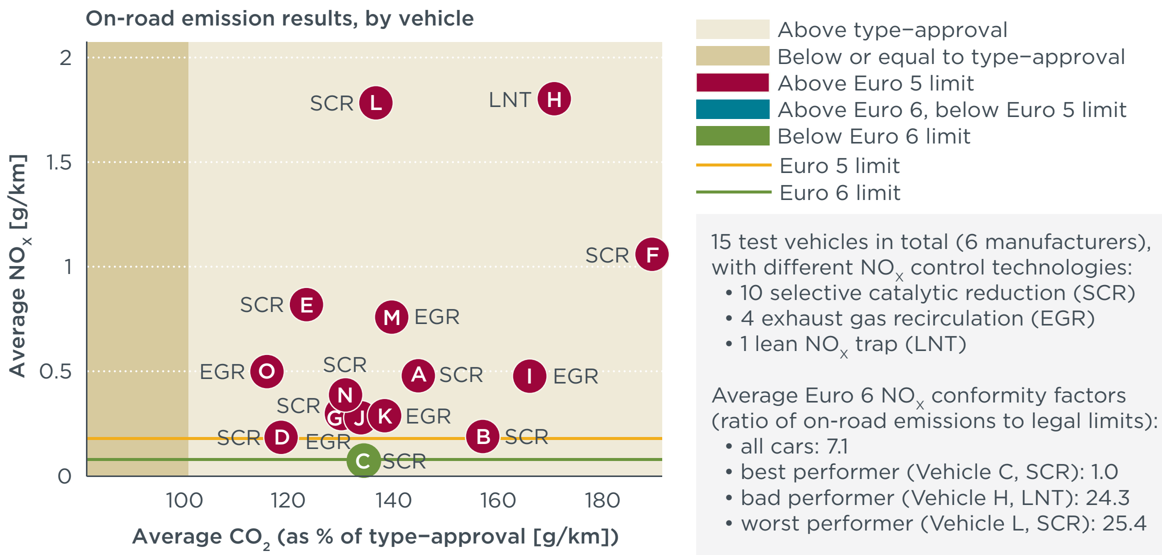

Figure 1. Overview of Euro 5 and Euro 6 diesel car PEMS emission measurements in Europe

The reason is that the NEDC test cycle used for type certification does not capture the full range of operating conditions of the engine map (that is, combinations of torque and engine speed) typical of real-world driving. Manufacturers are therefore able to design and meet these emission standards with vehicles that produce higher emissions in the real world. To ensure that Euro 6 diesel cars offer significant reductions over Euro 5 diesels, the European Commission has stated its intent to adopt regulations by 2017 setting out "not to exceed" limits in addition to the already agreed upon Euro 6 standards.[10]

The procedures for testing vehicles and the "not to exceed" limits are the subject of discussion within the European Commission, among E.U. Member States, and industry stakeholders. In May 2015, the European Union Technical Committee for Motor Vehicles (TCMV) voted in favor of a proposal to introduce a real driving emissions test procedure, which would come into force in September 2017. Tests are likely to be carried out using PEMS in real-world drives, although random drive cycles on a chassis dynamometer are a likely alternative for the measurement of particle number (PN) emissions. A large share of diesel cars will not meet the Euro 6 standards during the initial application period for real-drive testing, so in October 2015 this committee approved a second package of measures setting a "conformity factor" that defines

9 Vicente Franco, et al., "Real-world exhaust emissions from modern diesel cars," Oct. 1, 2014, The International Council on Clean Transportation, http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars.

10 The Clean Air Policy Package, European Commission, Dec. 18, 2013, http://ec.europa.eu/environment/air/clean_air_policy.htm.

the ratio of a "not to exceed" limit to the original Euro 6 standards. This committee agreed that a conformity factor of 2.1 will apply to all new vehicle types beginning in September 2017, and extending to all vehicle types beginning in September 2019. The committee also agreed to lower the conformity factor to 1.5 beginning in January 2020 for all new vehicle types, extending to all vehicle types by January 2021. At the time of this writing, these conformity factors were awaiting final approval from the European Council. Conformity factors for PN will be determined at a later date.

THE EURO VI STANDARDS FOR HEAVY-DUTY VEHICLES

The Euro VI standards were originally set out in Regulation 595/2009 and its implementing Regulation 582/2011, with further amendments contained in Regulation 133/2014. The Euro VI emission limits went into effect in 2013 for new type approvals and in 2014 for all registrations.[11]

EMISSION LIMIT VALUES

Table 3, below, shows the emission limits for the Euro V and Euro VI standards. As with light-duty vehicles, the move from Euro V to Euro VI saw a large reduction in the NO_x emission limit, from 2.0 g/kWh to 0.4 g/kWh in steady-state testing, and from 2.0 g/kWh to 0.46 g/kWh in transient testing, or reductions of 80% and 77% respectively. The particle mass limit was also significantly tightened, cut in half from 0.02 g/kWh to 0.1 g/kWh on steady-state testing, and from 0.03 g/kWh to 0.01 g/kWh on transient testing, a reduction of 66%. The Euro VI standards include for the first time a particle number limit. The limit is 8 x 10^{11} particles per kilowatt-hour under the WHSC test, and 6 x 10^{11} under the WHTC test. The vehicle certification test cycle to meet the Euro VI standards is different from that used for Euro V, so the comparisons are only approximate. The test cycles are discussed further in the "testing" section below.

The Euro VI standards also set emission limits for ammonia since the tighter NO_x standard will require the use of Selective Catalytic Reduction aftertreatment, which in turn relies on the injection of urea into the exhaust stream. The catalytic reaction can produce ammonia as an unwanted by-product, hence the limits on ammonia emissions for heavy-duty diesel vehicles (gasoline vehicles, also called "positive ignition" vehicles, are exempt from the ammonia limit since urea is not used for NO_x control). The Euro VI standards include a methane emission limit for "positive-ignition" vehicles (i.e., not diesels, but specifically natural gas and liquefied petroleum gas engines) based on the emergence of natural gas-powered vehicles in the heavy-duty vehicle sector and the potential impacts of methane on tropospheric ozone.

11 The amending Regulation 133/2014 introduced later dates for compliance with a PN limit for Positive Ignition engines.

Table 3. The Euro V and Euro VI heavy-duty vehicle emission standards for diesel engines

	Euro V Heavy-Duty		Euro VI Heavy-Duty	
	Euro V SS[a]	Euro V T[b]	Euro VI SS[a]	Euro VI T[b]
Emission limits (g/km)				
CO	1.5	4.0	1.5	4.0
HC	0.46	0.55	0.13	0.16[d]
CH_4[c]		1.1		0.5
NO_x	2.0	2.0	0.4	0.46
PM	0.02	0.03	0.01	0.01
PN (#/km)			8.0×10^{11}	6.0×10^{11}
Smoke (1/m)	0.5			
Ammonia (ppm)[12]			0.01	0.01
Fuel Sulfur Limit (ppm)	10	10	10	10
Test Cycle	ESC & ELR	ETC	WHSC	WHTC

[a] Steady-state testing; [b] Transient testing; [c] For Euro V for Natural Gas only, for Euro VI, NG and LPG; [d] Total HC for diesel engines, non-methane HC for others

TESTING

Regulatory test cycles for heavy-duty engines have continuously improved over the European regulatory pathway for these vehicle types. At Euro I and II levels, the tests were carried out over the R-49 cycle, which was a steady-state cycle sampling thirteen points on the engine map (which reflects all potential combinations of torque and engine speed).

Under the Euro III standards established in 2000, the testing regime was somewhat complex. Heavy-duty engines were tested over three different cycles: the European Steady-State Cycle (ESC), the European Transient Cycle (ETC), and the European Load Response Cycle (ELR, which was instituted to measure smoke emissions). The ESC consists of a weighted sum of emissions over thirteen modes, or combinations of engine load and engine speed, run at steady state. The ETC cycle is based on real-world drives and made up of 3 sections representing, respectively, urban drives with many stops and starts and an average speed of ~50 kph, rural drives with an average speed of ~72 km/h, and motorway driving with an average speed of ~88 kph. For Euro III, ESC/ELR tests were used for conventional diesel engines, ESC/ELR plus ETC tests were used for diesel engines with advanced aftertreatment (NO_x aftertreatment or diesel particulate filters or DPFs), and finally an ETC test was used for positive-ignition engines using natural gas or LPG. For Euro IV and V, diesel engines were tested using the ESC/ELR test and positive-ignition engines were tested on the ETC.

In the Euro VI standards, these tests were replaced by the World Harmonized Stationary Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC). These new cycles were agreed upon within the United Nations Economic Commission for Europe,[13] with

12 The emission limit for ammonia is expressed as a concentration rather than the usual g/kWh.

13 Despite the word "Europe" in the title, the UNECE negotiations cover Western, Central and Eastern Europe, Central Asia and North America.

the European emission limit values being established under both the World Harmonized Stationary Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC).

For certification of heavy-duty vehicle emissions, engines are tested on a test bed and emissions are reported as g/kWh. The WHSC is a steady-state cycle also based on a weighted sum of emissions over thirteen modes, which are combinations of engine speed and load. The cycle is based on real-world drives in Europe, the United States, Japan, and Australia. It is a hot-start cycle following preconditioning at an engine speed of 55% and 50% load. The WHTC test is a transient engine test of 1800 seconds, with several motoring segments, originally developed by the UNECE Working Party on Pollution and Energy. It is based on the worldwide pattern of real-world heavy commercial vehicle use based on typical driving conditions found in Europe, the United States, Japan, and Australia.

DURABILITY AND IN-SERVICE EMISSIONS

To ensure the tailpipe emissions are effectively limited throughout the normal life of the vehicle, under normal conditions of use, tests to ensure the durability of pollution-control devices and in-service conformity should be carried out by manufacturers at the mileage and time periods shown below in Table 4:

Table 4. Durability testing criteria for heavy-duty vehicles

Category of vehicle	Minimum service accumulation period	Useful life (years)[14]
M_1, M_2, N_1	160,000	5
M_3 (=<7.5 tonnes), N_2, N_3 (=<16 tonnes)	188,000	6
N_3 (>16 tonnes), M_3 (>7.5 tonnes)	233,000	7

On-board diagnostic (OBD) requirements for Euro VI heavy-duty vehicles are now quite comprehensive[15] (see EC Regulation 582/2011) and requirements have been strengthened compared with previous regulations. New requirements under the Euro VI standards involve monitoring the DPF (diesel particulate filter) substrate and system, the SCR system including the reagent, lean NO_X trap system capability and reagent, the oxidation catalyst hydrocarbon conversion efficiency, EGR (exhaust gas recirculation) flow and performance, fuel injection systems, and turbocharging systems. In addition, more stringent OBD threshold limits based on the WHTC have been set in Euro VI for PM and NO_X, which are lowered 75% and 82% respectively. A detailed discussion of OBD requirements in the EU and the rest of the world can be found in a recent ICCT report.[16]

14 Regulation (EC) No. 595/2009 of the European Parliament and of the Council, Official Journal of the European Union, L 188/1, July 18, 2009, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:188:0001:0013:EN:PDF.

15 Commission Regulation (EU) No. 582/2011, Official Journal of the European Union, L 167/1, June 25, 2011, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:167:0001:0168:en:PDF.

16 Francisco Posada and Anup Bandivadekar, "Global overview of on-board diagnostic (OBD) systems for heavy-duty vehicles," The International Council on Clean Transportation, Feb. 9, 2015, http://theicct.org/global-overview-board-diagnostic-obd-systems-heavy-duty-vehicles.

EMISSION-CONTROL STRATEGIES

Euro VI standards have been met by manufacturers through a combination of DPF and SCR technologies, in addition to DOCs, EGR and other advanced engine technologies. The move to a combination of DPF and SCR technologies requires a switch from Vanadium to Zeolite catalysts for the SCR systems. The end result of this technology change and the improved test cycle is that real-world NO_x emissions much more closely match the emissions limits than was the case with previous standards, especially at low vehicle speeds and cold start conditions.

Euro VI standards also require OBD systems to measure performance of emission-control systems in use and to provide early identification of any system failures. These systems operate in addition to the driver inducements for use of urea additives that are necessary for the proper operation of SCR systems required in Euro V.

The voluntary EEV (enhanced environmentally friendly vehicle) standard was first introduced in 1999. The EEV standard is slightly lower for PM and CO emissions limits over the transient test cycle, but does not require any additional vehicle or aftertreatment technologies compared to Euro V.

Table 5. Compliance approaches for heavy-duty Euro V and Euro VI engines

Euro V	Euro VI
• High fuel injection pressure • Variable fuel injection timing and quantity • Redesigns to combustion chamber • NO_x controlled mainly by SCR-Vanadium based systems • EGR offered by few manufacturers and mainly for small trucks	• DPFs required for Euro VI compliance with PM and PN standards • SCR catalyst changes from Vanadium to Zeolite • EGR no longer offered

REAL-WORLD EMISSIONS

Heavy-duty vehicles have historically not achieved the real-world NO_x emissions expected under Euro V and previous standards. In-service emissions for heavy-duty vehicles were initially addressed in Regulation 595/2009, and subsequently adopted in Regulation 582/2011. The Euro VI regulation set out the requirements for checking and demonstrating the conformity of in-service engines and vehicles using PEMS. Additional measures, such as the shift to world harmonized test cycles for stationary and transient testing, and the inclusion of cold-start testing, have greatly improved the certification test and its ability to guarantee real-world achievement of the Euro VI emission limits.

Data is now available to show whether these measures correct the NO_x emissions problems of the previous standards. The evidence thus far shows that NO_x emissions of Euro VI heavy-duty engines indeed are achieving the real-world performance not met under previous standards, even under the most difficult operating conditions.[17]

17 "Comparison of real-world off-cycle NO_x emissions control in Euro IV, V, and VI," The International Council on Clean Transportation, March 2015, http://www.theicct.org/sites/default/files/publications/ICCT_Briefing_EuroIV-V-VI-NOx_Mar2015.pdf.

Measures taken to achieve this level of performance include more efficient catalyst formulations, better thermal management of the catalyst, improved urea dosing strategies, and other aftertreatment optimizations. As a result, Euro VI standards are likely achieving a much greater reduction in NO_x emissions than the emission limits alone would indicate. Countries considering whether to tighten their heavy-duty vehicle emission standards from Euro III or Euro IV would be well advised to leapfrog to Euro VI for maximum real-world emissions benefits.

CONCLUSION

The Euro 6/VI emission standards for light- and heavy-duty vehicles require the greatest emission reductions of any previous stage along the European regulatory pathway. The light-duty Euro 6 standards include more stringent NO_x limits for diesel passenger cars, as well as a new particle number limit for gasoline direct injection engines. The heavy-duty Euro VI standards address high real-world NO_x and PM emissions from diesel trucks with changes to the heavy-duty vehicle test procedure in favor of the World Harmonized Transient Cycle, a new particle number limit, and stronger OBD requirements.

These changes with the Euro 6/VI standards will lead to further advances in the full suite of vehicle engine and aftertreatment design. For light-duty gasoline vehicles, the standards will lead to improvements in fuel injection timing and, for some vehicles, the installation of a gasoline particulate filter. Diesel passenger cars can expect to see an increase in injection pressure combined with an aftertreatment emissions control package that includes a diesel oxidation catalyst, a diesel particulate filter, and either a lean NO_x trap or a selective catalystic reduction. Heavy-duty diesel vehicles can expect to shift from vanadium- to zeolite-based SCR catalysts and to use a diesel particulate filter.

A further step remains on the European pathway for light-duty Euro 6 vehicles: adoption of PEMS and conformity factors under real-drive testing to further address NO_x from diesel engines, as well as a shift to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). These additional measures will lead to greater conformity with emission standards under real-world conditions.

Ensuring that Euro 6/VI vehicles meet the pollutant emissions limits set by the standards in actual real-world use is important to the achievement of health-related ambient air-quality standards, particularly for ambient particulate matter and nitrogen dioxide. Similarly, there are lessons to be learned in this context for those countries in the rest of the world implementing the European standards framework.

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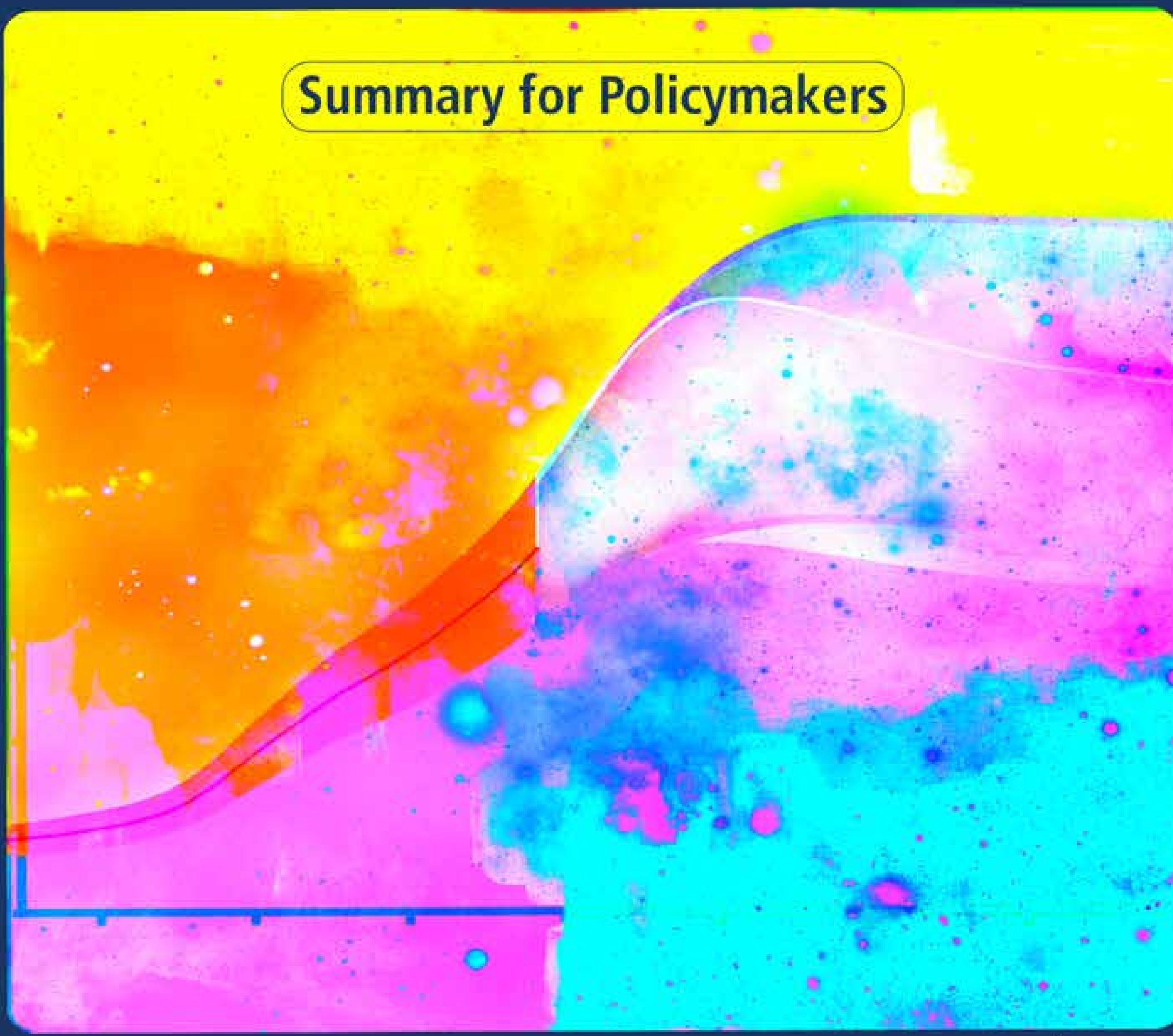
Global Warming of 1.5°C

An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty



WG I WG II WG III

WMO UNEP

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Summary for Policymakers

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Introduction

This Report responds to the invitation for IPCC '... to provide a Special Report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement.[1]

The IPCC accepted the invitation in April 2016, deciding to prepare this Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

This Summary for Policymakers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature[2] relevant to global warming of 1.5°C and for the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. The level of confidence associated with each key finding is reported using the IPCC calibrated language.[3] The underlying scientific basis of each key finding is indicated by references provided to chapter elements. In the SPM, knowledge gaps are identified associated with the underlying chapters of the Report.

A. Understanding Global Warming of 1.5°C[4]

A.1 Human activities are estimated to have caused approximately 1.0°C of global warming[5] above pre-industrial levels, with a *likely* range of 0.8°C to 1.2°C. Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*) (Figure SPM.1) {1.2}

A.1.1 Reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87°C (*likely* between 0.75°C and 0.99°C)[6] higher than the average over the 1850–1900 period (*very high confidence*). Estimated anthropogenic global warming matches the level of observed warming to within ±20% (*likely range*). Estimated anthropogenic global warming is currently increasing at 0.2°C (*likely* between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (*high confidence*). {1.2.1, Table 1.1, 1.2.4}

A.1.2 Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (*high confidence*) {1.2.1, 1.2.2, Figure 1.1, Figure 1.3, 3.3.1, 3.3.2}

A.1.3 Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.3.1, 3.3.2, 3.3.3}

1 Decision 1/CP.21, paragraph 21.

2 The assessment covers literature accepted for publication by 15 May 2018.

3 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5.

4 See also Box SPM.1: Core Concepts Central to this Special Report.

5 Present level of global warming is defined as the average of a 30-year period centred on 2017 assuming the recent rate of warming continues.

6 This range spans the four available peer-reviewed estimates of the observed GMST change and also accounts for additional uncertainty due to possible short-term natural variability. {1.2.1, Table 1.1}

A.2 Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are *unlikely* to cause global warming of 1.5°C (*medium confidence*). (Figure SPM.1) {1.2, 3.3, Figure 1.5}

A.2.1 Anthropogenic emissions (including greenhouse gases, aerosols and their precursors) up to the present are *unlikely* to cause further warming of more than 0.5°C over the next two to three decades (*high confidence*) or on a century time scale (*medium confidence*). {1.2.4, Figure 1.5}

A.2.2 Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*). On longer time scales, sustained net negative global anthropogenic CO_2 emissions and/or further reductions in non-CO_2 radiative forcing may still be required to prevent further warming due to Earth system feedbacks and to reverse ocean acidification (*medium confidence*) and will be required to minimize sea level rise (*high confidence*). {Cross-Chapter Box 2 in Chapter 1, 1.2.3, 1.2.4, Figure 1.4, 2.2.1, 2.2.2, 3.4.4.8, 3.4.5.1, 3.6.3.2}

A.3 Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*). (Figure SPM.2) {1.3, 3.3, 3.4, 5.6}

A.3.1 Impacts on natural and human systems from global warming have already been observed (*high confidence*). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (*high confidence*). (Figure SPM.2) {1.4, 3.4, 3.5}

A.3.2 Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate, they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (*high confidence*). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (*high confidence*). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8 in Chapter 3}

A.3.3 Adaptation and mitigation are already occurring (*high confidence*). Future climate-related risks would be reduced by the upscaling and acceleration of far-reaching, multilevel and cross-sectoral climate mitigation and by both incremental and transformational adaptation (*high confidence*). {1.2, 1.3, Table 3.5, 4.2.2, Cross-Chapter Box 9 in Chapter 4, Box 4.2, Box 4.3, Box 4.6, 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.4.1, 4.4.4, 4.4.5, 4.5.3}

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C

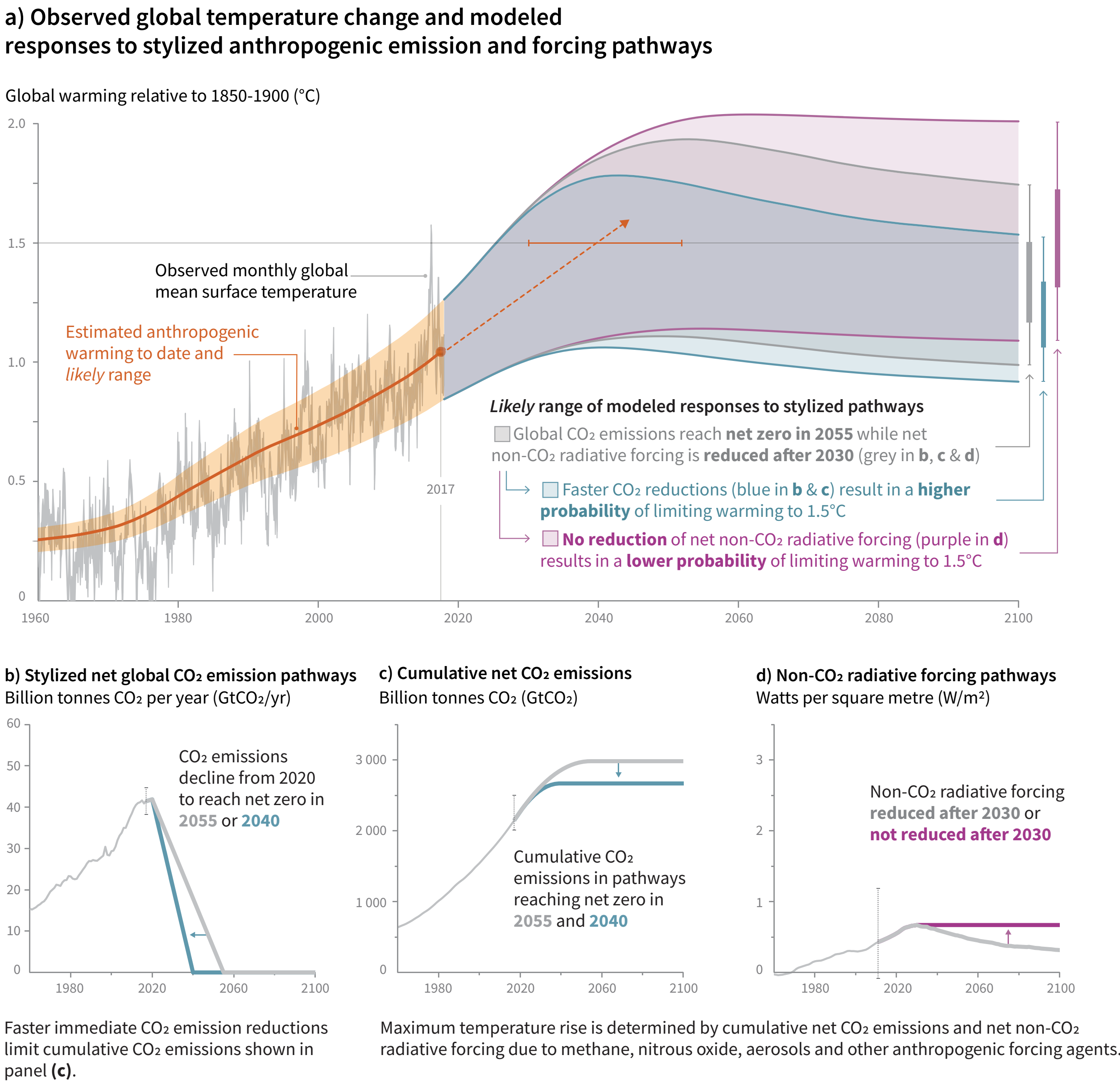

Figure SPM.1 | Panel a: Observed monthly global mean surface temperature (GMST, grey line up to 2017, from the HadCRUT4, GISTEMP, Cowtan–Way, and NOAA datasets) change and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed *likely* range). Orange dashed arrow and horizontal orange error bar show respectively the central estimate and *likely* range of the time at which 1.5°C is reached if the current rate of warming continues. The grey plume on the right of panel a shows the *likely* range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions (grey line in panels b and c) decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing (grey line in panel d) increases to 2030 and then declines. The blue plume in panel a) shows the response to faster CO_2 emissions reductions (blue line in panel b), reaching net zero in 2040, reducing cumulative CO_2 emissions (panel c). The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on right of panel a) show the *likely* ranges (thin lines) and central terciles (33rd – 66th percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways. Vertical dotted error bars in panels b, c and d show the *likely* range of historical annual and cumulative global net CO_2 emissions in 2017 (data from the Global Carbon Project) and of net non-CO_2 radiative forcing in 2011 from AR5, respectively. Vertical axes in panels c and d are scaled to represent approximately equal effects on GMST. {1.2.1, 1.2.3, 1.2.4, 2.3, Figure 1.2 and Chapter 1 Supplementary Material, Cross-Chapter Box 2 in Chapter 1}

B. Projected Climate Change, Potential Impacts and Associated Risks

B.1 Climate models project robust[7] differences in regional climate characteristics between present-day and global warming of 1.5°C,[8] and between 1.5°C and 2°C.[8] These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*). {3.3}

B.1.1 Evidence from attributed changes in some climate and weather extremes for a global warming of about 0.5°C supports the assessment that an additional 0.5°C of warming compared to present is associated with further detectable changes in these extremes (*medium confidence*). Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity, and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}

B.1.2 Temperature extremes on land are projected to warm more than GMST (*high confidence*): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about 4°C at 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at 1.5°C and about 6°C at 2°C (*high confidence*). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (*high confidence*). {3.3.1, 3.3.2, Cross-Chapter Box 8 in Chapter 3}

B.1.3 Risks from droughts and precipitation deficits are projected to be higher at 2°C compared to 1.5°C of global warming in some regions (*medium confidence*). Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C of global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (*medium confidence)*. Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). There is generally *low confidence* in projected changes in heavy precipitation at 2°C compared to 1.5°C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2°C than at 1.5°C of global warming (*medium confidence*). As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (*medium confidence*). {3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.6}

B.2 By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depend on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*). {3.3, 3.4, 3.6}

B.2.1 Model-based projections of global mean sea level rise (relative to 1986–2005) suggest an indicative range of 0.26 to 0.77 m by 2100 for 1.5°C of global warming, 0.1 m (0.04–0.16 m) less than for a global warming of 2°C (*medium confidence*). A reduction of 0.1 m in global sea level rise implies that up to 10 million fewer people would be exposed to related risks, based on population in the year 2010 and assuming no adaptation (*medium confidence*). {3.4.4, 3.4.5, 4.3.2}

B.2.2 Sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century (*high confidence*). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered at around 1.5°C to 2°C of global warming (*medium confidence*). (Figure SPM.2) {3.3.9, 3.4.5, 3.5.2, 3.6.3, Box 3.3}

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7 Robust is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

8 Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature.

B.2.3 Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (*high confidence*). Risks associated with sea level rise are higher at 2°C compared to 1.5°C. The slower rate of sea level rise at global warming of 1.5°C reduces these risks, enabling greater opportunities for adaptation including managing and restoring natural coastal ecosystems and infrastructure reinforcement (*medium confidence*). (Figure SPM.2) {3.4.5, Box 3.5}

B.3 On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services to humans (*high confidence*). (Figure SPM.2) {3.4, 3.5, Box 3.4, Box 4.2, Cross-Chapter Box 8 in Chapter 3}

B.3.1 Of 105,000 species studied,[9] 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5°C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2°C (*medium confidence*). Impacts associated with other biodiversity-related risks such as forest fires and the spread of invasive species are lower at 1.5°C compared to 2°C of global warming (*high confidence*). {3.4.3, 3.5.2}

B.3.2 Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1ºC of global warming, compared with 13% (interquartile range 8–20%) at 2°C (*medium confidence*). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (*medium confidence*). {3.4.3.1, 3.4.3.5}

B.3.3 High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (*high confidence*) and this will proceed with further warming. Limiting global warming to 1.5°C rather than 2°C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km^2 (*medium confidence*). {3.3.2, 3.4.3, 3.5.5}

B.4 Limiting global warming to 1.5°C compared to 2ºC is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm-water coral reef ecosystems (*high confidence*). {3.3, 3.4, 3.5, Box 3.4, Box 3.5}

B.4.1 There is *high confidence* that the probability of a sea ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales (*high confidence*). {3.3.8, 3.4.4.7}

B.4.2 Global warming of 1.5°C is projected to shift the ranges of many marine species to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced impacts are projected to be higher at 2°C than those at global warming of 1.5°C (*high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2ºC (*very high confidence*). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*). {3.4.4, Box 3.4}

9 Consistent with earlier studies, illustrative numbers were adopted from one recent meta-study.

B.4.3 The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, for example, from algae to fish (*high confidence*). {3.3.10, 3.4.4}

B.4.4 Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, disease incidence, and risk of invasive species (*medium confidence*) but are projected to be less at 1.5ºC of global warming than at 2ºC. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5°C of global warming compared to a loss of more than 3 million tonnes for 2°C of global warming (*medium confidence*). {3.4.4, Box 3.4}

B.5 Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. (Figure SPM.2) {3.4, 3.5, 5.2, Box 3.2, Box 3.3, Box 3.5, Box 3.6, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 5.2}

B.5.1 Populations at disproportionately higher risk of adverse consequences with global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island developing states, and Least Developed Countries (*high confidence*). Poverty and disadvantage are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). {3.4.10, 3.4.11, Box 3.5, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 4.2.2.2, 5.2.1, 5.2.2, 5.2.3, 5.6.3}

B.5.2 Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence*). Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*). {3.4.7, 3.4.8, 3.5.5.8}

B.5.3 Limiting warming to 1.5°C compared with 2ºC is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America, and in the CO_2-dependent nutritional quality of rice and wheat (*high confidence*). Reductions in projected food availability are larger at 2°C than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (*medium confidence*). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (*high confidence*). {3.4.6, 3.5.4, 3.5.5, Box 3.1, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4}

B.5.4 Depending on future socio-economic conditions, limiting global warming to 1.5°C compared to 2°C may reduce the proportion of the world population exposed to a climate change-induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Many small island developing states could experience lower water stress as a result of projected changes in aridity when global warming is limited to 1.5°C, as compared to 2°C (*medium confidence*). {3.3.5, 3.4.2, 3.4.8, 3.5.5, Box 3.2, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

B.5.5 Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century[10] (*medium confidence*). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2°C (*medium confidence*). {3.5.2, 3.5.3}

10 Here, impacts on economic growth refer to changes in gross domestic product (GDP). Many impacts, such as loss of human lives, cultural heritage and ecosystem services, are difficult to value and monetize.

B.5.6 Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}

B.5.7 There are multiple lines of evidence that since AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming to 2°C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high risk between 1.5°C and 2°C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1°C and 1.5°C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5°C and 2°C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5°C and 2.5°C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1°C and 2.5°C for RFC5 (Large-scale singular events) (*medium confidence*). (Figure SPM.2) {3.4.13; 3.5, 3.5.2}

B.6 Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*). {Table 3.5, 4.3, 4.5, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5}

B.6.1 A wide range of adaptation options are available to reduce the risks to natural and managed ecosystems (e.g., ecosystem-based adaptation, ecosystem restoration and avoided degradation and deforestation, biodiversity management, sustainable aquaculture, and local knowledge and indigenous knowledge), the risks of sea level rise (e.g., coastal defence and hardening), and the risks to health, livelihoods, food, water, and economic growth, especially in rural landscapes (e.g., efficient irrigation, social safety nets, disaster risk management, risk spreading and sharing, and community-based adaptation) and urban areas (e.g., green infrastructure, sustainable land use and planning, and sustainable water management) (*medium confidence*). {4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.5.3, 4.5.4, 5.3.2, Box 4.2, Box 4.3, Box 4.6, Cross-Chapter Box 9 in Chapter 4}.

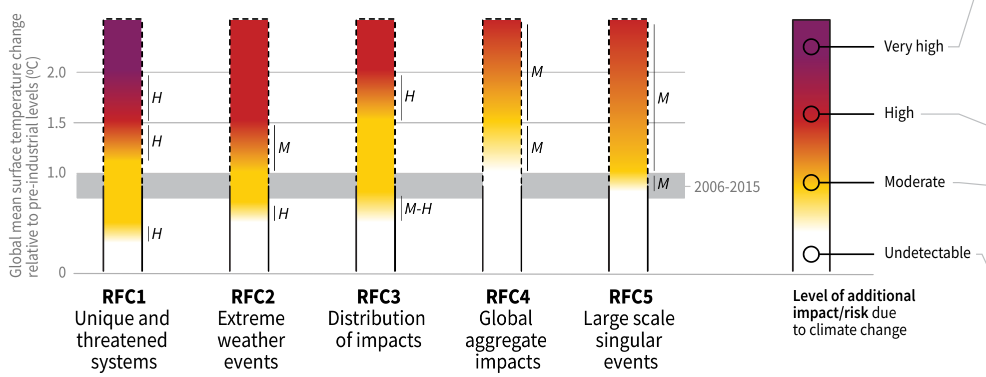
B.6.2 Adaptation is expected to be more challenging for ecosystems, food and health systems at 2°C of global warming than for 1.5°C (*medium confidence*). Some vulnerable regions, including small islands and Least Developed Countries, are projected to experience high multiple interrelated climate risks even at global warming of 1.5°C (*high confidence*). {3.3.1, 3.4.5, Box 3.5, Table 3.5, Cross-Chapter Box 9 in Chapter 4, 5.6, Cross-Chapter Box 12 in Chapter 5, Box 5.3}

B.6.3 Limits to adaptive capacity exist at 1.5°C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems and human health (*medium confidence*). {Cross-Chapter Box 12 in Chapter 5, Box 3.5, Table 3.5}

How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)



Purple indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.
Red indicates severe and widespread impacts/risks.
Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.
White indicates that no impacts are detectable and attributable to climate change.

Impacts and risks for selected natural, managed and human systems

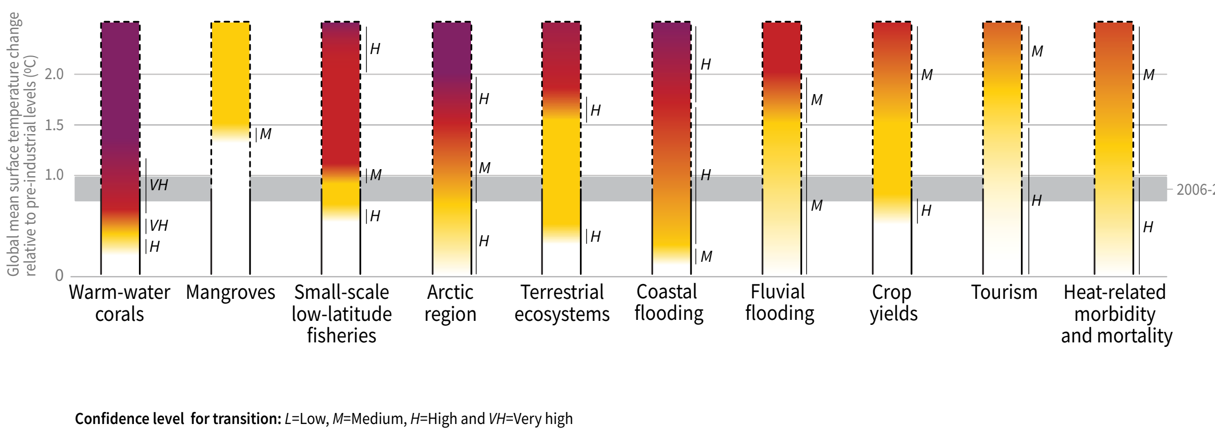


Figure SPM.2 | Five integrative reasons for concern (RFCs) provide a framework for summarizing key impacts and risks across sectors and regions, and were introduced in the IPCC Third Assessment Report. RFCs illustrate the implications of global warming for people, economies and ecosystems. Impacts and/or risks for each RFC are based on assessment of the new literature that has appeared. As in AR5, this literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable, moderate, high or very high. The selection of impacts and risks to natural, managed and human systems in the lower panel is illustrative and is not intended to be fully comprehensive. {3.4, 3.5, 3.5.2.1, 3.5.2.2, 3.5.2.3, 3.5.2.4, 3.5.2.5, 5.4.1, 5.5.3, 5.6.1, Box 3.4}

RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots.

RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.

RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability.

RFC4 Global aggregate impacts: global monetary damage, global-scale degradation and loss of ecosystems and biodiversity.

RFC5 Large-scale singular events: are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets.

C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C.1 In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C[11] CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (*high confidence*) (Figure SPM.3a) {2.1, 2.3, Table 2.4}

C.1.1 CO_2 emissions reductions that limit global warming to 1.5°C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation challenges and potential synergies and trade-offs with sustainable development. (*high confidence*) (Figure SPM.3b) {2.3.2, 2.3.4, 2.4, 2.5.3}

C.1.2 Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). These pathways also reduce most of the cooling aerosols, which partially offsets mitigation effects for two to three decades. Non-CO_2 emissions[12] can be reduced as a result of broad mitigation measures in the energy sector. In addition, targeted non-CO_2 mitigation measures can reduce nitrous oxide and methane from agriculture, methane from the waste sector, some sources of black carbon, and hydrofluorocarbons. High bioenergy demand can increase emissions of nitrous oxide in some 1.5°C pathways, highlighting the importance of appropriate management approaches. Improved air quality resulting from projected reductions in many non-CO_2 emissions provide direct and immediate population health benefits in all 1.5°C model pathways. (*high confidence*) (Figure SPM.3a) {2.2.1, 2.3.3, 2.4.4, 2.5.3, 4.3.6, 5.4.2}

C.1.3 Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the pre-industrial period, that is, staying within a total carbon budget (*high confidence*).[13] By the end of 2017, anthropogenic CO_2 emissions since the pre-industrial period are estimated to have reduced the total carbon budget for 1.5°C by approximately 2200 ± 320 $GtCO_2$ (*medium confidence*). The associated remaining budget is being depleted by current emissions of 42 ± 3 $GtCO_2$ per year (*high confidence*). The choice of the measure of global temperature affects the estimated remaining carbon budget. Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 $GtCO_2$ for a 50% probability of limiting warming to 1.5°C, and 420 $GtCO_2$ for a 66% probability (*medium confidence*).[14] Alternatively, using GMST gives estimates of 770 and 570 $GtCO_2$, for 50% and 66% probabilities,[15] respectively (*medium confidence*). Uncertainties in the size of these estimated remaining carbon budgets are substantial and depend on several factors. Uncertainties in the climate response to CO_2 and non-CO_2 emissions contribute ±400 $GtCO_2$ and the level of historic warming contributes ±250 $GtCO_2$ (*medium confidence*). Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_2$ over the course of this century and more thereafter (*medium confidence*). In addition, the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (*medium confidence*). {1.2.4, 2.2.2, 2.6.1, Table 2.2, Chapter 2 Supplementary Material}

C.1.4 Solar radiation modification (SRM) measures are not included in any of the available assessed pathways. Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps

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11 References to pathways limiting global warming to 2°C are based on a 66% probability of staying below 2°C.

12 Non-CO_2 emissions included in this Report are all anthropogenic emissions other than CO_2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface albedo is referred to as non-CO_2 radiative forcing. {2.2.1}

13 There is a clear scientific basis for a total carbon budget consistent with limiting global warming to 1.5°C. However, neither this total carbon budget nor the fraction of this budget taken up by past emissions were assessed in this Report.

14 Irrespective of the measure of global temperature used, updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to AR5. (*medium confidence*) {2.2.2}

15 These estimates use observed GMST to 2006–2015 and estimate future temperature changes using near surface air temperatures.

as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification. (*medium confidence*) {4.3.8, Cross-Chapter Box 10 in Chapter 4}

Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM.3b.

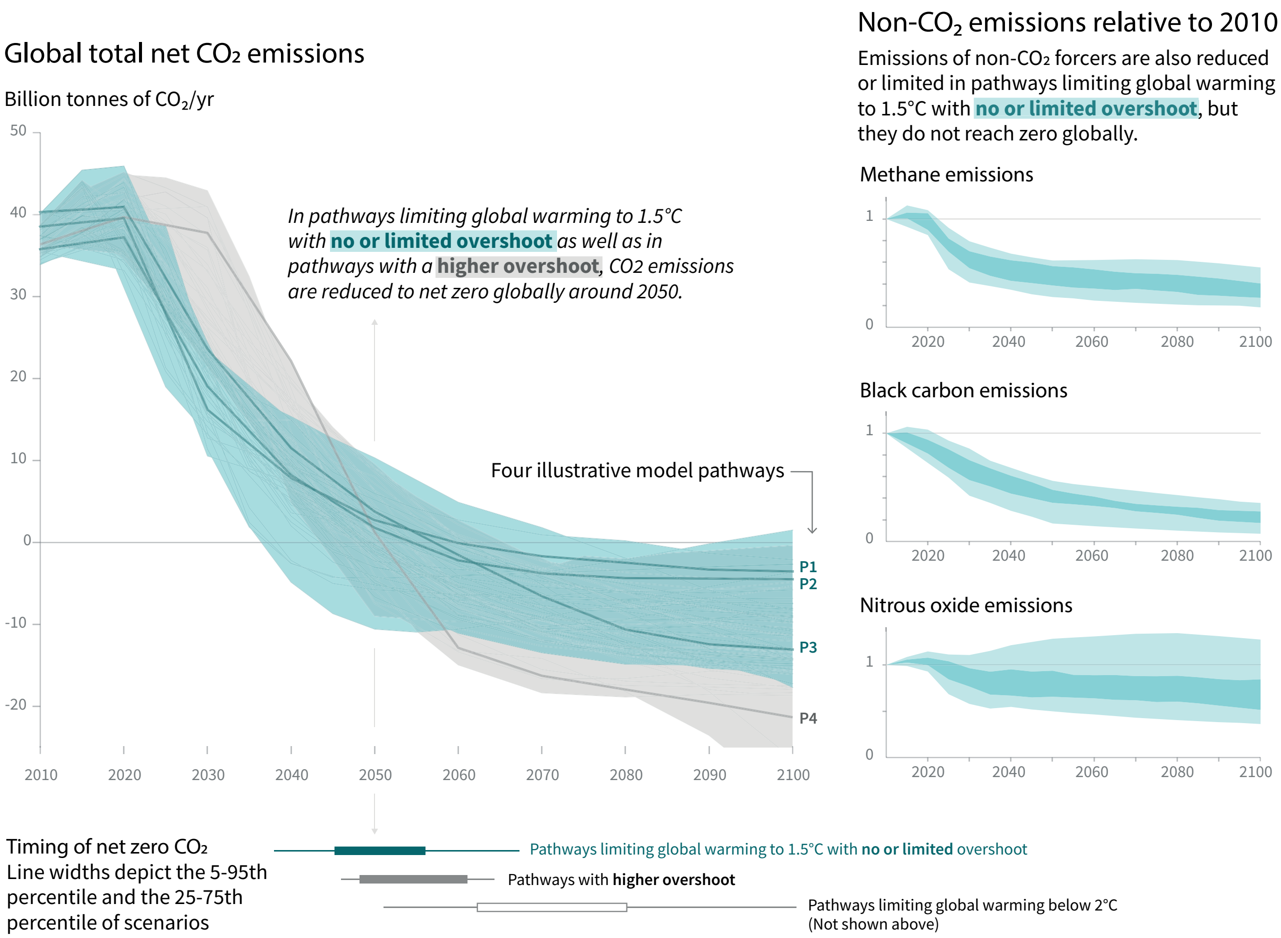
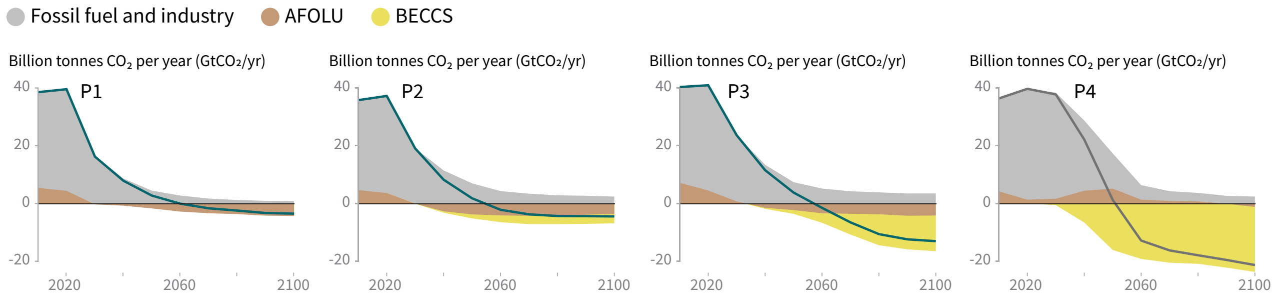


Figure SPM.3a | Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5°C with no or limited (less than 0.1°C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this Report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5°C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2°C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in Figure SPM.3b. {2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11}

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
└ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
└ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
└ in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
└ in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
└ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
└ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
└ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
└ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
└ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
└ in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550,1017)
└ of which BECCS ($GtCO_2$)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km²)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure SPM.3b | Characteristics of four illustrative model pathways in relation to global warming of 1.5°C introduced in Figure SPM.3a. These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socio-economic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry; agriculture, forestry and other land use (AFOLU); and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5°C. Pathways P1, P2, P3 and P4 correspond to the LED, S1, S2 and S5 pathways assessed in Chapter 2 (Figure SPM.3a). {2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

C.2 Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*). {2.3, 2.4, 2.5, 4.2, 4.3, 4.4, 4.5}

C.2.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show system changes that are more rapid and pronounced over the next two decades than in 2°C pathways (*high confidence*). The rates of system changes associated with limiting global warming to 1.5°C with no or limited overshoot have occurred in the past within specific sectors, technologies and spatial contexts, but there is no documented historic precedent for their scale (*medium confidence*). {2.3.3, 2.3.4, 2.4, 2.5, 4.2.1, 4.2.2, Cross-Chapter Box 11 in Chapter 4}

C.2.2 In energy systems, modelled global pathways (considered in the literature) limiting global warming to 1.5°C with no or limited overshoot (for more details see Figure SPM.3b) generally meet energy service demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2°C (*high confidence*). In 1.5°C pathways with no or limited overshoot, low-emission energy sources are projected to have a higher share, compared with 2°C pathways, particularly before 2050 (*high confidence*). In 1.5°C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (*high confidence*). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5°C pathways with no or limited overshoot. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2% interquartile range) of electricity (*high confidence*). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (*high confidence*). These improvements signal a potential system transition in electricity generation. (Figure SPM.3b) {2.4.1, 2.4.2, Figure 2.1, Table 2.6, Table 2.7, Cross-Chapter Box 6 in Chapter 3, 4.2.1, 4.3.1, 4.3.3, 4.5.2}

C.2.3 CO_2 emissions from industry in pathways limiting global warming to 1.5°C with no or limited overshoot are projected to be about 65–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2°C (*medium confidence*). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5°C with no or limited overshoot (*high confidence*). {2.4.3, 4.2.1, Table 4.1, Table 4.3, 4.3.3, 4.3.4, 4.5.2}

C.2.4 The urban and infrastructure system transition consistent with limiting global warming to 1.5°C with no or limited overshoot would imply, for example, changes in land and urban planning practices, as well as deeper emissions reductions in transport and buildings compared to pathways that limit global warming below 2°C (*medium confidence*). Technical measures and practices enabling deep emissions reductions include various energy efficiency options. In pathways limiting global warming to 1.5°C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming (*medium confidence*). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2°C of global warming (*medium confidence*). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (*high confidence*). {2.3.4, 2.4.3, 4.2.1, Table 4.1, 4.3.3, 4.5.2}

C.2.5 Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio. Model pathways that limit global warming to 1.5°C with no or limited overshoot project a 4 million km^2 reduction to a 2.5 million km^2 increase of non-pasture agricultural land for food and feed crops and a 0.5–11 million km^2 reduction of pasture land, to be converted into a 0–6 million km^2 increase of agricultural land for energy crops and a 2 million km^2 reduction to 9.5 million km^2 increase in forests by 2050 relative to 2010 (*medium confidence*).[16] Land-use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). Mitigation options limiting the demand for land include sustainable intensification of land-use practices, ecosystem restoration and changes towards less resource-intensive diets (*high confidence*). The implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions (*high confidence*). {2.4.4, Figure 2.24, 4.3.2, 4.3.7, 4.5.2, Cross-Chapter Box 7 in Chapter 3}

C.2.6 Additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to pathways without new climate policies beyond those in place today are estimated to be around 830 billion USD2010 (range of 150 billion to 1700 billion USD2010 across six models[17]). This compares to total annual average energy supply investments in 1.5°C pathways of 1460 to 3510 billion USD2010 and total annual average energy demand investments of 640 to 910 billion USD2010 for the period 2016 to 2050. Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Annual investments in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015 (*medium confidence*). {2.5.2, Box 4.8, Figure 2.27}

C.2.7 Modelled pathways limiting global warming to 1.5°C with no or limited overshoot project a wide range of global average discounted marginal abatement costs over the 21st century. They are roughly 3-4 times higher than in pathways limiting global warming to below 2°C (*high confidence*). The economic literature distinguishes marginal abatement costs from total mitigation costs in the economy. The literature on total mitigation costs of 1.5°C mitigation pathways is limited and was not assessed in this Report. Knowledge gaps remain in the integrated assessment of the economy-wide costs and benefits of mitigation in line with pathways limiting warming to 1.5°C. {2.5.2; 2.6; Figure 2.26}

16 The projected land-use changes presented are not deployed to their upper limits simultaneously in a single pathway.

17 Including two pathways limiting warming to 1.5°C with no or limited overshoot and four pathways with higher overshoot.

C.3 All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*). {2.3, 2.4, 3.6.2, 4.3, 5.4}

C.3.1 Existing and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization. These differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs (*high confidence*). To date, only a few published pathways include CDR measures other than afforestation and BECCS. {2.3.4, 3.6.2, 4.3.2, 4.3.7}

C.3.2 In pathways limiting global warming to 1.5°C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 $GtCO_2\ yr^{-1}$ in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 $GtCO_2\ yr^{-1}$ in these years (*medium confidence*). The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 $GtCO_2\ yr^{-1}$ and afforestation potential of up to 3.6 $GtCO_2\ yr^{-1}$ assessed based on recent literature (*medium confidence*). Some pathways avoid BECCS deployment completely through demand-side measures and greater reliance on AFOLU-related CDR measures (*medium confidence*). The use of bioenergy can be as high or even higher when BECCS is excluded compared to when it is included due to its potential for replacing fossil fuels across sectors (*high confidence*). (Figure SPM.3b) {2.3.3, 2.3.4, 2.4.2, 3.6.2, 4.3.1, 4.2.3, 4.3.2, 4.3.7, 4.4.3, Table 2.4}

C.3.3 Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5°C by 2100, with larger overshoots requiring greater amounts of CDR (Figure SPM.3b) (*high confidence*). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability to return global warming to below 1.5°C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (*high confidence*). {2.2, 2.3.4, 2.3.5, 2.6, 4.3.7, 4.5.2, Table 4.11}

C.3.4 Most current and potential CDR measures could have significant impacts on land, energy, water or nutrients if deployed at large scale (*high confidence*). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity, and other ecosystem functions and services (*high confidence*). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (*high confidence*). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (*high confidence*). (Figure SPM.3b) {2.3.4, 2.4.4, 2.5.3, 2.6, 3.6.2, 4.3.2, 4.3.7, 4.5.2, 5.4.1, 5.4.2; Cross-Chapter Boxes 7 and 8 in Chapter 3, Table 4.11, Table 5.3, Figure 5.3}

C.3.5 Some AFOLU-related CDR measures such as restoration of natural ecosystems and soil carbon sequestration could provide co-benefits such as improved biodiversity, soil quality, and local food security. If deployed at large scale, they would require governance systems enabling sustainable land management to conserve and protect land carbon stocks and other ecosystem functions and services (*medium confidence*). (Figure SPM.4) {2.3.3, 2.3.4, 2.4.2, 2.4.4, 3.6.2, 5.4.1, Cross-Chapter Boxes 3 in Chapter 1 and 7 in Chapter 3, 4.3.2, 4.3.7, 4.4.1, 4.5.2, Table 2.4}

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D.1 Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions[18] in 2030 of 52–58 $GtCO_2eq\ yr^{-1}$ (*medium confidence*). Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO_2 emissions start to decline well before 2030 (*high confidence*). {1.2, 2.3, 3.3, 3.4, 4.2, 4.4, Cross-Chapter Box 11 in Chapter 4}

D.1.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $GtCO_2eq\ yr^{-1}$ in 2030, and half of available pathways fall within the 25–30 $GtCO_2eq\ yr^{-1}$ range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence*). Pathways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3°C by 2100, with warming continuing afterwards (*medium confidence*). {2.3.3, 2.3.5, Cross-Chapter Box 11 in Chapter 4, 5.5.3.2}

D.1.2 Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5°C with no or limited overshoot (*high confidence*). Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 3.3, 4.3.7, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4}

D.1.3 The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5°C after 2030 with no or limited overshoot (*high confidence*). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long term (*high confidence*). These may increase uneven distributional impacts between countries at different stages of development (*medium confidence*). {2.3.5, 4.4.5, 5.4.2}

D.2 The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*). {1.1, 1.4, 2.5, 3.3, 3.4, 5.2, Table 5.1}

D.2.1 Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection. The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide an established framework for assessing the links between global warming of 1.5°C or 2°C and development goals that include poverty eradication, reducing inequalities, and climate action. (*high confidence*) {Cross-Chapter Box 4 in Chapter 1, 1.4, 5.1}

D.2.2 The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, as well as those from mitigation and adaptation, particularly for poor and disadvantaged populations, in all societies (*high confidence*). {1.1.1, 1.1.2, 1.4.3, 2.5.3, 3.4.10, 5.1, 5.2, 5.3. 5.4, Cross-Chapter Box 4 in Chapter 1, Cross-Chapter Boxes 6 and 8 in Chapter 3, and Cross-Chapter Box 12 in Chapter 5}

D.2.3 Mitigation and adaptation consistent with limiting global warming to 1.5°C are underpinned by enabling conditions, assessed in this Report across the geophysical, environmental-ecological, technological, economic, socio-cultural and institutional

18 GHG emissions have been aggregated with 100-year GWP values as introduced in the IPCC Second Assessment Report.

dimensions of feasibility. Strengthened multilevel governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5°C-consistent systems transitions. (*high confidence*) {1.4, Cross-Chapter Box 3 in Chapter 1, 2.5.1, 4.4, 4.5, 5.6}

D.3 Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*). {1.4, 4.3, 4.5}

D.3.1 Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (*high confidence*). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies. These benefits can occur in most regions with adaptation to 1.5°C of global warming (*high confidence*). {1.4.3, 4.2.2, 4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.4.1, 4.4.3, 4.5.3, 5.3.1, 5.3.2}

D.3.2 Adaptation to 1.5°C global warming can also result in trade-offs or maladaptations with adverse impacts for sustainable development. For example, if poorly designed or implemented, adaptation projects in a range of sectors can increase greenhouse gas emissions and water use, increase gender and social inequality, undermine health conditions, and encroach on natural ecosystems (*high confidence*). These trade-offs can be reduced by adaptations that include attention to poverty and sustainable development (*high confidence*). {4.3.2, 4.3.3, 4.5.4, 5.3.2; Cross-Chapter Boxes 6 and 7 in Chapter 3}

D.3.3 A mix of adaptation and mitigation options to limit global warming to 1.5°C, implemented in a participatory and integrated manner, can enable rapid, systemic transitions in urban and rural areas (*high confidence*). These are most effective when aligned with economic and sustainable development, and when local and regional governments and decision makers are supported by national governments (*medium confidence*). {4.3.2, 4.3.3, 4.4.1, 4.4.2}

D.3.4 Adaptation options that also mitigate emissions can provide synergies and cost savings in most sectors and system transitions, such as when land management reduces emissions and disaster risk, or when low-carbon buildings are also designed for efficient cooling. Trade-offs between mitigation and adaptation, when limiting global warming to 1.5°C, such as when bioenergy crops, reforestation or afforestation encroach on land needed for agricultural adaptation, can undermine food security, livelihoods, ecosystem functions and services and other aspects of sustainable development. (*high confidence*) {3.4.3, 4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

D.4 Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. (*high confidence*) (Figure SPM.4) {2.5, 4.5, 5.4}

D.4.1 1.5°C pathways have robust synergies particularly for the SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production) and 14 (oceans) (*very high confidence*). Some 1.5°C pathways show potential trade-offs with mitigation for SDGs 1 (poverty), 2 (hunger), 6 (water) and 7 (energy access), if not managed carefully (*high confidence*). (Figure SPM.4) {5.4.2; Figure 5.4, Cross-Chapter Boxes 7 and 8 in Chapter 3}

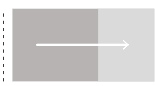
D.4.2 1.5°C pathways that include low energy demand (e.g., see P1 in Figure SPM.3a and SPM.3b), low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*high confidence*). Such pathways would reduce dependence on CDR. In modelled pathways, sustainable development, eradicating poverty and reducing inequality can support limiting warming to 1.5°C (*high confidence*). (Figure SPM.3b, Figure SPM.4) {2.4.3, 2.5.1, 2.5.3, Figure 2.4, Figure 2.28, 5.4.1, 5.4.2, Figure 5.4}

SPM

Indicative linkages between mitigation options and sustainable development using SDGs (The linkages do not show costs and benefits)

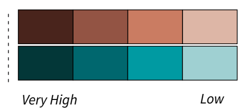
Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

Length shows strength of connection



The overall **size of the coloured bars** depict **the relative potential** for synergies and trade-offs between the sectoral mitigation options and the SDGs.

Shades show level of confidence



The shades depict **the level of confidence** of the assessed potential for Trade-offs/Synergies.

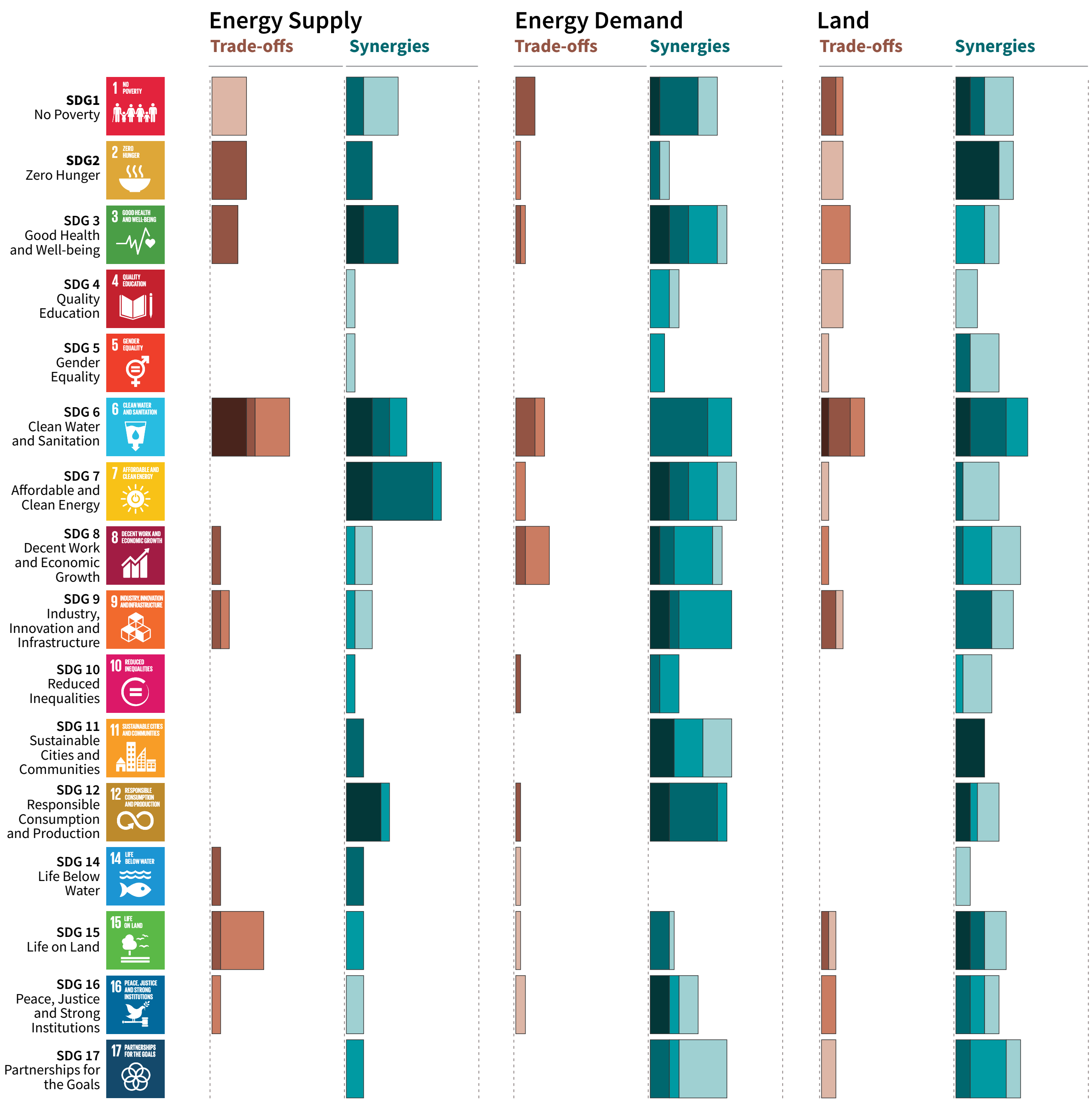


Figure SPM.4 | Potential synergies and trade-offs between the sectoral portfolio of climate change mitigation options and the Sustainable Development Goals (SDGs). The SDGs serve as an analytical framework for the assessment of the different sustainable development dimensions, which extend beyond the time frame of the 2030 SDG targets. The assessment is based on literature on mitigation options that are considered relevant for 1.5ºC. The assessed strength of the SDG interactions is based on the qualitative and quantitative assessment of individual mitigation options listed in Table 5.2. For each mitigation option, the strength of the SDG-connection as well as the associated confidence of the underlying literature (shades of green and red) was assessed. The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector (see Table 5.2) are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have *low confidence* due to the uncertainty and limited number of studies exploring indirect effects. The strength of the connection considers only the effect of mitigation and does not include benefits of avoided impacts. SDG 13 (climate action) is not listed because mitigation is being considered in terms of interactions with SDGs and not vice versa. The bars denote the strength of the connection, and do not consider the strength of the impact on the SDGs. The energy demand sector comprises behavioural responses, fuel switching and efficiency options in the transport, industry and building sector as well as carbon capture options in the industry sector. Options assessed in the energy supply sector comprise biomass and non-biomass renewables, nuclear, carbon capture and storage (CCS) with bioenergy, and CCS with fossil fuels. Options in the land sector comprise agricultural and forest options, sustainable diets and reduced food waste, soil sequestration, livestock and manure management, reduced deforestation, afforestation and reforestation, and responsible sourcing. In addition to this figure, options in the ocean sector are discussed in the underlying report. {5.4, Table 5.2, Figure 5.2}

Information about the net impacts of mitigation on sustainable development in 1.5°C pathways is available only for a limited number of SDGs and mitigation options. Only a limited number of studies have assessed the benefits of avoided climate change impacts of 1.5°C pathways for the SDGs, and the co-effects of adaptation for mitigation and the SDGs. The assessment of the indicative mitigation potentials in Figure SPM.4 is a step further from AR5 towards a more comprehensive and integrated assessment in the future.

D.4.3 1.5°C and 2°C modelled pathways often rely on the deployment of large-scale land-related measures like afforestation and bioenergy supply, which, if poorly managed, can compete with food production and hence raise food security concerns (*high confidence*). The impacts of carbon dioxide removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as BECCS and AFOLU options would lead to trade-offs. Context-relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). (Figure SPM.4) {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

D.4.4 Mitigation consistent with 1.5°C pathways creates risks for sustainable development in regions with high dependency on fossil fuels for revenue and employment generation (*high confidence*). Policies that promote diversification of the economy and the energy sector can address the associated challenges (*high confidence*). {5.4.1.2, Box 5.2}

D.4.5 Redistributive policies across sectors and populations that shield the poor and vulnerable can resolve trade-offs for a range of SDGs, particularly hunger, poverty and energy access. Investment needs for such complementary policies are only a small fraction of the overall mitigation investments in 1.5°C pathways. (*high confidence*) {2.4.3, 5.4.2, Figure 5.5}

D.5 Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*). {2.3, 2.4, 2.5, 3.2, 4.2, 4.4, 4.5, 5.2, 5.5, 5.6}

D.5.1 Directing finance towards investment in infrastructure for mitigation and adaptation could provide additional resources. This could involve the mobilization of private funds by institutional investors, asset managers and development or investment banks, as well as the provision of public funds. Government policies that lower the risk of low-emission and adaptation investments can facilitate the mobilization of private funds and enhance the effectiveness of other public policies. Studies indicate a number of challenges, including access to finance and mobilization of funds. (*high confidence*) {2.5.1, 2.5.2, 4.4.5}

D.5.2 Adaptation finance consistent with global warming of 1.5°C is difficult to quantify and compare with 2°C. Knowledge gaps include insufficient data to calculate specific climate resilience-enhancing investments from the provision of currently underinvested basic infrastructure. Estimates of the costs of adaptation might be lower at global warming of 1.5°C than for 2°C. Adaptation needs have typically been supported by public sector sources such as national and subnational government budgets, and in developing countries together with support from development assistance, multilateral development banks, and United Nations Framework Convention on Climate Change channels (*medium confidence*). More recently there is a growing understanding of the scale and increase in non-governmental organizations and private funding in some regions (*medium confidence*). Barriers include the scale of adaptation financing, limited capacity and access to adaptation finance (*medium confidence*). {4.4.5, 4.6}

D.5.3 Global model pathways limiting global warming to 1.5°C are projected to involve the annual average investment needs in the energy system of around 2.4 trillion USD2010 between 2016 and 2035, representing about 2.5% of the world GDP (*medium confidence*). {4.4.5, Box 4.8}

D.5.4 Policy tools can help mobilize incremental resources, including through shifting global investments and savings and through market and non-market based instruments as well as accompanying measures to secure the equity of the transition, acknowledging the challenges related with implementation, including those of energy costs, depreciation of assets and impacts on international competition, and utilizing the opportunities to maximize co-benefits (*high confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 2.5.2, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4, 4.4.5, 5.5.2}

D.5.5 The systems transitions consistent with adapting to and limiting global warming to 1.5°C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation. These imply enhanced technological innovation capabilities, including in industry and finance. Both national innovation policies and international cooperation can contribute to the development, commercialization and widespread adoption of mitigation and adaptation technologies. Innovation policies may be more effective when they combine public support for research and development with policy mixes that provide incentives for technology diffusion. (*high confidence*) {4.4.4, 4.4.5}.

D.5.6 Education, information, and community approaches, including those that are informed by indigenous knowledge and local knowledge, can accelerate the wide-scale behaviour changes consistent with adapting to and limiting global warming to 1.5°C. These approaches are more effective when combined with other policies and tailored to the motivations, capabilities and resources of specific actors and contexts (*high confidence*). Public acceptability can enable or inhibit the implementation of policies and measures to limit global warming to 1.5°C and to adapt to the consequences. Public acceptability depends on the individual's evaluation of expected policy consequences, the perceived fairness of the distribution of these consequences, and perceived fairness of decision procedures (*high confidence*). {1.1, 1.5, 4.3.5, 4.4.1, 4.4.3, Box 4.3, 5.5.3, 5.6.5}

D.6 Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (*high confidence*). {Box 1.1, 1.4.3, Figure 5.1, 5.5.3, Box 5.3}

D.6.1 Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*). {5.5.2, 5.5.3, Box 5.3, Figure 5.1, Figure 5.6, Cross-Chapter Boxes 12 and 13 in Chapter 5}

D.6.2 The potential for climate-resilient development pathways differs between and within regions and nations, due to different development contexts and systemic vulnerabilities (*very high confidence*). Efforts along such pathways to date have been limited (*medium confidence*) and enhanced efforts would involve strengthened and timely action from all countries and non-state actors (*high confidence*). {5.5.1, 5.5.3, Figure 5.1}

D.6.3 Pathways that are consistent with sustainable development show fewer mitigation and adaptation challenges and are associated with lower mitigation costs. The large majority of modelling studies could not construct pathways characterized by lack of international cooperation, inequality and poverty that were able to limit global warming to 1.5°C. (*high confidence*) {2.3.1, 2.5.1, 2.5.3, 5.5.2}

D.7 Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*). {1.4, 2.3, 2.5, 4.2, 4.4, 4.5, 5.3, 5.4, 5.5, 5.6, 5, Box 4.1, Box 4.2, Box 4.7, Box 5.3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 13 in Chapter 5}

D.7.1 Partnerships involving non-state public and private actors, institutional investors, the banking system, civil society and scientific institutions would facilitate actions and responses consistent with limiting global warming to 1.5°C (*very high confidence*). {1.4, 4.4.1, 4.2.2, 4.4.3, 4.4.5, 4.5.3, 5.4.1, 5.6.2, Box 5.3}.

D.7.2 Cooperation on strengthened accountable multilevel governance that includes non-state actors such as industry, civil society and scientific institutions, coordinated sectoral and cross-sectoral policies at various governance levels, gender-sensitive policies, finance including innovative financing, and cooperation on technology development and transfer can ensure participation, transparency, capacity building and learning among different players (*high confidence*). {2.5.1, 2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, Cross-Chapter Box 9 in Chapter 4, 5.3.1, 5.5.3, Cross-Chapter Box 13 in Chapter 5, 5.6.1, 5.6.3}

D.7.3 International cooperation is a critical enabler for developing countries and vulnerable regions to strengthen their action for the implementation of 1.5°C-consistent climate responses, including through enhancing access to finance and technology and enhancing domestic capacities, taking into account national and local circumstances and needs (*high confidence*). {2.3.1, 2.5.1, 4.4.1, 4.4.2, 4.4.4, 4.4.5, 5.4.1 5.5.3, 5.6.1, Box 4.1, Box 4.2, Box 4.7}.

D.7.4 Collective efforts at all levels, in ways that reflect different circumstances and capabilities, in the pursuit of limiting global warming to 1.5°C, taking into account equity as well as effectiveness, can facilitate strengthening the global response to climate change, achieving sustainable development and eradicating poverty (*high confidence*). {1.4.2, 2.3.1, 2.5.1, 2.5.2, 2.5.3, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, 5.3.1, 5.4.1, 5.5.3, 5.6.1, 5.6.2, 5.6.3}

Box SPM.1: Core Concepts Central to this Special Report

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[19] {1.2.1.1}

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial GMST. {1.2.1.2}

Global warming: The estimated increase in GMST averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. {1.2.1}

Net zero CO_2 emissions: Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Total carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the pre-industrial period to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from a given start date to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Temperature overshoot: The temporary exceedance of a specified level of global warming.

Emission pathways: In this Summary for Policymakers, the modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways. Emission pathways are classified by their temperature trajectory over the 21st century: pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5°C are classified as 'no overshoot'; those limiting warming to below 1.6°C and returning to 1.5°C by 2100 are classified as '1.5°C limited-overshoot'; while those exceeding 1.6°C but still returning to 1.5°C by 2100 are classified as 'higher-overshoot'.

Impacts: Effects of climate change on human and natural systems. Impacts can have beneficial or adverse outcomes for livelihoods, health and well-being, ecosystems and species, services, infrastructure, and economic, social and cultural assets.

Risk: The potential for adverse consequences from a climate-related hazard for human and natural systems, resulting from the interactions between the hazard and the vulnerability and exposure of the affected system. Risk integrates the likelihood of exposure to a hazard and the magnitude of its impact. Risk also can describe the potential for adverse consequences of adaptation or mitigation responses to climate change.

Climate-resilient development pathways (CRDPs): Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation and climate resilience.

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19 Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

THE CONVERSATION

Academic rigour, journalistic flair

Traffic congestion on the M5 motorway in Sydney. Government assumptions that Australian cars are becoming more fuel efficient are incorrect, research shows. Dean Lewins/AAP

We thought Australian cars were using less fuel. New research shows we were wrong

October 11, 2019 1.45pm AEDT

In several speeches of late, Prime Minister Scott Morrison insisted with a straight face that Australia is doing its bit on climate change. The claim was swiftly and thoroughly debunked. The truth is that the Morrison government is piggybacking on the efforts of others, to varying degrees of success.

We saw it in electricity generation, where the federal government has rejected a string of schemes to reduce emissions. Nonetheless the electricity sector is getting cleaner as ageing coal-fired power stations are replaced by renewables. This outcome owes nothing to federal government action. It reflects state government policies and the residual effects of the previous Labor government's Renewable Energy Target, and public pressure that forced banks and insurance companies to stop supporting fossil fuels.

In the transport sector, after decades of inaction, the government rejected recommendations from the Climate Change Authority to impose fuel efficiency

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standards on passenger vehicles, leaving Australia as the only OECD country without such standards. It has similarly derided action to promote the use of electric vehicles.

Read more: Australians could have saved over $1 billion in fuel if car emissions standards were introduced 3 years ago

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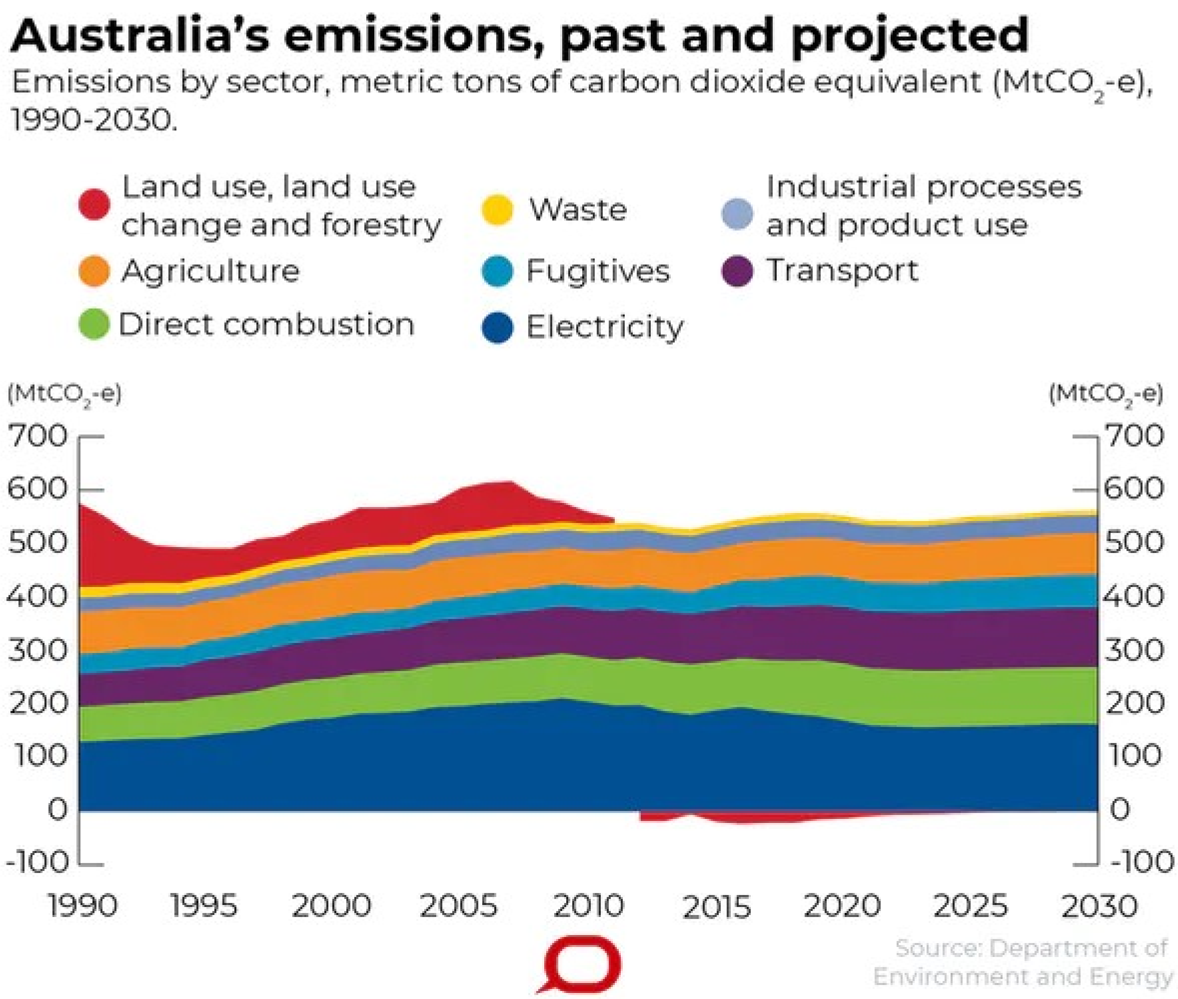
Instead, the Coalition is relying on the hope that carbon dioxide emission rates of Australia's new passenger vehicle fleet will reduce over time without any effort by governments, because vehicle emissions legislation overseas, where Australia's cars are made, is delivering technological improvements. Official projections state that some, but not all, of this improvement will flow through to Australia.

Unfortunately, this assumption is not reliable. New research shows that for the first time, fuel efficiency in Australia is getting worse, not better. In the absence of positive action from governments, transport emissions will continue to grow, and even accelerate.



A nation of car lovers, and carbon belchers

Total road travel in Australia rose from 181 billion km in 2000 to 255 billion km in 2018 - a 41% increase.

Total CO_2 emissions from road transport increased by 31% between 2000 and 2017, rising from 16% of total emissions in 2000 to 22% in 2017. With no action, transport emissions are projected to reach 111 million tonnes of CO_2 by 2030.

Emissions have grown more slowly than kilometres travelled, which suggests that improvements in fuel efficiency have partially mitigated the effect of increased travel. Reducing emissions from transport will require a stronger decline in emissions intensity (CO_2 emissions per kilometre travelled) from our vehicles. Under current policies, this will not happen.

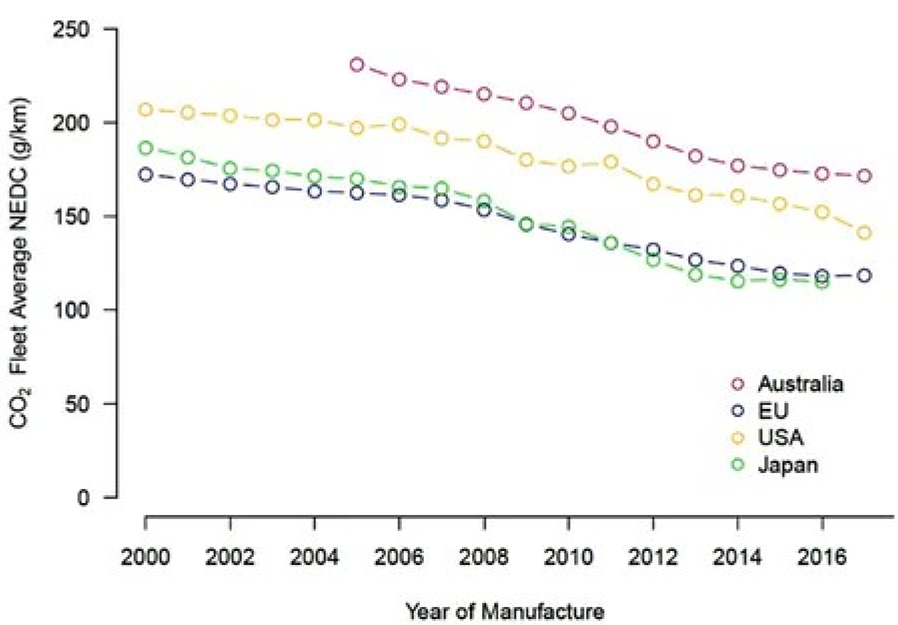
Our assumptions are all wrong

A recent analysis by Transport Energy/Emission Research (TER) found the actual emissions intensity of new Australian passenger vehicles has stabilised and likely increased in recent years.

This finding directly contradicts projections that emissions intensity will fall without government intervention.

The chart below shows the average fleet emission rates officially reported in Europe, the US and Japan, and based on laboratory tests. When compared to these jurisdictions, Australia's new passenger vehicles have significantly higher average CO_2 emission rates, and thus fuel consumption, than other countries, but all show a decline.

Official new private vehicle fleet average CO_2 emission rates 2000-17



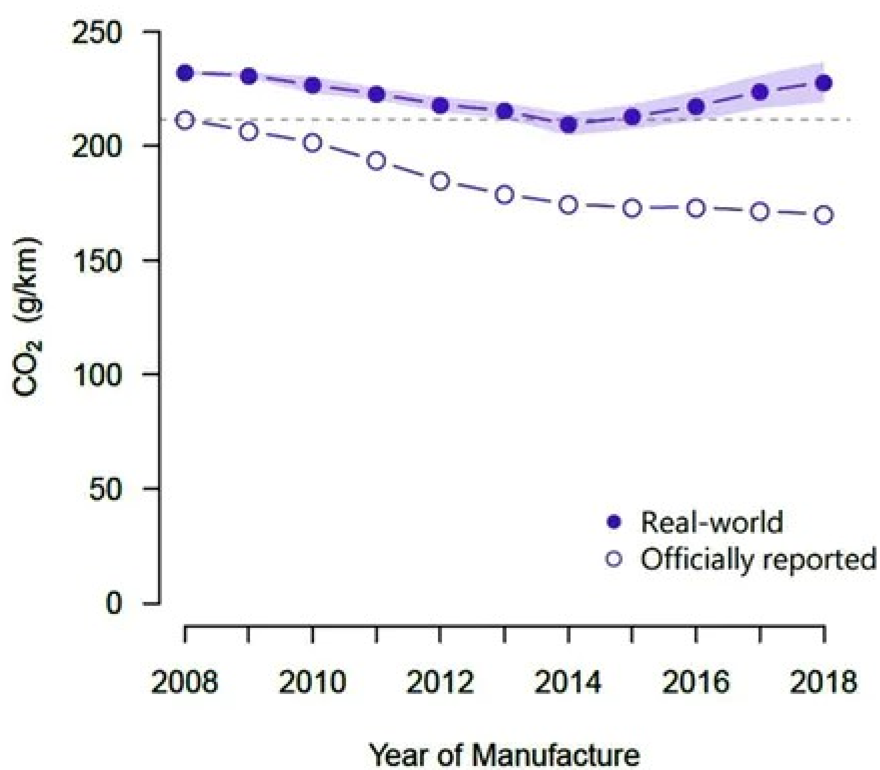
Real-World CO2 Emissions Performance of the Australian New Passenger Vehicle Fleet 2008-2018, TER

Unfortunately, real-world emissions and fuel consumption deviate substantially – and increasingly – from laboratory tests that are used to produce the officially reported CO_2 figures. This discrepancy is often referred to as "the gap". So in reality, the reduction in CO_2 emission rates is not as large as official laboratory results suggest.

There are multiple reasons for this gap, such as the laboratory test protocol itself, and strategies used by car manufacturers -and allowed by the test - to achieve lower emissions in laboratory conditions.

TER corrected the official Australian figures to reflect real world emissions. It found that carbon emission intensity stopped declining around 2014 and is now increasing. This suggests that, for the first time, fuel efficiency is no longer improving and is actually getting worse.

Official vs real-world CO_2 emission rates for Australia's new private vehicle fleet



Real-World CO2 Emissions Performance of the Australian New Passenger Vehicle Fleet 2008-2018, TER

The upshot is that total CO_2 emissions from road transport are increasing, and will accelerate in the future.

The TER study identified the likely reasons for this: increased sales of heavy vehicles, such as four-wheel drives, and diesel cars. The latter may have a reputation for fuel efficiency, but they still emit, on average, about 10% more CO_2 than petrol cars. Australian diesel cars are, on average, about 40%

heavier than petrol cars, and have 15% higher engine capacity.

The road ahead

The worsening picture in road transport emissions will increasingly drag down Australia's efforts to meet its modest climate goals set in Paris - even with the accounting tricks the government plans to deploy to reduce the task. Of course it also means Australia is far less likely to make the much sharper emissions reductions needed by all nations to stabilise the global climate.

What can be done about this? The most obvious first step is to implement mandatory fuel efficiency or vehicle emission standards. This policy, fundamental in other countries, would significantly lower weekly fuel costs for vehicle owners.

The federal government must adjust policy settings to encourage the uptake of electric vehicles. AAP

Read more: Clean, green machines: the truth about electric vehicle emissions

Second, a rapid shift to electric cars will help, and increasingly so as the electricity supply transitions to renewables. Deep emission cuts are then possible.

The third is to provide better information about actual emissions. This could be achieved by restoring the large testing programs conducted in Australia up to 2008, involving hundreds of Australian vehicles over different real-world Australian test cycles which generated large databases of raw measurements.

For the moment, Australia's national greenhouse gas emissions strategy seems to be: do nothing, rely on the work of industry, state governments and other nations, and hope that nobody notices. But climate change is not going away. Dodging it now will only increase the costs we accumulate in the long run.