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Costs and benefits of emerging road transport technologies

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Costs and benefits of emerging road transport technologies Report 146

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Foreword

Uptake of Intelligent Transport Systems (ITS) technology is already improving the efficiency, productivity and safety of our commercial and passenger road transport sectors. Although the timing and precise nature of these technologies are not yet clear, further development of ITS together with the widespread use of Cooperative Intelligent Transport Systems (C-ITS) and Automated vehicles have the potential to radically change road transport.

Australian governments are considering the implications of these evolving technologies. The *National Policy Framework for Land Transport Technology* outlines Australia's approach to these technologies and the National Transport Commission is examining regulatory options for automated vehicles. To complement this work, BITRE is examining the costs and benefits of ITS, C-ITS and automated vehicle technologies. The findings of the study will aid analysts and policy makers seeking to evaluate future changes in technology.

Edwina Heyhoe and Pearl Louis prepared the report under the direction of David Mitchell. Jack McAuley and Thomas Rutherford made early contributions to the study. BITRE also acknowledges the assistance of Jeremy Burnett of the Department of Infrastructure and Regional Development.

Dr Gary Dolman Head of Bureau Canberra June 2017

At a glance

Road vehicle technology is advancing at a rapid rate. This report presents the costs and benefits of three emerging technology categories:

- intelligent transport systems (ITS)
- cooperative intelligent transport systems (C-ITS)
- automated vehicles

Applications of ITS can improve road capacity and road safety and reduce congestion. The available empirical evidence suggests that signal coordination, ramp metering and variable speed limits all generate high benefit-cost ratios. Variable messaging signs have lower BCRs because of the relatively high cost of providing real-time information. Hard shoulder running demonstrates large increases in road capacity.

Australian state and territory road agencies are actively investing in ITS, signal coordination and managed motorways. The Queensland government, for example, has released guidelines to promote the use of ITS in its road infrastructure.

Many jurisdictions are trialling C-ITS applications and they show the potential to improve safety outcomes, particularly in the urban environment. Comprehensive studies in the European Union show large benefits from applications such as intersection collision avoidance and right-turn assist.

The literature varies on the relative economic outcomes from dedicated short-range communication (DSRC) and hybrid DSRC-cellular communication platforms. Conducting Australia-specific analysis of the issue that accounts for infrastructure needs in rural Australia and local data costs would be beneficial.

The term 'automated vehicles' encompasses six levels of automation including Level 0 representing no automation and Levels I to 5 covering increasing degrees of automation, from driver assistance technologies, such as adaptive cruise control to fully automated vehicles. Driver warning systems, such as lane departure warning, are a precursor to automation.

Many driver warning and driver assistance systems achieve BCRs above 2, although, studies of United States insurance data show that lane departure warning may be less effective.

The economic outcomes of fully automated vehicles are less certain at this time but are potentially transformational. The literature is consistent in estimating large safety benefits but the widely quoted 90 per cent reduction is probably not achievable.

The effect of a fully automated vehicle fleet on total vehicle kilometres travelled is highly contentious with estimates ranging from a decline of 9 per cent relative to baseline levels to

an increase of over 100 per cent. Changes in total vehicle kilometres travelled combined with expected increases in road capacity will determine travel time and congestion cost outcomes.

Broader social outcomes include potential changes in urban form and employment. Job losses may occur in the directly affected trucking, bus and taxi industries and job creation may occur in high-technology industries.

This review of the literature highlights several important areas needing further analysis, these include:

- implications of automated vehicles for congestion costs and travel time
- role automated vehicles could play in public transport provision and the implications of automated vehicles for the cost of public transport
- implications of automated vehicles at a disaggregated level, for example, employment in directly affected industries and implications for rural and regional transport.

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Executive summary

Road transport technologies

As recent advances in vehicle automation, such as the Waymo, formerly Google car show, road transport technologies are evolving rapidly. In the future, fully automated road vehicles could deliver benefits such as improved safety, more efficient and productive transport networks, more liveable city environments and better access to transport services for those unable to drive.

The intent of this report is to identify and, where possible, quantify the costs and benefits of the following three technology categories.

- Intelligent transport systems (ITS) systems in which information and communication technologies are applied in the field of road transport, including road-side infrastructure, vehicles and users (European Union 2010).
- Cooperative-ITS (C-ITS) technology that enables vehicles to wirelessly communicate with other vehicles, infrastructure or other parts of the road network.
- Automated vehicles vehicles capable of sensing their environment and navigating without human input.

These technologies may greatly help ameliorate the two largest social costs associated with road transport, accidents and congestion. Currently, the annual avoidable costs of road accidents are estimated to be around \$27 billion and the annual congestion costs are estimated to reach \$30 billion in 2030 (Bureau of Infrastructure, Transport and Economics 2014: 2015).

This work fits into a broader government framework as outlined in the *National Policy Framework for land Transport Technology*. The policy framework outlines the four main roles of government as:

- providing policy leadership
- enabling the private sector
- providing a supportive regulatory environment
- investing in research, development and real-world trials.

Benefits and costs of road transport technologies

Intelligent transport systems

Studies indicate most ITS technologies generate benefit-cost ratios (BCR) in excess of I but that benefits are highly variable depending on the volume of traffic and pre-existing technologies. As the technologies are relatively mature, studies incorporate ex-post analysis of real world applications and are therefore robust.

The literature highlights the strong benefits derived from Australian investment in traffic signal coordination system technology over many decades, with many BCRs above 10.

Ramp metering is another highly beneficial ITS technology with BCRs typically exceeding 10. The technology is becoming standard in the construction of new motorways in Australia.

There is limited literature comparing the benefits and costs of high occupancy vehicle (HOV) lanes but evidence shows reductions in travel times of up to 21 per cent for bus travellers.

Variable messaging signs (VMS) is one ITS technology for which benefits are not clear. The costs of providing real-time information sometimes outweigh the benefits of doing so. 'End-of-queue' warnings are not cost effective whereas weather-related messages have BCRs above 1.

Variable speed limits clearly provide safety and efficiency benefits that clearly outweigh the costs of the technology, with BCRs around 4 and under some circumstances above 10.

Cooperative-ITS

Cooperative-ITS supports a wide range of applications that improve safety. Examples include collision avoidance systems and right turn assist. Applications of C-ITS may also improve travel time and reduce congestion.

Cooperative-ITS is economically efficient with Dedicated Short-Range Communication (DSRC) or hybrid cellular-DSRC technologies. Some evidence suggests that the hybrid model may be more cost effective because it utilises DSRC to facilitate safety-related applications, for which it is highly suited, and cellular to facilitate information transfer applications.

The largest cost associated with C-ITS is the on-board units needed in all vehicles. Many applications will also require government investment in road-side units or back-end infrastructure. In major metropolitan areas of Australia, where ITS infrastructure is already in place, the additional cost of implementing C-ITS road-side units is relatively low.

Given that all C-ITS applications need the same infrastructure, the literature generally assesses the BCRs for bundles of applications. It is clear that far larger benefits arise from urban deployment than deployment on regional arterials. A study of the European road network estimate a BCR of around I for C-ITS applications applied to its regional arterial road network and 2.9 when extended to urban roads (Ricardo-AEA 2016). An Australian analysis of safety-of-life applications elicited a BCR of 3.8 with 90 per cent penetration rates (Blogg et al. 2016).

Automated vehicles

The term 'automated vehicles' encompasses vehicles with features that reduce the need for human intervention. Automated vehicles encompass features ranging from adaptive cruise control through to potentially future 'fully automated' vehicles. Although they do not fall under automated vehicle technology, this report also considers the costs and benefits of driver warning systems, such as lane departure warning.

Some advances in vehicle technologies are already demonstrably economic based on their safety benefits. Examples include autonomous emergency braking and lane departure warning systems with BCRs up to 4.1 and 3.3, respectively.

Vehicles may become automated on certain road classes, for example highways. However, vehicles that are driverless on all roads offer the greatest potential to alter private and commercial vehicle transport patterns, however, the timing and nature of these outcomes are highly uncertain at the present time.

The effect on total vehicle use (measured in vehicle kilometres travelled) vary widely, ranging from a decline of 9 per cent relative to baseline levels to an increase of over 100 per cent. The degree to which road users adopt car- and ride-sharing models drives much of this variability.

If vehicle kilometres travelled do not increase substantially, then congestion costs may decline. Assuming a 10 per cent increase in vehicle kilometres travelled and an offsetting increase in road capacity leads to a \$715 reduction in congestion costs per automated vehicle per year (Fagnant & Kockelman 2015).

Fully automated vehicles will almost certainly provide safety benefits because these vehicles remove the human element from accidents. However, the size of these benefits are far from clear with analysts estimating the economic benefits of safety reduction based on assumed reductions in accident rates.

The introduction of automated vehicles has the potential to generate other economic changes, these include:

- changes in employment in professional driving and related industries
- changes in the nature of jobs in the automotive industry as electronics become an increasing part of vehicle manufacturing
- changes in urban form, with potential for increased urban sprawl if commuters perceive the drive to work as more pleasant in an automated vehicle
- technology enabling commuters to make more productive use of time spent travelling, thereby reducing the cost of commuting.

The estimated costs of automated vehicles are in the order of an extra \$10 000 per car on the purchase and increased maintenance costs of several hundred dollars per year.

Table ES.1 provides a summary of BCRs across ITS, C-ITS and automated vehicle technologies.

Table ES.IBenefit-cost ratio summary

Technology	Indicative BCR
ITS	
Traffic signal coordination	> 0
Ramp metering	> 0
Variable speed limits	5-10
Variable message boards	1
Cooperative-ITS	
Non-urban corridor deployment	
Urban deployment	3
Annual DSRC only ^a	6
Annual hybrid cellular-DSRC ^a	7
Automated vehicles	
Driver warning systems	2–3
Driver assistance systems	2-4
Fully automated vehicles ^b	2-17
Cooperative automated vehicles ^b	2–10
BCR for 2030 only all other BCRs in this table are cumulative.	

b Based on assumptions of limited growth in vehicle-kilometres travelled.

Source: BITRE, adapted from papers cited elsewhere in the report

Policy insights

Widespread uptake of fully automated vehicles is likely to introduce new policy issues or create new solutions for existing ones.

- The government's goal in land transport market reform is to align road revenue with costs in the longer term. Potential declines in registration and fuel excise revenue arising from automated vehicles may increase projected discrepancies between revenue and costs.
- Advanced road transport may also affect the need for and, therefore, the cost of road infrastructure. Given the long life of road infrastructure, investment decision-making will need to factor in the potential impact these technologies have on road capacity and road demand.
- Automated vehicle taxi fleets may provide a low cost alternative to those bus services with low patronage, thereby, improving the efficiency of the public transport network.
- Improving road safety is a long-standing government goal. While market forces may see consumers take up many of the safety-enhancing aspects of specific automated technologies, government incentives or mandate may be needed if social benefits of the technologies exceed the private benefits.

Future research

Australian governments and industry are actively involved in research and pilots of road transport technology. The Queensland DTMR, for example, has commissioned research on the impacts of automated vehicles in southeast Queensland. However, given much of this technology is in early stages of development a great deal of research is warranted. The recommendations listed here will provide a greater certainty around economic outcomes and support policy development.

Research to understand vehicle kilometres travelled under automated vehicles is essential for estimating congestion costs. Such research would include:

- induced travel demand from non-drivers such as the young, elderly and disabled
- changes in the value of time for existing drivers
- the likely uptake of car and ride sharing options
- the implication of automated vehicles for private vehicle operating costs.

Even if a move to automated vehicles is economically beneficial to society as a whole, such significant changes may not benefit everyone. This report highlights the need for further research into the:

- potential changes to jobs in transport and related sectors arising from the progressive automation of vehicles
- relative costs and benefits of road transport technologies in urban, regional, rural and remote Australia.

Exploring the financial and economic implications for public transport of moving to automated vehicles in the Australian context may improve the efficiency of public transport.

Further research into the safety implications of some technologies is warranted, these include:

- potential safety implications of transitioning from traditional vehicles to fully automated vehicles. How will traditional and fully automated vehicles will interact and how safe are automated vehicles are unanswered questions
- further investigation of the benefits of mandating or incentivising some safety-related driver warning and driver assistance technologies to maximise economic and social benefits. The current focus of the National Road Safety Strategy is to facilitate their safe introduction into the Australian Fleet, rather than incentivising or mandating them. Technologies, such as lane departure warning systems and adaptive cruise control, are promoted under the Australasian New Car Assessment Program.

Given that most of these technologies are being developed overseas, there is a need to understand the economic outcomes in Australian conditions. One example is the relative costs and benefits of DSRC and hybrid communication options for supporting C-ITS.

CHAPTER I Introduction

Defining road transport technologies

Technological change is affecting consumer behaviour and many industries, including road transport. This report examines those computer-based technologies that are changing the way our vehicles operate and the way road agencies manage roads. These technologies are developing in three, distinct but related, streams:

- Intelligent transport systems (ITS) systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users (European Union 2010).
- Cooperative-ITS (C-ITS) technology that enables vehicles to wirelessly communicate with other vehicles, infrastructure or other parts of the road network.
- Automated vehicles vehicles capable of sensing their environment and navigating without human input.

Many ITS technologies are established parts of current road infrastructure management systems. For example, traffic control systems have been operational in Australia since the 1920s and Australia has led the development of Coordinated Adaptive Traffic Signalling Control Systems since the 1970s. These systems operate in most of Australia's capital cities and in many cities across the world.

Smart phones and navigational devices already enable people to remain connected while in their vehicles. A move to C-ITS embeds communication devices in vehicles. These technologies are being trialled in Australia and elsewhere but are not yet fully operational.

While, driverless, or fully automated vehicles, are unlikely to become commercially available in the near future, in the next few decades, they will be potentially transformational to the existing road network, urban form and vehicle ownership models. Of more immediate interest are the implications of the partial automation technologies already available in our vehicle fleet.

How are these technologies influencing transport decision-making?

The roles of Australian governments in developing these technologies are outlined in the *National Policy Framework for Land Transport Technology*. The policy framework outlines the four main roles of government as:

- providing policy leadership
- enabling the private sector
- providing a supportive regulatory environment
- investing in research, development and real-world trials.

The policy framework is underpinned by a three-year action plan for work on ITS, C-ITS and automated vehicles that includes undertaking research and trials.

Governments in Australia and elsewhere are incorporating ITS technologies into their infrastructure development and traffic management strategies. Most new Australian motorways incorporate some form of ITS. Recognising that ITS can increase road capacity, Queensland has gone as far as formalising ITS as part of their infrastructure decision-making (Queensland Department of Transport and Main Roads 2016c).

For C-ITS and automated vehicle technologies, Australian governments are focused on understanding policy and operational issues, investigating requirements for supporting infrastructure, regulating appropriately and supporting research and trialling of these technologies (Transport and Infrastructure Council 2016). The Australian Communications and Media Authority (ACMA) has concluded consultation on a proposal to align with European standards on electro magnetic spectrum regulation in the 5.9 Ghz range to support ITS.

Geoscience Australia is leading a project to demonstrate the value of improving the accuracy of satellite positioning information in Australia. The Satellite-Based Augmentation System technology is widely available in the Northern Hemisphere and could be an important enabler of automated vehicles.

State governments are undertaking pilots of C-ITS and automated vehicle technologies. Transport for NSW and partners are trialling C-ITS in heavy vehicles on the south coast of NSW (Transport for NSW 2016). In Queensland, residents of Ipswich will soon have the opportunity to participate in a C-ITS trial (Bailey 2016). A driverless shuttle is currently operating along the Esplanade in Perth (Royal Automobile Club of Western Australia 2016). Austroads maintain a full list of trials on their website (http://www.austroads.com.au/drivers-vehicles/connected-and-automated-vehicles/trials)

The National Transport Commission (NTC) is currently examining the regulatory changes needed to operate automated vehicles (National Transport Commission 2016). This work includes clarifying legal issues around control of automated vehicles and developing a safety assurance regime for the commercial deployment of automated vehicles.

Austroads has established a connected and automated vehicle program focusing on the operational impacts of automated vehicles. Current projects examine vehicle registration, driver licensing, third-party insurance, physical and digital infrastructure requirements and traffic management implications.

The House of Representatives Standing Committee on Industry, Innovation, Science and Resources is currently undertaking an inquiry into the social issues relating to land-based driverless vehicles in Australia (Standing Committee on Industry, innovation, Science and Resources 2016). This inquiry's focus is on issues such as community acceptance of driverless vehicles.

The private sector is driving technological enhancements to the vehicle fleet. Traditional manufacturers are at the forefront on connected vehicles and low-level automation of the existing vehicle fleet. Technology companies, including Tesla, Google and more recently Uber have joined traditional car manufacturers, such as Volvo and Ford actively developing more highly automated vehicles. In Australia, the mining industry is using autonomous vehicles in selected applications at their mine sites. Mapping service companies such as HERE and Google are developing detailed data that may underpin some of these technologies.

Project Overview

Project aims

The overarching aim of this report is to support much of the above-mentioned government and private sector activity by identifying the costs and benefits of selected ITS, C-ITS and automated vehicle technologies.

These technologies have a vast array of purposes and a correspondingly large array of benefits. Road transport technologies have the potential to improve the safety, efficiency, sustainability and accessibility of road transport. For example, variable speed limits already smooth the traffic flow along freeways reducing accidents and travel time (Gaffney 2010). In the future, driverless vehicles may enhance the mobility of the elderly and disabled. The aims of this report are to describe and where possible quantify the benefits.

The costs of these technologies encompass a range of infrastructure and software development costs. The report also includes available cost estimates.

The economic efficiency of any technology depends on its net benefit to society. The report provides conclusions on the economic viability of the selected applications by comparing costs and benefits with a benefit cost ratio (BCR).

Considerable uncertainty attaches to estimates of benefits and costs for those technologies currently under development. For example, no consensus exists on the platform for implementing C-ITS. Therefore, the report identifies those areas where further research on costs and benefits would be most beneficial.

Project scope

Table 1.1 provides an overview of the technologies included under each of the three categories, ITS, C-ITS and automated vehicles. The project does not cover all related technologies, with attention paid to those technologies where policy changes may be warranted, through a:

- wish to implement or promote technologies with external benefits, such as improved safety or reduced emissions and congestion
- need for standards or infrastructure investment such as those potentially arising from C-ITS
- need for greater understanding of potentially transformational change as is the case for full automation.

Table 1.1 Selected road transport technologies

ITS	C-ITS	Automated vehicles
Coordinated traffic management systems	Safety-of-life systems	Driver warning systems
Motorway management systems (ramp metering,	Information provision	Driver assistance systems
variable speed limits, driver information)		Situation-specific full automation
Incident management systems (driver information)		Full automation

Source: BITRE

Categorising these technologies is useful but does not reflect a future in which vehicles are equipped with technologies across the three categories. This report also touches briefly on the potential synergies and incompatibilities between different technology types.

The C-ITS discussion in this report does not include communication products using smart phone technology despite their benefits and proliferation. This report does, however, include in-vehicle navigational aids.

The automated vehicle category includes driver warning systems although they are not true automation. These systems are an important precursor to driver assistance systems.

Many of these technologies enable the collection of large amounts of data on vehicle movements. This, so called 'big data', generates its own benefits and costs. Such data may improve government and private industry decision-making but may create privacy concerns. Issues around 'big data' are beyond the scope of this project. The BITRE is currently developing a Data Collection and Dissemination Plan, to help improve and coordinate information and data collection, and ultimately better inform infrastructure planning and delivery. Identifying and promoting opportunities to harness new data sources (including 'big data') will be a key part of the Plan's development.

Additionally, some ITS and C-ITS technologies may reduce the costs of implementing more direct pricing for the use of roads. The benefits and costs of any changes to road pricing are also beyond the scope of this paper.

Our approach

Literature review is our principal method of investigation for this report. The nature of the economic literature varies between ITS, C-ITS and automated vehicle categories and to some extent within each category.

For ITS technologies, evaluation studies are available that demonstrate the costs and benefits (and benefit-cost ratios) of existing ITS applications in Australia and elsewhere. However, available studies are not readily comparable with each other and not easily applied to other regions or countries (Lu 2016). In this paper, Australian studies are cited where possible and the comparability of international studies to Australian conditions is discussed.

Care is needed when translating results from other countries to Australian conditions and even when transferring results between Australian cities. Benefits of road transport technologies are location specific. For example, traffic volumes will affect the expected benefits from technologies that reduce congestion.

For consistency, all cost and benefit estimates have been converted to 2016 Australian dollars, unless otherwise stated.

The benefits of implementing new technologies also depend on the quality of existing technologies. Benefits from improving signal coordination are likely to be lower in Australia than in the United States because Australian traffic management systems (SCATS and STREAMS) already provide benefits not seen by many road users in the US.

Given the number of C-ITS pilots and the strong interest in the technology in the US and EU, the international literature is quite extensive but the results are less certain because real world applications are not yet available. The report includes discussion of characteristics of the different communication mechanisms, DSRC and 4G and 5G cellular technologies underpinning C-ITS.

The uncertainty around the implications of fully automated vehicles gives rise to additional analytical challenges. The number of evaluations of full automation are limited and highly contingent on assumptions about future penetration rates and driver behaviour. The impacts go far beyond traditional transport investment to vehicle ownership decisions and changes to employment in the transport and vehicle manufacture sectors.

Methods of evaluation vary across the literature. Cost-benefit analysis (CBA) is widely used for evaluating established and well-understood technologies. Other methods, such as cost effectiveness analysis (CEA) and multi-criteria analysis (MCA) are also suitable for analysing complex problems. This report includes studies using different analytical techniques such as impact assessment studies and scenario analysis.

Report outline

The next three chapters describe ITS, C-ITS and automated vehicle technologies, respectively. Each of these chapters describes the capabilities of the applications of the technology category and our understanding of the benefits and costs. Chapter 5 draws policy insights and provides recommendations for further research.

CHAPTER 2 Intelligent transport systems

Defining ITS

Intelligent transport systems (ITS) integrate advanced electronic technologies into transport infrastructure and vehicles. These technologies improve traffic management and information dissemination to road users thereby improving the safety, efficiency and environmental outcomes of the road network. Table 2.1 provides information on the purpose and functionality of selected ITS technologies.

Technology	Description
Signal coordination	Such as SCATS, improve network efficiency by coordinating signals in response to real world traffic conditions.
High occupancy vehicle prioritisation	Extends SCATS to provide priority to buses and other high occupancy vehicles.
Ramp metering	Facilitates higher speeds and throughput on freeways by using signals on entrances to control access. The signals operate with varying degrees of sophistication, from fixed timing to a coordinated response to congestion along the length of the freeway.
Variable speed limits	Improve safety and efficiency by varying speed limits in response to congestion levels on freeways.
Variable message boards	Improve efficiency by providing drivers with real-time congestion, weather and incident information
Hard shoulder running	Reduces travel times and increases capacity by allowing vehicles access to shoulders when the freeway is congested. The decision to open the shoulder is based on loop data and camera information and communicated to road users through electronic signs.
Emergency vehicle prioritisation	Is a refinement of traffic management systems that enable emergency vehicles right of way through traffic lights.

Table 2.1 Purpose and functionality of selected ITS technologies

Source: BITRE

Costs and benefits of ITS

Many countries have evaluated the costs and benefits of selected ITS systems in recent years (Lu 2016). The evaluation techniques are well developed enabling clear judgements of the value of these systems. Some jurisdictions have published standardised cost and benefit estimates as part of their decision-making processes. Queensland (Queensland Department of Transport and Main Roads 2016c) and Sweden (Sachse et al. 2016) being two examples.

Infrastructure costs

Intelligent transport systems add costs over and above those of conventional infrastructure. Typically, these involve the construction of an ICT backbone to support the ITS deployment, as well as the ITS assets themselves; others may be incurred depending on the nature of the project (Table 2.2).

The cost of retrofitting a site for ITS often exceeds that of a greenfield deployment. Retrofitting involves additional costs associated with modifying the infrastructure, such as cutting into pavement to install in-road sensors, digging to deploy conduit and the disruption to existing operation caused by the works.

/1	
ICT backbone	ICT assets
Conduit and fibre-optic cable	Gantries, sensor mounts and installation
Electrical and network cabinets	Electronic signs and displays
Wireless transmitters	Sensor equipment
Data centre space	CCTV
Server equipment	

Table 2.2 Typical infrastructure requirements of ITS applications

Signal coordination

Source: BITRE

In Australia, the most widely used ITS is signal coordination.

Signal coordination can be 'dynamic', in that timing responds to the level of traffic on the road, for example by detecting when no more vehicles are waiting to pass through a green phase. A system can be 'coordinated' in the sense that traffic signals along a road can be timed in such a way to reduce overall waiting time, for example by giving drivers a progression of green lights. Finally, these systems can also be 'adaptive', in that 'traffic signal timing is updated in some automated way' in response to traffic conditions.

Transport for New South Wales estimates that Sydney Coordinated Adaptive Traffic System (SCATS) provides \$3.6 billion in time savings benefits to Sydney motorists each year (Transport for NSW 2015), as well as producing significant environmental benefits. A review of the US Department of Transportation's ITS costs and benefits database yields many benefit costs analyses most of which show BCRs well in excess of 1. USDOT (2014) report that BCRs for signal coordination systems range from 1.58:1 to 62:1. Estimated travel time reductions, that vary between 0 and 20 per cent are the main cause of the large variation in BCRs.

The City of Chula Vista, California, found that replacing a set of fixed-timing signals with SCATS delivered first-year benefits 1.08 times the cost. On a set of road corridors, average travel speed was improved by up to 18 per cent, average delay time was reduced by up to 43 per cent, and average travel time was reduced by up to 15 per cent (City of Chula Vista 2013).

The city of Portland, Oregon, reported a BCR of 5:1 with around 90 per cent of the benefits derived from travel time savings and smaller benefits from fuel consumption and emission reductions (Bertini et al. 2005).

The widespread use of SCATS (and similar technologies, such as STREAMS) across many Australian urban road networks means the benefits from further investment in coordinated signalling may be lower in Australia than elsewhere.

High occupancy vehicle prioritisation

High occupancy vehicle (HOV) prioritisation is an extension of signal coordination under which public transport gets priority ahead of private vehicles. For example, the Public Transport Information and Priority System (PTIPS) is linked to the SCATS system in Sydney. If buses are running more than 2 minutes late, PTIPS gives them priority at traffic signals. A 2001 trial of PTIPS on the Sydney Airport Express Bus service showed the PITPS reduced mean travel times of buses by 21 per cent and variability of travel time by up to 49 per cent.

Although not generally quantified, the benefits of high occupancy vehicle prioritisation can also include increased public transport patronage and reduced emissions in addition to the travel time benefits. The literature does not provide conclusive evidence of the impact of HOV prioritisation on travel times for other vehicles.

The direct costs of a bus prioritisation system are relatively small, with capital costs of between \$13,000 and \$21,000 per intersection and operational costs of between \$3000 and \$5000 per year (Queensland Department of Transport and Main Roads 2016b).

Ramp metering

Ramp metering controls access to freeways thereby maximising the throughput. *Coordinated ramp metering* allows road agencies to control freeway access in a coordinated way across multiple entrances so as to maintain reasonable traffic flow on the freeway.

Ramp metering is in place on the Pacific Motorway in Brisbane and M1 in Melbourne, and in planning in Sydney and Adelaide. The Monash Freeway in Melbourne uses coordinated ramp metering technology.

Reductions in travel time is considered the major benefit of ramp metering. However, reduced travel time on the freeway is somewhat offset by increased wait time on the ramp. Drivers travelling longer distances on the freeway are more likely to experience reduced travel times, whereas, drivers travelling shorter distances may experience increased travel times to the extent that on-ramp wait-times lengthen. Reduced travel time and smoother journeys lead to reduced fuel consumption and reduced emissions. In addition, ramp metering is observed to reduce accidents on freeway entrances.

The introduction of ramp metering with the HERO algorithm on the Monash Freeway was shown to increase inbound peak throughput per lane and vehicle speed by 19 per cent (VicRoads 2015).

In a summary of the existing benefits literature Queensland Department of Transport and Main Roads estimates the travel time savings from ramp metering to be between 8 and 26 per cent and average accident rate reductions by between 24 and 50 per cent (Queensland Department of Transport and Main Roads 2016b).

Ramp metering requires investment in signalling infrastructure and equipment and potentially redevelopment of the freeway on-ramp. Queensland DTMR estimate the capital costs at \$130000 and \$190000 per ramp with associated operational costs of between \$26000 and \$38000 (at 2016 prices).

In one of the few controlled studies of the impact of ramp metering, the city of Minneapolis-St Paul shut down its ramp metering system for five weeks to evaluate the system's benefits (Minnesota Department of Transportation 2001). The study demonstrated the overall benefits of ramp metering but also highlighted the trade-off between freeway travel time and ramp delay. Box I provides a summary of this study.

Box I Minnesota ramp metering shutdown study

Ramp meters were introduced to the Minneapolis-St Paul metropolitan area in 1969, with 430 meters in operation at the time of the study. In 1999 and 2000, local media debate about the contribution of ramp metering to travel time inequity between long-distance and inner-city commuters, as well as the system's long-term impact on urban form, lead to a 'shutdown study' of the benefits and costs of the system. Data was collected for five weeks with meters on and five without. Measured variables included traffic volumes, speeds, safety incidents, ramp queue length and delay and frequency of over-full ramp queues.

The average per trip travel time of 12 minutes was around 0.2 minutes lower with ramp meters on. The net travel time effects comprised a transfer from mainline reduction in travel time of 2.5 minutes and a ramp delay 2.3 minutes.

Table 2.3 summarises the benefits and costs of the ramp metering. The largest component of net benefits was reduction in travel time variability, followed by safety benefits. Fuel use increases arise from increasing vehicle speed. Despite, the increase in fuel use, reductions in hydrocarbons and carbon monoxide generate environmental benefits. The study does not value changes in carbon dioxide emissions. As the costs of implementing ramp metering were not separable from the other components of the broader congestion management system, for the headline benefit-cost ratio, the full costs were conservatively attributed to ramp metering. When only the costs attributable to ramp metering are used, the BCR is 15.

orta 27
USIS 2.7
maintenance costs 2.0
ts 4.7

Table 2.3 Summary of annual benefits and costs from Minnesota ramp metering

Source: Minnesota Department of Transportation (2001)

The study report recommended that metering should be focused on the most congested freeway sections—typically with peak speeds below 48 km/hr, queues should not be allowed to impact arterial roads and wait-time messages be introduced.

Studies indicate that coordinated ramp metering achieves better outcomes than traditional ramp metering. A rapid cost benefit analysis of the recently developed coordinated ramp metering program HERO¹ suggests that a BCR of 13.8 to 1 is achievable (Faulkner et al. 2013). The Queensland Department of Transport and Main Roads has implemented the HERO system on the M1/M3 system in Brisbane. The study also showed that the coordinated system improved travel times when compared with the conventional fixed-rate system.

There is scope to expand ramp metering to additional urban freeways in Australia, and improving the underlying algorithms may improve the efficiency of existing ramp metering systems (Gaffney 2010).

Variable speed limits

Variable speed limits (VSL) are becoming more common in Australia, many of the motorways and freeways built in the last decade have VSL, including the M7 in Sydney. The technology is known to provide travel time savings and reduce accidents.

The Swedish Transport Authority recommends analysts assume a 5 per cent increase in road capacity and a 10 per cent decrease in accident rates from the introduction of VSL (Sachse et al. 2016). Ex-post analysis of a German autobahn investment concludes that VSL reduces accident rates but does not reduce travel time, except insofar as it reduces the impact of incidents on travel time (Weikl et al. 2013).

The costs of implementing a VSL system comprise the capital costs of signals, cabling and traffic monitoring cameras together with associated maintenance and replacement costs (Schirokoff et al. 2006). Queensland DTMR estimate capital costs of between \$140 000 and \$240 000 per kilometre and operating costs between \$30 000 and \$50 000.

According to ARRB Consulting and SJ Wright & Associates (2006), a benefit cost ratio of between 4.7 and 11.4 has been estimated for the Wellington-Ngauranga advanced traffic management system (ATMS) in New Zealand.

In urban areas, speed limits typically vary with traffic levels, whereas, in rural areas, speed limits vary in response to particular events, such as flooding. In New Zealand, a technology has been trialled involving reducing the speed limit when vehicles are approaching on a side road. This technology gives drivers more time to respond if the oncoming vehicle fails to give way. Mackie et al. (2014) found that the vehicle activated speed limit signs of this kind were successful in reducing speeds. It was too early to measure the safety benefits, given the low frequency of crashes at particular intersections. However, given the relationship between speeds and safety risk on rural roads, the safety impacts are likely to be positive (Bureau of Infrastructure, Transport and Regional Economics 2014).

Variable message boards

Road agencies across the world commonly use variable message boards (VMB), or variable message signs (VMS) to communicate real-time information to drivers. The information may cover congestion, weather and incident alerts (including end-of-queue alerts).

I HEuristic Ramp metering cOordination

By providing real-time information, these systems enable road users to make informed decisions on route choice, potentially reducing congestion arising from the incident. Safety may also improve as drivers get advance warning of road blockages.

The European Commission undertook a cost benefit analysis of providing information on message boards (European Commission 2013). The study showed that this information might reduce fatal and injury-causing accidents by 2.7 and 1.8 per cent, respectively.

The costs of the service include capital and maintenance costs associated with the physical infrastructure, data processing and data sharing costs. The BCRs are between 1 and 2.8 if end-of-queue alerts are not provided. However, BCRs typically fall below 1 if end-of-queue alerts are provided because of the high cost of collecting this data.

Hard shoulder running

Under a hard shoulder running regime, road agencies open the road shoulders to traffic when the road is congested.

The principal benefit of hard shoulder running is the increase in road capacity, with a US study showing increases in capacity of between 7 and 22 per cent (United States Department of Transportation no date). Some studies have estimated substantial safety benefits, whereas others have shown no change. In the UK, road agencies have also introduced refuges in concert with hard shoulder running and have seen reductions in accident rates (ITS International 2014).

The costs of hard shoulder running include reconfiguring the existing road space and installing equipment for supporting the IT. The capital costs are estimated at between \$180 000 and \$240 000 per road kilometre with ongoing operating costs of between \$40 000 and \$60 000 per road kilometre (Queensland Department of Transport and Main Roads 2016b).

The literature on hard shoulder running measures its effectiveness in terms of changes in accident rates and road capacity. Although there are no BCRs, qualitatively the UK government considers hard shoulder running a cost effective alternative to road expansion at least in the short term (ITS International 2014).

Managed motorways

The preceding sections describe the costs and benefits of individual ITS applications, however, state agencies commonly implement combinations of the above-mentioned ITS technologies on a stretch of road. Managed motorways, common in Australia, typically include ramp metering, VSL and VMBs.

For example, the recent introduction of ramp metering on the Bruce Highway in Queensland coincided with the introduction of VSL technology together with coordinated ramp metering (Queensland Department of Transport and Main Roads 2016a)

Similarly, in Victoria, the STREAMS system on the MI freeway has a range of capabilities:

- adaptive ramp metering
- variable speed limits
- reversible lanes
- variable message boards
- real-time traffic information
- vehicle detection
- integration of on-ramps with traffic signals.

The integrated system allows the vehicle detection infrastructure to inform the algorithms controlling ramp metering and variable speed limits and neighbouring traffic signals. Drivers are kept informed through the variable message boards.

Similarly, the ITS for the Northern Connector, in Adelaide, will also enable incident detection and traffic information services (South Australian Department for Transport, Energy and Infrastructure 2011).

While understanding the benefits of different technologies is valuable for designing an ITS capability, the overall BCR is contingent on the package of benefits. Given the proliferation of managed motorways, some research into the combined benefits of the system under real world conditions is warranted. For example, managed motorways may reduce the overall costs of implementing a range of applications because these applications share infrastructure such as back-to-base cabling.

Conclusions

State and territory road agencies are at the forefront of implementing ITS technologies in Australia. Given that the suitability of applications and the scale of the benefits is highly location specific this is appropriate. Results from the literature suggest that, in many circumstances benefits greatly outweigh costs, so evaluating ITS options as part of the development of any major transport infrastructure development is important. The recently released Austroads guide is of value in this regard (Austroads 2016).

Table 2.4 summarises available benefit, cost and BCR estimates for selected ITS technologies.

Technology	Costs	Benefits	BCRS
Signal coordination	Capital: \$100 000-\$130 000 per intersection On-going: \$20 000-\$30 000	Reduced travel time 0 to 20 per cent across multiple studies	17 in California 62 in Texas 57 in Pennsylvania
HOV prioritisation	Capital:\$13 000–\$21 000 per intersection On-going: \$3 000–\$5 000	21 per cent decrease bus travel time in Sydney	na
Ramp metering	Capital: \$130 000-\$180 000 Ongoing: \$26 000-\$38 000	Reduced travel time	13.8 in Australia 15 in Minnesota
Variable speed limits	Capital: \$140 000-\$240 000 per km Operating: \$30 000-\$50 000	10 and 30 per cent reduction in crashes. Small increases in throughput.	4.7 to 11.4 in New Zealand
Variable message boards	Capital: \$250 000–\$440 000 per km Ongoing: \$50 000–\$90 000	Up to 2.8 per cent reduction in accidents and potential decrease in travel time	1.1 to 1.9 for VMBs providing weather information in Finland
Hard shoulder running	Capital: \$180 000-\$240 000 per km Ongoing: \$40 000-\$60 000	57 per cent reduction in crashes in the M42 in UK Up to 22 per cent increase in capacity in the US	na

Table 2.4 Summary of costs and benefits of selected ITS technologies

na not available

Sources: Queensland Department of Transport and Main Roads (2016b); United States Department of Transportation (2017)

CHAPTER 3 Cooperative-ITS

Defining C-ITS and connected vehicles

Cooperative (or Connected) Intelligent Transport Systems is the term used to refer to technology that enables vehicles to communicate wirelessly with other vehicles, infrastructure or other parts of the road network. C-ITS technology predominantly includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication systems. There are also vehicle-to-pedestrian (V2P) and broader vehicle-to-network (V2N) systems (Qualcomm 2016). The term V2X (vehicle-to-other/everything/anything) is used as an umbrella term to describe all of these technologies (EC 2016; Harding et al. 2014; MRWA 2015; Qualcomm 2016).

C-ITS technologies support a wide range of applications designed mainly to improve road safety and reduce congestion.

Table 3.1 lists the most prospective future applications.

Application	Examples
Cooperative vehicle-highway automation system	Platooning
Pre-crash sensing	Vehicle-to-vehicle communication to avoid a collision
Intersection collision avoidance	Traffic signal violation warning, right-turn assistant, intersection collision warning
Information from other vehicles	Cooperative forward collision warning, lane change warning, cooperative collision warning, cooperative adaptive cruise control
Public safety	Emergency vehicle signal pre-emption, post-crash warning
Sign extension	In-vehicle signage, curve speed warning, wrong way driver warning
Road condition warning	Advice on road works
Highway/rail collision warning	Level crossing alert
Traffic management	Intelligent on-ramp metering, intelligent traffic flow control
Source: BITRE	

Table 3.1 Potential applications of C-ITS technologies

Broader than C-ITS, the term 'connected vehicles' describes vehicles that can connect to the internet and directly access parking apps, traffic alerts, road tolls, real-time navigation updates and entertainment. For example, Tesla vehicles directly connect to a WiFi network to download software updates, and vehicles with the European eCall or the USA OnStar systems automatically pass data to emergency services when a serious accident occurs.

C–ITS applications may also support automated vehicles through applications such as truck platooning. The costs and benefits of connected and automated vehicles are described in chapter 4.

Wireless communication platforms

The choice of wireless communication platform will affect the types of C-ITS applications available, the timeline to commercialisation and the costs of implementation. Therefore, the first part of this chapter outlines the technological requirements of C-ITS applications and the suitability of the prospective communications platforms.

Most research on C-ITS technology and investigations to date has focused on dedicated short-range communications (DSRC). However, with the upcoming 5G update to the cellular network and efforts to use the existing $4G^2$ network for connected vehicle applications, cellular technology is emerging as a possible alternative to DSRC. The European Union is considering a hybrid of the two technologies.

Requirements for C-ITS

Each C-ITS application has distinct technological requirements. The sections below and Table 3.2 describe these requirements.

(a) Latency

Latency is the maximum tolerable elapsed measure of time delay experienced between the sending and receiving of information. Latency is important in C-ITS because of the high speeds vehicles can travel. For example, a vehicle travelling at 100 km/h^3 will cover 28 m in one second and at 60 km/h, 17 m. If the latency is one second, a vehicle signalling it is about to enter an intersection may have entered and even have left by the time other vehicles have even received the message.

Safety-of-life and driving applications such as collision avoidance, lane change warnings, co-operative collision warning and co-operative adaptive cruise controls have maximum tolerable latencies of less than 100 ms.

(b) Range

Range is the distance that the wireless signal needs to be able to travel to communicate with wireless network infrastructure or other vehicles. Generally speaking, the range requirements for both C-ITS and broader connected vehicle applications is only a few hundred metres.

(c) Data transmission rate

Data transmission rate is the lower of the speeds at which data is uploaded or downloaded. Both download and upload data transmission speeds matter as bi-directional communication

^{2 3}G does not have the potential to meet C-ITS technical requirements.

³ The relevant speed may be lower (e.g. 60 km/h in an urban setting) or higher—in a head-on collision, the relevant speed is the sum of the two vehicles' speed.
is important in C-ITS. For safety-of-life applications, the vehicle needs to be able to transmit or upload data related to its speed and position.

(d) Ability to handle high vehicle speeds

The combination of very high vehicle speed and the high frequency of C-ITS signals make these signals susceptible to Doppler spreading.⁴ C-ITS safety-of-life applications must be robust to this effect.

(e) Ability to directly communicate between receivers

While C-ITS signals can be carried through intermediary infrastructure, the ability to directly communicate between receivers is necessary to handle situations where there is no supporting infrastructure. For example, in communication blackspots or rural areas. Without this ability C-ITS would be highly geographically restricted. Direct communication is especially important to enable truck platooning in sparsely populated areas of rural Australia.

(f) Reliability

A reliable communication network needs wide geographic coverage, stable wireless connections, robust hardware and the ability to handle congestion, communication errors and degraded signals. Reliability is important for any safety-of-life applications.

⁴ The Doppler effect causes shifts in the frequency of the wireless signal due to the relative velocities of the receivers. At high vehicle speeds, the presence of potential scatterers like other vehicles and the high frequencies of C-ITS cause the signal to noticeably smear (Doppler spreading) which causes problems with performance.

Table 3.2	Technical	specifications	for C-	ITS and	other	connected	applications
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Application	Critical latency (ms)	Data range (m)	Data rate (Mbps)	Doppler Effect	Device to device	Reliability
C-ITS						
Cooperative vehicle-highway automation system (platooning)	<20	~ 00	na	Yes	Yes	Yes
Pre-crash sensing	<20	~50	na	Yes	No	Yes
Intersection collision avoidance	< 00	250-300	na	Yes	No	Yes
Information from other vehicles	< 00	150-300	~0.01	Yes	No	Yes
Public safety messages	< 000	300-1000	na	No	No	Yes
Sign extension	< 000	100-500	na	No	No	Yes
Road condition warning	< 000	~200	na	No	No	Yes
Highway/rail collision warning	< 000	~300	na	Yes	No	Yes
Traffic management	< 000	100-250	na	Yes	No	Yes
Other connected						
Tolling	50–200	~50	na	No	No	No
Service announcements	<500	0–90	~0.002	No	No	No
Instant messaging between vehicles	< 000	~50	na	No	Yes	No
Adaptive vehicle management	< 000	~200	na	No	No	No
Navigation	< 000	200-400	na	No	No	No
Video streaming	< 000	na	> 0	No	No	No
Vehicle diagnostics and maintenance	<5 000	~400	na	No	No	No
Connected and automated driving (CA	V)					
Connected and automated driving	~	na	> 0	Yes	Yes	Yes

na not available

Sources: CAMP (2005); GSMA Intelligence (2014); Karagiannis et al. (2011); Xu et al. (2004)

Dedicated short-range communications (DSRC)

DSRC is currently the de-facto standard for C-ITS. The technical capabilities of DSRC appear well suited, which is not surprising as the technology was developed specifically for C-ITS, Table 3.3.

Table 3.3 Technical capabilities of DSRC C-ITS

Technical specification	DSRC capability
Latency	<15ms
Communication range	300-500m
Data transmission rate	27 Mbps
Handle high vehicle speeds	Yes
Direct communication	Yes
Reliability	Good ^a

a Experts consider DSRC reliable, apart from it being untested in congested conditions.

Sources: EC (2016), Maitipe and Hayee (2010), Wang et al. (2013), Ertico (2015), Ertico ITS Europe and 5GPPP (2015) and Huawei (2016).

The underperformance of DSCR in congested conditions is an unresolved technical issue (EC 2016; ERTICO ITS Europe & 5GPPP 2015; Turnbull 2015). Even the most advanced DSRC systems may not be sufficient for more data-heavy applications, such as vehicle maintenance (EC 2016).

Regulatory approvals for DSRC are underway. The Australian Communications and Media Authority (ACMA) has concluded consultations on licensing DSRC devices in line with European arrangements (ACMA 2016).

In the private sector, General Motors is deploying DSRC technology in their production model year 2017 Cadillac CTS vehicles (Cadillac 2017). Vehicles manufactured in Europe could also be fitted with DSRC C-ITS equipment in 2017 (ACMA 2016).

Existing mobile networks (4G-LTE and 4G-LTE Advanced)

The most recently released cellular networks 4G-LTE and 4G-LTE Advanced meet the technological requirements for some C-ITS applications but not all. ERTICO ITS Europe and 5GPPP (2015) summarises the technical applicability of the 4G-LTE cellular networks.

- With latency ranging between 50 and 100 ms, 4G-LTE does not support safety-of-life applications. In contrast, with a latency of between 10 and 20 ms, 4G-LTE Advanced supports most C-ITS applications. Latency may deteriorate with increased congestion on the cellular network.
- The data range for 4G cellular technology through mobile towers is around 1000 m, making it appropriate for C-ITS applications. Similarly, the data rates for 4G-LTE and 4G-LTE Advanced support all C-ITS applications.
- Currently, 4G-LTE technologies are not robust against Doppler spreading, but researchers are working to rectify this problem (Jinling 2015; Sun et al. 2016).
- The most recent release of 4G-LTE Advanced is the first cellular technology with device-to-device communication capability. However, the technology is designed to support emergency services operating in areas without network coverage and is not suited to C-ITS applications (Lopez 2016).
- The 4G-LTE and 4G-LTE Advanced technologies at this point in time are less reliable than DSRC safety-of-life applications because of limited coverage and congestion issues.

If the above issues can be resolved it is possible that 4G-LTE Advanced could be used for C-ITS. If 4G-LTE Advanced coverage increases greatly over the next few years, then C-ITS applications would not require additional infrastructure. In addition, V2V communication may not need infrastructure and V2I generally exists in locations with 4G coverage.

The 5G cellular network

The 5G cellular network is in planning stages and its technical specifications are not final. However, C-ITS communication capability is part of the impetus for its development

The proposed specifications include very low latencies (1 ms for direct communications and 5 ms via a tower) and high data rates (> I GBps). Moreover, it will be designed with high reliability and with high vehicle speeds in mind (Cordero 2016; Ertico ITS Europe & 5GPPP 2015; GSMA Intelligence 2014; Qualcomm 2016). Device-to-device communication will also likely be part of 5G to provide V2V direct communications (ERTICO ITS Europe & 5GPPP 2015; Qualcomm 2016).

However, the transmission range of 5G is limited to several hundred metres compared with the several thousand metres achievable using older cellular technologies (Greenemeier 2015). Therefore, 5G would need as much new infrastructure as DSRC.

With technical specifications and C-ITS capability being only one development option, 5G is a long way from providing commercially available C-ITS services.

The hybrid option

Cooperative-ITS applications vary greatly in terms of technical communication requirements. Safety-of-life applications need the characteristics of DSRC whereas cellular technologies may better serve information transfer applications. The European Commission considers a hybrid communication approach, where DSRC or available cellular technologies are selected based on their suitability to a particular application (EC 2016).

Economic analysis of C–ITS

Because C-ITS technologies are in developmental or pilot phases, ex-post analyses of these technologies are unavailable. The benefits, costs and BCRs derive from modelling undertaken in the US, EU and Australia

Benefits

The economic benefits of C-ITS depend on:

- the number and type of applications
- the penetration of C-ITS devices in the vehicle fleet
- the geographic location.

While the research done to date on the economic benefits of C-ITS have focused on DSRC C-ITS, it is likely that cellular C-ITS would have the same benefits, assuming that the same applications could be implemented.

Europe

Ricardo-AEA (2016) models all safety-of-life and other connected applications listed in Table 3.1 except CAV. All major intercity connectors (the Trans European Transport Network (TEN-T)) and urban road networks are assumed to become C-ITS capable.

Ricardo-AEA (2016) estimate large travel time and safety benefits with smaller environmental benefits, Figure 3.1.



Figure 3.1 Annual benefits in 2030 from European implementation of C-ITS

Source: Adapted from Ricardo-AEA (2016).

The estimated \$14 billion⁵ travel time savings represent a 3 per cent reduction in total time spent on roads. Enhanced route guidance and navigation generates an 8.2 per cent increase in average car speed and traffic signal priority generates a 9.0 per cent increase in average bus speed.

The \$5.7 billion per year of safety benefits in 2030 reflects a 7 per cent reduction in accident rates from the baseline. Most of these benefits, \$5.0 billion, derive from preventing serious injuries. The largest percentage reduction in accidents in 2030 comes from cooperative collision risk warning. This C-ITS technology is expected to result in 4.9 to 9.5 per cent reduction in accidents by 2030 depending on vehicle, road and accident type. Other C-ITS technologies that result in significant reductions in accidents include: traffic signal violation warnings⁶, traffic shockwave damping and in-vehicle signage⁷.

Environmental benefits are expected to be relatively minor compared to time savings and safety benefits. Around \$2.3 billion in environmental benefits are expected by 2030, nearly all of which derive from reductions in fuel consumption.

Ricardo-AEA (2016) indicate that network effects make the benefits of C-ITS higher when the rate of penetration is high. Therefore, reaching a critical mass of deployment is important.

The urban deployment applications — intersection related services, parking and traffic information — make up about half of the benefits of the European C-ITS rollout. However Ricardo-AEA (2016) note that the data behind these benefits is very limited and more research is required.

Australia

The Queensland Government has undertaken a rapid cost benefit analysis of implementation of C-ITS in southeast Queensland (Blogg et al. 2016).

The study covers nine safety-of-life applications such as emergency electronic brake light, in-vehicle speed warning, and right turn assist. The three scenarios reflect differences in penetration rates in the total vehicle fleet in 2040:

- Pessimistic—around 14 per cent
- Moderate—around 70 per cent
- Optimistic—around 88 per cent.

The estimated benefits of C-ITS increase with the penetration rate; ranging from \$575.7 million in the pessimistic scenario to \$3953.5 million in the optimistic scenario, Table 3.4. Around 70 per cent of the total benefits in each scenario derive from crash savings and a further 16 per cent from fuel savings.

⁵ Assuming a value of time of \$12.60 per hour in 2015.

⁶ In Europe this is known as 'signal violation/intersection safety'.

⁷ In Europe this is known as 'in-vehicle speed limits'.

Benefits	Discounted benefits for each scenario (\$m 2015)				
	Pessimistic	Moderate	Optimistic		
Crash savings	399.6	878.	2 754.5		
Crash delays	17.4	82.0	104.8		
Fuel savings	94.8	448.3	656.2		
Emissions	63.8	298.2	438.1		
Total	575.7	2 706.6	3 953.5		

Table 3.4Discounted benefits for Queensland C-ITS deployment
from 2021 to 2050

Note: A discount rate of 7 per cent is used.

Source: Adapted from Blogg et al. (2016).

United States

The National Highway Traffic Safety Administration (NHTSA) presented an economic analysis of the adoption of two safety applications in cars: intersection movement assist and right-turn assist⁸ (Wright et al. 2014).

The NHTSA found that these two technologies could potentially prevent between 425 000 and 595 000 crashes and save between 955 and 1320 lives per year when fully deployed. In 2051, this would reduce the costs resulting from motor vehicle crashes by \$72 to \$97 billion per year. Reduced property damage and congestion makes up about 14 per cent of these cost savings.

Costs

The costs of implementing C-ITS will depend on the:

- choice of DSRC or DSRC-cellular hybrid wireless technology
- penetration rate in the vehicle fleet
- existing infrastructure.

DSRC equipment appears to have standard unit costs; the Australian cost estimates cited in Table 3.5 use estimates from the US study. The US estimate of upfront per unit hybrid DSRC cellular costs at \$272, lower than the cost of a DSRC unit, whereas the EU study estimates the costs of the hybrid unit to be greater than DSRC alone.

Table 3.5 Unit costs for Queensland DSRC C-ITS deployment

Cost	Unit	Value
On-board unit (upfront)	\$/unit	347
On-board unit (ongoing)	\$/unit/year	34
Roadside unit (upfront)	\$/site	13 000
Roadside unit (ongoing)	\$/site/year	3 696

Source: Adapted from Blogg et al. (2016)

Unlike DSRC, cellular C-ITS will only need to install infrastructure in areas not currently covered. Hence, cellular C-ITS infrastructure costs varies between countries depending on the quality and coverage of the existing mobile phone network. Governments may also restrict coverage to those areas where benefits exceed costs.

Both DSRC and cellular C-ITS need infrastructure to connect to central ITS systems. The US government (Wright et al. 2014) have estimated the costs of installing and maintaining a DSRC and the costs of connecting that site to 'back-room' operations. For DSRC sites where a connection with sufficient bandwidth exists, costs of upgrade are very low, around \$4 000 per site. The costs progressively rise with the level of upgrade. Installing a new system costs over \$50 000.

Table 3.6 shows the total discounted costs vary with penetration in Queensland (Blogg et al 2016). The costs range from \$275.6 million for the pessimistic uptake scenario to around one billion dollars for the optimistic uptake scenario. Upfront and ongoing costs are roughly equal.

As with the European study, by far the largest costs is installing on-board units in vehicles. They make up 84 per cent of the upfront costs in the moderate scenario and 74 per cent of the ongoing costs. Both the upfront and ongoing costs for the on-board units increase with the penetration rate. Whereas, the costs of the central ITS system and roadside units remain relatively static.

		Uptake Scenario			
Costs		Pessimistic	Moderate	Optimistic	
			\$m 2015		
Upfront costs	Pilot	24.6	24.6	24.6	
	Central ITS systems	11.1	15.6	17.5	
	Roadside units	21.3	21.3	21.3	
	On-board units	71.8	328.9	442.2	
	Sub-total	128.8	390.4	505.6	
Ongoing costs	Central ITS systems	21.2	25.9	25.9	
	Roadside units	63.3	78.6	78.6	
	On-board units	62.3	295.7	432.7	
	Sub-total	146.8	400.2	537.2	
Total costs		275.6	790.6	042.9	

Table 3.6 Total discounted costs for Queensland C-ITS deployment

Note: Discount rate of 7 per cent is used. Adapted from: Blogg et al. (2016)

Figure 3.2 shows the annual costs of the C-ITS equipment deployment in Europe assumed in Ricardo-AEA (2016). The costs are expected to rise rapidly as deployment starts in 2019 reaching their peak in the mid-2020s at around \$4.6 billion per year before falling. Around 95 per cent of total annual C-ITS equipment costs and 82 per cent of cumulative costs to 2030 are from installing on-board units in new vehicles.



Figure 3.2 Total additional annual equipment costs for the European deployment of C-ITS

Note: Aftermarket units are similar to portable units in Australia, though in-vehicle rather than carried by pedestrians and cyclists.

Source: Adapted from Ricardo-AEA (2016) with currency converted to 2016 Australian dollars.

Aftermarket or portable units are smartphones or personal navigation devices (such as TomToms) used in vehicles but not connected to the vehicle itself. These units are the second largest component of the equipment costs and are expected to peak at around \$1 billion per year in 2021. However, once the whole vehicle fleet has factory-installed equipment, from 2027, portable units will be no longer needed.

Road agency costs are likely to be small relative to vehicle costs. Infrastructure costs (road-side units) are a minor part of costs and are dominated by new infrastructure on inter-urban roads and upgrades of urban road infrastructure.

Ricardo-AEA (2016) model costs for different implementation scenarios—varying C-ITS applications and geographic location—and found there was very little variation in costs between scenarios. Even in the most restrictive scenarios, all vehicles must be equipped with on-board units and these units comprise almost all the cost of implementation.

Ricardo-AEA (2016) model a hybrid scenario with cellular C-ITS (4G-LTE) as an addition to DSRC. As Figure 3.3 shows, the high cost of data transmission on the cellular network under the hybrid scenario make it more costly than DSRC only.



Figure 3.3 DSRC-only and cellular-DSRC hybrid cumulative roadside infrastructure and data costs

There are large areas of Australia not covered by 4G-LTE and cellular data costs vary considerably around the world. Therefore, the costs of a DSRC-cellular hybrid model for Australia may be substantially different than for Europe.

The NHTSA estimated that the annual cost of complying with their proposed mandate in 2050 would range from \$5.3 billion to \$6.6 billion. This includes the costs for on-board units, applications, security systems, supporting equipment and communication networks including data costs and the fuel economy impact due to the increased weight from the in-vehicle equipment.

The primary source of the difference between the lower and upper cost estimates is whether manufacturers choose the one-DSCR radio hybrid option or the two-DSCR radio (pure DSRC) option. The hybrid approach has substantially higher data costs than the pure DSRC approach. However, the savings in total on-board device costs are higher meaning the total hybrid cost is lower.

Source: Adapted from Ricardo-AEA (2016) with legend changes and currency converted to Australian dollars.

Benefit-cost analyses

Australia

Based on the scenarios described in Blogg et al. (2016), the estimated BCR for C-ITS deployment is 3.4 for the moderate penetration rate scenario, 2.1 for the pessimistic penetration rate scenario and 3.8 for the optimistic penetration rate scenario.

The payback year, or the year where the cumulative benefits exceed the cumulative costs, is 2033 for the moderate scenario, 2031 for the pessimistic scenario and 2030 for the optimistic scenario. Benefits accrue from 2021.

Due to the importance of the crash reduction rate, the authors performed sensitivity tests on this parameter. If crash reduction is the only benefit, the crash reduction benefit would need to be at least 8.1 per cent for C-ITS to be economically viable. With fuel and emission savings included the crash reduction benefit needs to be far lower, at least 0.4 per cent, to break-even.

United States

The NHTSA presents their BCR estimate as a 'breakeven' analysis to identify the calendar year during which the cumulative economic value of safety benefits from intersection movement assist and right-turn assist exceed costs. This breakeven year is between 2029 and 2031 at a 3 per cent discount rate and between 2030 and 2032 at a 7 per cent discount rate.

Europe

The European Ricardo-AEA (2016) study provides a number of BCR estimates across different assumptions regarding choice of C-ITS applications and geographic locations. Table 3.7 shows the cumulative BCR to 2030 for the different scenarios.

For the most restrictive rollouts, Scenarios A and B, where only basic safety-based V2V applications, some V2I applications and enhanced route guidance and navigation are implemented on regional arterials, the BCR is only around one.

Fuller rollouts (Scenarios C to E) have a much higher BCR of 2.9 as the addition of more applications greatly increases the benefits while costs remain the same as the smaller rollouts. Interestingly there is no discernible difference in estimated BCRs between these three scenarios suggesting that it is the urban deployment of intersection-related services, parking services and enhanced route guidance and navigation, and also equipping buses with safety-based V2V that make up the nearly all of the additional benefits and most of the total benefits.

Scenario	Description	Cumulative BCR to 2030 ^a
Scenario A	Basic safety V2V; Enhanced route guidance and navigation in cars for TEN-T [®] Corridors and Core	1.0
Scenario B	Scenario A plus: Roadside units in all specified motorways and inter-urban roads Some V2I services Enhanced route guidance and navigation to all TEN-T roads	1.3
Scenario C	Scenario B plus: Urban deployment of intersection-related services, parking services and enhanced route guidance and navigation on urban roads Buses with safety based V2V	2.9
Scenario D	Scenario C plus: Loading zone management Urban zone access control	2.9
Scenario E	Scenario D plus: Vulnerable road user protection Cooperative collision risk warning Motorcycle approaching indication Wrong way driving Parking services for freight	2.9

Table 3.7 Cumulative BCRs to 2030 for different European C-ITS rollout scenarios

a A discount rate of 4 per cent is used.

b TEN-T (Trans European Transport Network) is a collection of roads linking major centres across the EU.Source: Adapted from Ricardo-AEA (2016).

A hybrid Scenario C where cellular C-ITS for V2I only⁹ was included in lieu of DSCR road-side unit infrastructure roll-out results in a higher BCR in 2030 (based only on the benefits and costs in 2030) of 7.4, compared to the DSRC-only scenario of 6.1. These higher benefits arise because the widespread availability of cellular technologies mean benefits accrue earlier.

Ricardo-AEA (2016) also compares a DSRC rollout with a hybrid rollout. The BCR for the hybrid option is higher because readily available cellular technology means time saving benefits from navigation applications accrue earlier.

⁹ This is likely because direct communication between cellular devices for V2V is still being researched (see earlier in this chapter).

Conclusions

The results of economic analysis of C-ITS in Australia, Europe and the United States is remarkably consistent in many respects despite methodological and reporting differences.

- The cost of implementing C-ITS is independent of the choice of applications because all vehicles need to include on-board units regardless of the number of applications.
- Total benefits and BCRs increase as the number of applications increase up to the point where applications are duplicating benefits.
- Travel time and safety are the two largest benefit categories and the largest benefits accrue with urban deployment.
- Finally, evidence from both the US and European studies suggests that a DSRC-cellular hybrid approach is an economic solution to implementing C-ITS. Under the hybrid approach, DSRC technology would support safety-of-life applications and cellular would support traffic and navigations applications. However, more research is needed to understand outcomes in Australia.

CHAPTER 4 Automated Vehicles

Defining automation

Automated vehicles encompass a range of vehicle types with differing levels of automation. At the lowest level of automation, the system assists the driver in certain tasks but the driver does all other tasks and retains overall control of the vehicle. At the highest level of automation, the system controls the vehicle independent of the driver. Table 4.1 shows the Society of Automotive Engineers' (SAE) definitions of automation levels. From Level 3 and above (the shaded area) the system monitors the driving environment.

Level	Name	Steering & Acceleration/ Deceleration	Monitoring environment	Fallback performance	System capability
I	Driver assistance	Human & system	Human	Human	Some
2	Partial automation	System	Human	Human	Some
3	Conditional automation	System	System	Human	Some
4	High automation	System	System	System	Some
5	Full automation	System	System	System	All

Table 4.1 SAE levels of vehicle automation

Source: Center for Internet and Society (2013)

Reaching SAE level 5 capability, where the automated system is in control at all times and in all road environments is a very complex engineering problem. It is not clear if or when these vehicles may become commercially available (Department of Infrastructure and Regional Development 2017). Given this uncertainty, understanding the costs and benefits associated with points along the pathway is important. The development path to full automation is currently following two broad pathways.

- Incremental automation of conventional vehicles. Essentially, development occurs left to right across Table 4.1. The driver warning, driver assistance sections below describe progress to date.
- Some manufacturers began development at Level 4 automation and are now incrementally increasing the road conditions that their vehicles can autonomously manage. The potential impacts of fully automated vehicles are discussed in the full automation section below.

This paper does not consider Level 3, conditionally automated vehicles. The literature on the costs and benefits of conditionally automated vehicles is scarce and that which exists suggests

conditional automation may introduce additional human risk factors. For example, Williamson (2016) notes there is good evidence that leaving the driver 'out of the loop' when technology is in control leads to significant performance impairment when the driver is asked to resume control quickly.

This report also does not consider the implications of maintaining roads that allow traditional and automated vehicles to operate simultaneously. Given the average lifespan of a vehicle in Australia is over 10 years (Australian Bureau of Statistics 2016), traditional vehicles are likely to be operational well after the introduction of automated vehicles.

Driver warning systems

Although related to vehicle automation, driver-warning systems are a separate development in vehicle technology. These technologies are a precursor to automation where sensors alert the driver rather than activate an automated response.

Warning systems are currently available to advise drivers of excessive speed, drowsiness, maintaining lane position and night vision warning. Driver warning systems principally provide safety benefits with some indirect benefits arising from the reduction in accidents. Malone et al. (2008) estimates that speed warnings could reduce fatalities by up around 8 per cent and drowsiness alert by around 5 per cent.

A 2008 eIMPACT study estimate BCRs of over 3 for lane change assistance warnings and 2 for driver drowsiness warning systems based on expected outcomes (Malone et al. 2008). However, the widespread recent uptake of these technologies means studies are beginning to emerge demonstrating real world outcomes. Insurance claim data from the US is suggesting that Lane Departure Warning Systems are not reducing accidents (Insurance Institute for Highway Safety 2012).

Driver assistance systems

One weakness of driver warning systems is that drivers may not respond appropriately to the warning, thereby reducing the effectiveness of the system. With driver assistance systems, the vehicle responds, potentially improving safety.

Vehicles with driver assistance systems, are currently commercially available (Table 4.2). Electronic stability control (ESC) is mandatory in new vehicles in Australia and has penetrated around 40 per cent of the fleet. Many heavy vehicles are equipped with Automated Emergency Braking Systems (AEBS) and Lane Departure Assistance Systems (LDAS). Similar to the warning systems, driver assistance systems provide safety benefits with some accompanying traffic flow benefits.

Technology	Description
Electronic stability control	Improves safety by automatically applying the brakes in the event the vehicle becomes unstable.
Adaptive cruise control	Improves safety by automatically maintaining a safe distance from the vehicle in front.
Adaptive headlights	Improves safety by giving drivers better nighttime vision.
Autonomous emergency braking	Improves safety in critical situations by warning the driver; and reducing the severity of crashes by lowering the speed of collision and, in some cases, by preparing the vehicle and restraint systems for impact.
Lane departure assistance systems	Improves safety by warning the driver of lane departures and in more advanced technologies automatically correcting the vehicle course.

Table 4.2 Purpose and functionality of driver assistance technologies

Source: BITRE

The eIMPACT study (Malone et al. 2008) gives BCRs of between 2.8 and 4.4 for electronic stability control, between 3.6 and 4.1 for automatic emergency braking and between 2.6 and 3.7 for lane departure assistance systems.

Insurance claim data in the US shows that adaptive headlights and adaptive cruise control are effective in reducing accidents (Insurance Institute for Highway Safety 2012). Front to rear collisions declined by around 5 per cent for models with adaptive cruise control. Vehicles with collision warning systems also reduce accidents, but to a lesser degree than those with adaptive cruise control.

The value of driver assistance systems in buses

Lutin and Kornhauser (2013) examines the costs and the safety benefits of implementing collision avoidance technologies to the New Jersey Transit Bus Fleet. Given the uncertainty, the authors assume benefits ranging from 10 to 90 per rent reductions in accidents and a cost of implementation of between 1 and 5 times the cost of upgrading a Mercedes car. Except for three scenarios, installation costs will be recouped well within the vehicle life.

Driverless vehicles in selected environments

Driverless vehicles have operated for several years in specific environments. Ports, including the Port of Sydney and the Port of Brisbane, move containers with automated vehicles (Autostrads) operated from a control centre. The mining industry makes use of automated vehicles for haulage across mine sites. For example, Rio Tinto has operated driverless vehicles on its Pilbara mine sites for several years from a control centre in Perth.

Perth, Darwin, London, Paris and many cities are trialling automated shuttle buses. In all trials, buses travel relatively slowly. These trials aim to build consumer acceptance of automated vehicles and test the technology's capabilities.

The next step forward will be high automation on limited road types. The US trucking industry is interested in the potential of vehicles that can autonomously drive on highways to help manage driver fatigue (Short & Murray 2016). If drivers could rest for extended periods on long-haul journeys both productivity and driver well-being could improve.

Full automation

Fully automated vehicles that can operate in all conditions are potentially transformational to road transport. The available literature suggests potentially large, but highly uncertain implications for:

- the size of the vehicle fleet
- total vehicle kilometres travelled
- congestion
- road safety
- emissions
- urban form
- employment.

Vehicle fleet and vehicle kilometres travelled

If road users were free to undertake other tasks whilst driving some of the disutility of road travel would disappear. Understanding the consequences of this change for vehicle kilometres travel and vehicle ownership is the subject of considerable speculation and research. The literature to date has used scenario analysis to determine the impacts.

The International Transport Forum (ITF) Oundertook scenario analysis for the Portuguese capital, Lisbon. The study considered two scenarios: an 'autobot' scenario consisting of a fleet of driverless vehicles that provide single user transport services and a 'taxibot' fleet of driverless vehicles that provide ride sharing services (International Transport Forum 2015). The key insights from the study were:

- When 100 per cent of vehicles are automated the vehicle fleet could be as low as 10 per cent of the baseline vehicle fleet providing ride sharing and mass public transport are implemented.
- Under the autobot model with no mass public transport the vehicle fleet is estimated to be 22.8 per cent of the baseline fleet.
- Despite dramatically declining vehicle numbers, total vehicle kilometres travelled increases relative to the baseline¹⁰ under all scenarios and almost doubles under the autobot scenario with no mass public transport. The reasons for this increase are the impact of replacing buses with standard automated vehicles and 'empty running'.
- When the authors assumed a 50/50 split between 'autobot' or 'taxibot' and private ownership, both the vehicle fleet and vehicle kilometres travelled were higher than other scenarios.

Using theirTransposition model, Davidson and Spinoulas (2016) describe the potential changes in vehicle kilometres travelled and generalised costs in Australia. The overall conclusions of the Davidson and Spinoulas study are that high uptake of automated vehicles without ride or vehicle sharing is likely to lead to increases in vehicle kilometres travelled of 54 per cent

¹⁰ The baseline in this study reflects the current vehicle ownership model, that is, a fleet of privately owned traditional vehicles.

in 2046. With ride sharing the total vehicle kilometres travelled are 9 per cent lower than base case levels. Ride sharing leads to lower vehicle kilometres travelled in part because of higher vehicle occupancy but also because of the higher costs assumed in the ride share model dampen demand. The study estimates that daily per capita generalised costs rise from \$25 without ride sharing to \$30 with ride sharing.

The literature is consistent in recognising that ride sharing will reduce vehicle fleet size (Dia et al. 2016). The impact of ride sharing on vehicle kilometres travelled varies more, depending on assumed wait times and length of journey. If people are prepared to tolerate a longer route, then the number of trips and total vehicle kilometres travelled falls.

A full assessment of the likely uptake of car and ride sharing is beyond the scope of this study. However, it is worth noting that car sharing does not suit all road users. Litman (2017) suggests it is uneconomic for drivers travelling more than 10 000 km per year to share a vehicle and that tradesmen that carry dirty loads would need a personal vehicle. Moreover, road users with particular preferences, such as prestige vehicle owners, may prefer not to use ride-sharing services.

Road safety

Highly automated vehicles remove the 'human' element from driving and therefore have the potential to reduce greatly both the number and severity of road accidents. Accidents caused by drivers impaired by alcohol, drugs and fatigue could largely disappear. If Artificial Intelligence (AI) controlled vehicle speed, many speed related accidents might also disappear.

However, automated vehicles may introduce new causes of accidents such as system failures. Also, automated vehicles will always have some interaction with people. Accidents may occur between automated and traditional vehicles using the same road space, and some crashes with pedestrians and cyclists may be unavoidable.

US studies have shown that if accidents could be reduced by 90 per cent, the economic benefit per automated vehicle per year is \$1250 (Fagnant & Kockelman 2015). Even at 50 per cent the benefit and lower uptake rates the saving is around \$560 per year. The estimated cost of automation in this study assumed to be \$13 000 per vehicle at 10 per cent uptake rate and \$3900 at 100 per cent uptake. Davidson and Spinoulas (2016) includes similar estimates for Australia where a 90 per cent reduction in accidents yields benefits of around \$3.5 billion.

Of course, the safety benefits of fully autonomous vehicles are untested in real world conditions and are therefore subject to considerable uncertainty. Further research is needed here.

Vehicle emissions

Available international evidence suggests that emissions reduction will occur if total vehicle kilometres travelled decline because of increased ride sharing or if automated vehicles are powered by electricity. Because electric vehicles have higher capital costs and lower operating costs than conventional vehicles, the overall cost of running a ride or car sharing fleet is lower for electric vehicles.

However, Australian electricity generation is presently highly emissions intensive because of our heavy reliance on coal; 61 per cent of Australia's electricity came from coal fired power plants in 2013-14 (Commonwealth Department of Industry and Science 2015). Therefore, even if automated vehicles are also electric it does not follow that Australia's greenhouse gas emissions will decline significantly. The Australian Government has committed to reduce greenhouse gas emissions to between 26 and 28 per cent below 2005 levels by 2030 as part of the Paris Climate Agreement (Australian Government 2015).

Road infrastructure

The cost of road building and maintaining infrastructure may change with the introduction of automated vehicles. Studies to date largely give anecdotal examples rather than quantify costs. For example, some automated vehicles need well-maintained lane markings and cannot understand a road worker using hand signals (Ng & Lin 2016). Automated vehicles will require high quality lane markings, traffic signals and other road infrastructure (Short & Murray 2016).

To ensure the reliability of fully automated vehicles, all roads will need to meet automated vehicle standards. Australian Governments are already investigating future infrastructure needs through trials and Austroads' Connected and Automated Vehicles Program.

Urban form

Because automated vehicles can 'run empty' they reduce the need for parking. International Transport Forum (2015), in its analysis of Lisbon, estimated a potential decline in the need for parking spaces of between 5.6 and 16 per cent of the baseline with 100 per cent use of shared automated vehicles. Under the assumption that the fleet comprises of a 50/50 split between 'autobot' or 'taxibot' and private ownership, the estimated change in parking space requirements ranges between a 25 per cent decline and 6 per cent increase. The capacity of existing road space may increase if on-street parking is no longer required.

One implication of improving the utility of driving is that long commuting distances become less onerous potentially increasing urban sprawl (Litman 2017). The same study also suggests that urban living may become more attractive if automated vehicles lead to safer and cleaner road environments.

Congestion

Congestion costs are a function of traffic volumes and road capacity. The introduction of automated vehicles may change both. As discussed above, vehicle kilometres travelled may increase substantially under some scenarios. However, road capacity may also increase if on street parking becomes unnecessary and automated vehicles can travel with smaller headway and in narrower lanes than traditional vehicles (Veitch Lister Consulting 2016). The overall effect on congestion is uncertain.

BITRE scenario analysis suggests that if automated vehicles do not induce extra travel then a 30 per cent penetration rate would result in a substantial decline in congestion costs at 2030 (Bureau of Infrastructure, Transport and Economics 2015).

Other studies suggest that automated vehicles could reduce road congestion, by increasing per lane capacity (Somers & Weeratunga 2015). Fagnant and Kockelman (2015) estimate a per automated vehicle annual reduction in congestion costs of around \$715. However, that saving is contingent on the assumption of a 10 per cent increase in vehicle kilometres travelled, which is far lower than estimated in other studies.

Increased mobility for non-drivers

One of the most often cited benefits of automated vehicles is increased mobility for the elderly, the disabled and other non-drivers. The literature contains very little quantification of these benefits either in terms of the number of induced trips or the value of the increased mobility. Recent analysis of a survey of drivers in the US, suggest that if automated vehicles were readily available to non-drivers then passenger vehicle kilometres travelled could increase by up to 11 per cent (Sivak & Schoettle 2015).

Many non-drivers will be able to use standard automated vehicles without assistance. However, some non-drivers will continue to need help in accessing vehicles even with the move to automation. Ride and car-sharing schemes will likely rely on smart apps that may not be suited to all people with disabilities. Ensuring equity of access will remain a government concern.

Reduced labour costs for commercial transport operators

Labour costs are a significant component of costs of commercial trucking, taxi and bus operations. American Transport Research Institute (2014) estimates that labour contributed 34 per cent to average marginal operating costs for trucking companies in the United States. If automation reduces the need for labour, the cost of commercial transport may decline.

Changing value of time for private vehicle drivers

Non-commercial drivers will also benefit from the alternatives automated vehicles offer. Drivers could use their travel time working or engaging in some leisure activity. The economic cost of time spent driving is commonly valued at 40 per cent of the average wage. However, if such time could be more productively used this cost could decline.

Varying the assumption around the effect of automated vehicles on value of time could vary the overall change in vehicle kilometres travelled. Auld et al. (2016) estimate that a 25 per cent decline in value of time could induce an increase in vehicle kilometres travelled of around 10 per cent whereas a 75 per cent decline in value of time could induce an increase in vehicle kilometres travelled of 59 per cent.

Do road users want driverless cars?

The studies cited above demonstrate that costs and benefits of automation vary substantially with assumed uptake rates of driverless vehicles. Literature investigating driver preferences, willingness to pay and uptake rates is beginning to emerge, most commonly in the US.

Schoettle and Sivak (2016) asked 618 survey respondents to express a preference between conventional vehicles, partially automated vehicles and fully automated vehicles. Only 15.8 per cent of respondents preferred fully automated vehicles and over 45.8 per preferred conventional vehicles. The results remain relatively unchanged from a survey conducted by the authors in 2015.

Kockelman et al. (2016) surveyed 2167 Americans on their willingness to pay (WTP) for selected automation technologies. The technologies ranged from readily available driver assistance technologies, such as electronic stability control, to fully automated vehicles. The market penetration of automated vehicles would reach 87 per cent even assuming 10 per cent per year decline in technology costs and 5 per cent per year increase in WTP.

One recent Australian study, Ellis et al. (2016), estimated the average willingness to use driverless vehicles at between 52 and 75 per cent of drivers depending on awareness of the potential benefits of the technology. Improved safety has the biggest impact on the attractiveness of driverless vehicles for respondents. The study also estimated an average WTP for driverless capability of \$6903 per vehicle and that 100 per cent uptake would occur around 2038. The authors acknowledge further research is needed to better understand consumer preferences in Australia.

As Australians become more familiar with automated vehicles, it is likely that willingness to use and WTP estimates will increase. Early automation of taxis may enable consumers to become more comfortable with automated vehicles and accelerate the uptake rate among private vehicle owners.

Employment

The overall effect of automated vehicles on Australian employment are difficult to estimate with available research showing the potential for both job losses and job creation across several sectors.

Around 247 000 Australians were employed driving trucks, buses and taxis in 2015 of which 173 000 were truck drivers (Australian Government 2016). Studies acknowledge that an automated vehicle fleet will require fewer drivers but point to the creation of new jobs managing and maintaining the automated fleet (Robotics VO 2016). Job opportunities may arise under the ride-sharing model within the taxi industry. Vehicles will need to be cleaned and cleared of lost property and many disabled people will need help entering vehicles. Any decrease in long-haul driving jobs may be offset by last-mile jobs.

The demographic characteristics of people working in effected industries will influence the impact on employment. Of the 25 351 people employed as taxi drivers in 2011, 46 per cent were aged 50 or over, Figure 4.1. Automation will be a gradual process, enabling current drivers to move to retirement and future drivers to move to other jobs.



Figure 4.1 Age profile of Australia taxi drivers in 2011

If automated vehicles were to drive an expansion of 'mobility as a service', the size of the car fleet could fall significantly resulting in a far smaller global car manufacturing industry.

Australia has a small and declining car manufacturing industry but some automated vehicle proponents think government investment could generate highly skilled technology-related jobs in Australia (Australian Driverless Vehicle Initiative 2016). Industry analysts also see automated vehicles and related ICT technologies becoming an increasing part of the vehicle manufacturing supply chain. Kearney (2016) estimates it to be \$66.3 billion in 2020 growing to \$246 billion in 2030.

However, Australia is not unique in considering the economic and employment benefits of automated vehicles. With its established car manufacturing sector, Germany currently generates \$728 million in value add from driver assistance technologies. With the expected expansion of driver assistance technologies and the roll out of highly automated vehicles, this could grow to \$3.3 billion in 2020 with 120 000 jobs (Cacilo 2016).

Additionally, any productivity enhancing effects of automated vehicles are likely to increase economic activity and generate new jobs. However, drivers who lose their jobs may not be readily employable in these new roles. If automated vehicles increase the mobility of people with disabilities, their job opportunities may also expand. Government will need to consider the implications of any large-scale changes in employment opportunities.

Source: ABS, 2011 Census

The cost of automation

Automation capability (from driver warning systems to full automation) needs a variety of equipment not needed in a traditional vehicle. Litman (2017) lists the following typical additional requirements:

- · diverse and redundant sensors capable of operating in all weather and road conditions
- short- and long-range wireless network connections that enable V2V communication and access to maps, software upgrades and emergency messages
- GPS systems and maps
- automated controls for steering, braking and signals
- highly reliable servers, software and power supplies
- additional testing, maintenance and repair of critical components.

The list highlights the need to ensure the reliability of the technology through redundant sensors and additional maintenance.

Kockelman et al. (2016) presents estimates of in-vehicle costs for current, emerging and future technologies, Table 4.3. The estimates provided here are for 2015, however, the Kockelman study also assumes that costs will decline at a rate of 5 per cent a year to 2045.

Table 4.3 In-vehicle	cost of	automation
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Automated function	Cost (\$)
Electronic stability control	130
Lane centring	235
Right-turn assist	585
Cross traffic sensor	715
Adaptive headlight	300
Pedestrian detection	585
Adaptive cruise control	520
Blind-spot monitoring	520
Traffic sign recognition	585
Autonomous emergency braking	585
Connectivity	260
Self-parking	2 400

Source: Kockelman et al. (2016)

Vehicle manufacturers generally offer 'driver assistance packages' that incorporate a variety of functions. In 2009, the Volvo package included collision avoidance, adaptive cruise control and distance alert and cost consumers around \$2500 and a BMW system with blind spot detector, lane departure warning system and high beam assist cost around \$2000 (Pitale et al. 2009).

Estimates of the costs of fully automated vehicles is highly uncertain at this time given that such vehicles are not yet available. Kockelman et al. (2016) estimates automated vehicles would cost \$52 000 more than conventional vehicles in 2015 falling to around \$11 000 in 2045 as the technology matures. Litman (2017) estimates that mature automated vehicle technology

could add several thousand dollars to the cost of a new vehicle and several hundred dollars to annual maintenance costs.

The modifications needed to install automated technologies in heavy vehicles are similar to those needed for passenger vehicles. Industry estimates put the cost of upgrading a truck to be fully automated at around \$39 000 (Short & Murray 2016).

Benefit-cost analysis

Fagnant and Kockelman (2015) provides one of a limited number of studies examining both the benefits and costs of automated vehicles. The key assumptions underlying this analysis are:

- automated vehicle penetration rates of 10, 50 and 90 per cent
- cost per automated vehicle of \$13 000 at 10 per cent penetration rate to \$4000 at 90 per cent penetration
- an increase in travel distance of 20 per cent per automated vehicle at 10 per cent penetration and 10 per cent at 50 and 90 per cent penetration
- accident reduction rates of between 15 and 60 per cent and comprehensive accident savings costs
- congestion reduction of up to 25 per cent on arterial roads and 15 per cent on freeways.

Based on these assumptions, the study estimates net present value of benefits of between \$18 000 per vehicle at 10 per cent penetration rate and \$66 000 per vehicle at 90 per cent penetration rate. These NPV estimates yield BCRs of around 2.4 and 17. However, the \$4000 estimated marginal cost is lower than many other studies and the assumption of a 10 per cent increase in travel distance per automated vehicle may could lead to an overestimate of congestion benefits. Nevertheless, considering only the safety benefits and a \$16 000 cost of automation yields a BCR above 1.3.

Combining connected and automated technologies

C-ITS and automated vehicles are often discussed together but they are independent technologies. Although, C-ITS could improve the situational awareness of AI driving and allow vehicles to coordinate actions with other vehicles. Road authorities could also communicate directly with the vehicle AI via V2I to manage traffic flow.

Kockelman et al. (2016) examines the benefits and costs of connected and automated vehicles in Austin, Texas. Table 4.4 summarises the results with BCRs always greater than 2 regardless of the penetration rate. The estimated per vehicle congestion benefits are highest at the 10 per cent penetration rate as the initial influx of CAVs has a strong traffic smoothing effect.

		Connected and automated market penetration		penetration (%)
		10	50	90
Benefits				
Congestion reduction	\$/Veh/Year	443	222	325
Comprehensive crash savings	\$/Veh/Year	2 707	3 574	4 098
Productivity and leisure	\$/Veh/Year	89	89	89
Total annual benefits	\$/Veh/Year	5 041	5 687	6312
Costs				
Cost of automation and connectivity capabilities	\$/Veh	13 934	6 967	4 80
BCR		2.4	5.4	10

Table 4.4 Estimated BCRs for connected and automated vehicle adoption in Texas

Note: Currency in 2016 Australian dollars.

Source: Adapted from Kockelman et al. (2016).

Connected adaptive cruise control (CACC), one of the most developed technologies, enables a vehicle to adjust its speed in response to the vehicle in front. The literature includes studies of the benefits and costs of CACC applied to cars, buses and heavy vehicles.

Lutin and Kornhauser (2013) examines the potential capacity improvements if New Jersey Transit were to apply CACC to its Trans-Hudson bus fleet. The authors consider scenarios in which CACC enables the average distance between vehicles to fall from 5 seconds (64m) to I second (2m). Bus throughput increases from 700 to 3600 buses per hour. The authors consider the potential for CACC as a cost effective alternative to expanding the rail network. New Jersey to New York is a very busy commuter route therefore the cost effectiveness of CACC in Australian cities is likely to be different.

Truck platooning involves the use of cooperative adaptive cruise control (CACC) technologies that enable heavy vehicles to communicate and maintain small but safe distances between vehicles. Currently available technologies require drivers to steer the vehicle but the AI controls the distance between vehicles. Future technologies are likely to require a driver in the leading vehicle only.

Truck platooning pilots and research are underway in Europe and the United States. Early evidence suggests that when trucks achieve a following distance of between 14 and 20 metres average fuel efficiency can improve by 4 per cent across all platooning vehicles (Bishop 2016).

CHAPTER 5 Policy insights and further research

Technology is greatly changing the way our vehicles and road networks operate. In the future, automated road vehicles could deliver benefits such as improved safety, more efficient and productive transport networks, more liveable city environments and better access to transport services for those unable to drive.

This chapter begins with a summary of potential benefits and combining ITS, C-ITS and automated vehicle technologies. Then, drawing on this information the chapter provides insights for policy development. The six issues raised in this chapter are:

- implications for infrastructure investment
- implications for government road-related revenue
- realising the social benefits of road transport technologies
- implications for public transport
- technology in rural and remote Australia
- further research into implementing fully automated vehicles.

Summary of benefits and costs of road technologies

The literature highlights the strong benefits derived from Australian investment in signal coordination over a number of decades, with many BCRs above 10.

Ramp metering is another highly beneficial ITS technology with BCRs typically estimated as greater than 10. The technology is becoming standard in the construction of new motorways in Australia.

There is limited literature comparing the benefits and costs of high occupancy vehicle (HOV) lanes but evidence shows reductions in travel times of up to 21 per cent for bus travellers.

Variable messaging signs is one ITS technology for which benefits are not clear. The costs of providing real-time information sometimes outweigh the benefits of doing so. 'End-of-queue' warnings are not cost effective whereas weather-related messages have BCRs above 1.

Variable speed limits clearly provide safety and efficiency benefits that clearly outweigh the costs of the technology, with BCRs around above 4 and under some circumstances above 10.

Cooperative-ITS is economically efficient with DSRC or a hybrid cellular-DSRC technologies. Some evidence suggests that the hybrid model may ultimately prove superior because it utilises the DSRC to facilitate safety-related applications for which it is highly suited and cellular to facilitate information transfer applications.

The largest cost associated with C-ITS is the on-board units needed in all vehicles. Many applications will also need road-side units, although these are relatively low cost. In areas of Australia, where ITS infrastructure is already in place the cost of road-side units is very low.

Given that all C-ITS applications need the same infrastructure, the literature generally assesses the BCRs of bundles of applications. It is clear that far larger benefits arise from urban deployment than deployment on regional arterials. A study of the European road network estimated a BCR of around 1 for C-ITS applications applied to its regional arterial road network and 2.9 when extended to urban roads (Ricardo-AEA 2016). An Australian analysis of safety-of-life applications elicited a BCR of 3.8 with 90 per cent penetration rates (Blogg et al. 2016).

Some low-level automated vehicle technologies are already demonstrably economically efficient based on their safety benefits. Examples include autonomous emergency braking and lane departure warning systems with BCRs up to 4.1 and 3.3, respectively.

The outcomes for fully automated vehicles are less certain because they depend on a combination of factors affecting congestion. These factors include the benefits of increased road capacity and operational efficiency balanced with potential increases in demand for road travel.

The estimates for change in vehicle kilometres travelled range from a decline of 9 per cent relative to baseline levels to an increase of over 100 per cent. Assuming a 10 per cent increase in vehicle kilometres travelled and an offsetting increase in road capacity leads to a \$715 reduction in congestion costs per automated vehicle per year (Fagnant & Kockelman 2015).

Automated vehicles will almost certainly provide large safety benefits because they remove the human factor from driving. However, the size of these benefits are not yet known, with analysts estimating the economic benefits of safety reduction based on assumed reductions in accident rates.

The implementation of automated vehicles has the potential to generate other economic changes, these include:

- changes in employment in the trucking, bus and taxi industries as automated vehicles reduce the need for drivers
- changes in the nature of jobs in the automotive industry as electronics become an increasing part of vehicle manufacturing
- changes in urban form, with potential for urban sprawl if commuters perceive the drive to work as more pleasant in an automated vehicle.

The costs of automated vehicles are likely to be in the order of an extra \$10 000 per car on the purchase and increased maintenance costs of several hundred dollars per year.

Implications for infrastructure investment

Evidence presented in Chapter 2 suggests that road agency investment in ITS technologies, such as ramp metering, can increase throughput by up to 19 per cent economically. Jurisdictions worldwide are showing increasing interest in using ITS as a substitute for building new road capacity. In its assessment of transport infrastructure projects seeking Commonwealth funding, the Australian Government considers the extent to which technology solutions, such as ITS, could optimise the capacity of new and existing infrastructure. The Queensland Government require project proponents to consider ITS options in conjunction with conventional investment. This practice enables jurisdictions to optimise the capacity of road infrastructure.

Governments may also face changes to road expenditure as automated vehicles change road use patterns. The combined effects of increasing road capacity and changes in vehicle kilometres travelled may change the need for road infrastructure. It is not clear whether that change will be an increase or a decrease.

Under a scenario where the induced demand from non-drivers and increased urban sprawl outweigh the increase in road capacity, the need for roads may increase. Conversely, if the increase in road capacity outweighs any increase in demand, car and ride sharing contribute significantly to the travel task or car and ride sharing become more prolific, then the need for road infrastructure may decline.

Implications for government road-related revenue

The Australian Government has initiated a discussion on land transport market reform with a view to aligning cost and revenue streams for roads over the long term.

The consequences of a fully automated vehicle fleet may put downward pressure on road revenue. For example:

- significant increases in car and ride-sharing would reduce the vehicle fleet thereby reducing vehicle registration revenue
- if automated vehicles were powered by electricity then revenue from the petroleum-based fuel excise would also decline.

Advances in road transport technologies may lower the costs of developing and implementing more efficient road pricing systems, such as congestion pricing.

Realising the social benefits of road transport technologies

Governments have a number of levers to ensure the social benefits of ITS can be fully realised. State agencies have directly invested in ITS technologies and are actively investigating investing in C-ITS. Evidence from this report suggests that many of these ITS technologies provide benefits and that investing in C-ITS could provide safety and time saving benefits and that these benefits alone warrant government investment.

Australian governments regulate to ensure road safety outcomes and this responsibility will remain important as C-ITS and automated vehicle technologies evolve. The safety benefits of some technologies indicate that making them mandatory may benefit society. For example, mandating autonomous emergency braking could save 600 lives at a BCR of 1.3 (Bureau of

Infrastructure, Transport and Economics 2014). Evidence presented in this report suggests that cooperative adaptive cruise control may also provide large safety benefits.

Implications for public transport

Advanced technologies can improve the safety and efficiency of on-road public transport. Utilising high occupancy vehicle prioritisation has been shown to cost effectively improve public transport performance.

Widespread adoption of fully automated vehicles has the potential to reduce demand for public transport, particularly bus services with low patronage. The availability of ride share services is already providing 'first mile – last mile' solutions for public transport users; automation will lower the costs of ride-share services potentially reducing the attractiveness of buses while increasing the attractiveness of rail services.

Technology in rural and remote Australia

Regional, rural and remote Australia is characterised by low population densities and long distances to major service centres. These characteristics affect the type of road transport technologies that are effective and the costs and feasibility of implementation.

Researchers in the United States are investigating the benefits and costs of communicating weather-related information to and from vehicles. The Western Australian Government sees potential for receiving and transferring information on floods, cyclones and bushfires (MRWA 2015) through a C-ITS system.

As described earlier, C-ITS applications are heavily reliant on the underlying wireless communication network. The costs of rolling out DSRC or cellular network information into the sparsely populated areas of Australia will affect the availability of certain applications in these regions.

Available evidence suggests that human factors, such as alcohol, distraction and not using a seat belt are primary causes of accidents in rural and remote Australia (Siskind et al. 2011). Given that fully automated vehicles take the human element out of driving, its potential for reducing accident rates is high.

Across the five years ending in 2015, 65 per cent of road fatalities occurred in regional, rural and remote Australia (Bureau of Infrastructure, Transport and Regional Economics 2016). Therefore, identifying technologies that improve safety outcomes is valuable.

Truck platooning or cooperative adaptive cruise control has the potential to ease the difficulty of transporting road freight across Australia. Studies to date have shown potential for platooning to deliver lower fuel costs in the US and Europe. Australia-specific work would help stakeholders understand the benefits of CACC compared with the mechanical coupling, such as road trains, that freight operators use in Australia.

Research needed to better understand the benefits of fully automated vehicles

Researchers do not have a good understanding of the implications of automated vehicles for total vehicle kilometres travelled. To gain a better picture of vehicle kilometres travelled further research into the following areas is of value:

- consumer acceptance of automated vehicles, although this research is in progress with, among others, the Australian Driverless Vehicle Initiative having announced its intention to undertake an annual public perception survey
- consumer acceptance of car and ride sharing
- induced demand for additional travel from non-drivers
- the value of time spent travelling in automated vehicles
- the implications of autonomy for private and commercial vehicle operating costs.

Gaining a better understanding of vehicle kilometres travelled would also improve understanding of government road-related revenue and costs.

While research indicates that automated vehicles will improve road safety, the extent of the improvement is unclear. Existing studies note that human error causes around 90 per cent of accidents and then assume that automated vehicles will reduce a proportion of those accidents. To understand fully the benefits, automated vehicle trials need to measure safety outcomes under real world conditions.

Funding efficient and equitable public transport is an ongoing challenge for government. Exploring the financial and economic implications of moving to automated vehicles in the Australian context is valuable.

Even if a move to automated vehicles is economically beneficial to society as a whole, such a significant changes may not benefit everyone. This report highlights the need for further research into the:

- labour market impacts as vehicle automation progresses
- relative costs and benefits of road transport technologies in urban, regional, rural and remote Australia.

Abbreviations

- AEB Autonomonous Emergency Braking
- Al Artificial Intelligence
- BCA Benefit Cost Analysis (also known as Cost Benefit Analysis)
- BCR Benefit Cost Ratio
- BITRE Bureau of Infrastructure, Transport and Regional Economics
- CACC Coordinated Adaptive Cruise Control
- CEA Cost Effectiveness Analysis
- C-ITS Cooperative (or Coordinated) Intelligent Transport Systems
- DIRD Department of Infrastructure and Regional Development
- DSRC Dedicated Short-Range Communication
- EU European Union
- ITS Intelligent Transport Systems
- MCA Multi-criteria analysis
- SCATS Sydney Coordinated Adaptive Traffic System
- US United States
- WTP Willingness to Pay

Glossary

Automated vehicles are vehicles capable of sensing their environment and navigating without human input. The definition encompasses low-level driver assistance technologies, such as lane departure assistance systems through to fully automated vehicles.

Autonomous emergency braking can sense slowing or stationary traffic ahead and apply the brakes if the driver fails to respond.

Car sharing model operates like a car rental service with automated vehicles.

Connected and automated vehicles combine automated and C-ITS technologies in a single vehicle.

Cooperative adaptive cruise control is communication-enabled speed and distance control technology that uses vehicle-to-vehicle communication.

Cooperative Intelligent Transport Systems enable vehicles to communicate wirelessly with other vehicles, infrastructure or other parts of the road network.

Dedicated short-range communication is a two-way short-to-medium-range wireless communication capability that permits a vehicle to communicate with other vehicles, road-side infrastructure and other road users. In Australia, the United States and the European Union, governments have indicated that DSRC will operate on the 5.9 GHz spectrum.

Driver assistance systems encompass Level 1 and 2 automation technologies such as automatic emergency braking.

Driver warning systems are a precursor to automated vehicles in which sensors warn the driver of an impending problem. Examples include blind spot detection and lane departure warning systems.

Intelligent transport systems apply information and communication technologies to the field of road transport, including infrastructure, vehicles and users.

Lane departure assistance systems are a Level 1 automation feature that will autonomously return the vehicle to its lane after warning the driver.

Lane departure warning systems warn the driver if the vehicle leaves its lane without the driver indicating.

Managed motorways combine more than one ITS feature, such as ramp metering and variable speed limits

Platooning is a fleet of vehicles with the lead vehicle driving and subsequent vehicles maintaining safe distance

Ramp metering uses traffic signals to regulate the flow of traffic onto a freeway with the intent of improving traffic throughput on the freeway.

Ride sharing is a service that allows one-time shared rides on short notice. The service is currently widely available and may become more prevalent with automated vehicles.

Right-turn assist provides real-time advice to drivers on safe right turn. In countries with rightside drive the technology is known as left-turn assist.

Signal coordination improves traffic flow by coordinating traffic signal timing in response to real-world conditions.

Variable message boards (or variable message signs) communicate real-time congestion, weather or incident related information to drivers

Variable speed limits changes the speed limit on freeways in response to the level of congestion, thereby improving traffic flow.

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